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THE ERA OF INTERNATIONAL SPACE STATION UTILIZATION BEGINS: RESEARCH STRATEGY, INTERNATIONAL COLLABORATION, AND REALIZED POTENTIAL

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With the assembly of the International Space Station (ISS) nearing completion and the support of a full-time crew of six, a new era of utilization for research is beginning. For more than 15 years, the ISS international partnership has weathered financial, technical and political challenges proving that nations can work together to complete assembly of the largest space vehicle in history. And while the ISS partners can be proud of having completed one of the most ambitious engineering projects ever conceived, the challenge of successfully using the platform remains. During the ISS assembly phase, the potential benefits of space-based research and development were demonstrated; including the advancement of scientific knowledge based on experiments conducted in space, development and testing of new technologies, and derivation of Earth applications from new understanding. The configurability and human-tended capabilities of the ISS provide a unique platform. The international utilization strategy is based on research ranging from physical sciences, biology, medicine, psychology, to Earth observation, human exploration preparation and technology demonstration. The ability to complete follow-on investigations in a period of months allows researchers to make rapid advances based on new knowledge gained from ISS activities. During the utilization phase, the ISS partners are working together to track the objectives, accomplishments, and the applications of the new knowledge gained. This presentation will summarize the consolidated international results of these tracking activities and approaches. Areas of current research on ISS with strong international cooperation will be highlighted including cardiovascular studies, cell and plant biology studies, radiation, physics of matter, and advanced alloys. Scientific knowledge and new technologies derived from research on the ISS will be realized through improving quality of life on Earth and future spaceflight endeavours. Extension of the ISS through 2020 and beyond will insure that the benefits of research will be achievable for the International Partnership.

INTRODUCTION

Historical Perspective

Several years before the first module of the International Space Station (ISS) was launched in 1998, an international collaboration between the Canadian Space Agency (CSA), European Space Agency (ESA), Japanese Aerospace Exploration Agency (JAXA), Federal Space Agency of Russia (Roscosmos) and the National Aeronautics and Space Administration (NASA) was developed. This partnership has worked together for nearly two decades to complete one of the most ambitious engineering projects ever conceived.

Over the past 12 years, the ISS Program has successfully navigated financial, technical and political challenges to put the largest manned vehicle in history into low-Earth orbit (LEO).

As the assembly phase of the ISS nears completion, the focus is shifting to the utilization phase and to the potential research achievements conducted on this research platform. Even before the first crewmember took up residency on the ISS, science and technology experiments were onboard and operating. Over the assembly period, there has been a significant increase in the number of experiments conducted and the disciplines they span. This trend will continue through 2020 and beyond – the "Era of ISS Utilization". [1]

RESEARCH STRATEGY

Scientists from around the world have a unique opportunity for their experiments to be conducted in microgravity. Over the past year international and national organizations of scientists have reviewed the important scientific potential of ISS as a research platform[1,2] To date, there have been 59 countries represented by research and educational activities on the ISS. As the era of utilization begins, it is anticipated that this number will grow.

From 1998 through March 2010, a total of 552 experiments have been conducted on ISS by the partner agencies. The experiments have been placed into seven categories in order to track the accomplishments: physical and material sciences; biology and biotechnology; human research; Earth and space science; technology development; commercial development; and, educational activities. (Figure 1)

Physical and Material Sciences Much of our understanding of physics is based on the inclusion of gravity in fundamental equations. Using the unique laboratory environment of the ISS, scientists are able to study long-term physical effects in the absence of gravity, without the complications of gravity-related processes such as buoyancy-driven convection and sedimentation. The microgravity environment allows different physical properties to dominate systems, and these have been harnessed for a wide variety of investigations in the physical sciences.[3] Within this discipline, the experiments fall into one of the following subcategories: combustion science, fluid physics, materials science, fundamental physics, plasma physics and macromolecular crystal growth (non-biological).

Biology and Biotechnology The 21st century has been referred to as the "era of biology" due to advances in genomic research and sequencing of the human genome. Microgravity represents a distinct path of biological challenge to use in exploring genomic response. Biological systems behave differently in the microgravity environment. Studying biological development and processes under varying levels of gravity for long periods of time is possible on the ISS. Previous studies have shown that microbes have an increased virulence after exposure to microgravity[4]. Studies in rotating wall bioreactors (a ground-based simulator of microgravity) have suggested potential increase in the pluripotency of cells and improves tissue morphogenesis in culture (for recent diverse examples, see references [5, 6, 7]). All levels of biological organization, from cells to whole organisms, respond to

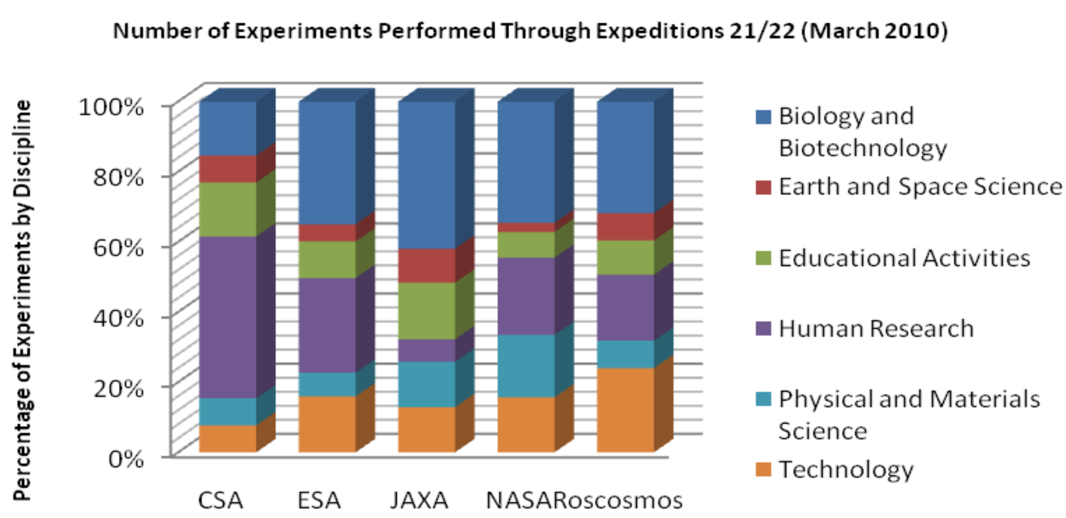

Figure 1: Number of experiment conducted on the ISS through March 2010.

the absence of gravity and can be studied on ISS. Furthermore, important exobiology questions can be addressed particularly by using the platforms on the exterior of the ISS, such as the European Technology Exposure Facility (*EuTEF*). [8] In addition, the ISS is proved to be an excellent laboratory for biotechnology implementation.

Human Research The ISS provides an environment to study various aspects of human health that will benefit long duration spaceflight crewmembers and life on Earth. Many of the investigations conducted on the ISS address the mechanisms of the risks of spaceflight to the human body[2][9] – the relationship to the microgravity and radiation environments – including musculoskeletal physiology, cardiovascular health, neurological systems, and human behavior and performance. While this research is used to develop countermeasures to reduce the risks of spaceflight, there are also many benefits that can be applied to daily life of people on Earth.

Earth and Space Science Low-Earth Orbit (LEO) is a vantage point to observe Earth and the solar system. The ISS provides a dedicated permanent orbital platform for observation instruments, external and internal, plus the capability of servicing should it be necessary. The ISS is home to several instruments that are used to view cosmic radiation, solar events, Earth's ionosphere and surface to name a few.

Technology Development The ISS provides a unique opportunity for scientists and engineers to test new technologies that are applicable for future space exploration and for use on Earth. This discipline covers many applications of technology development including environmental monitoring, communications, characterizing the microgravity environment, micro-, nano- and picosatellites, spacecraft systems, and robotics.

Commercial Development Through the history of the ISS, experiments have led to commercial development of new technology that is used on Earth. These early applications include rapid screening of candidate vaccines, microencapsulation for improved anti-tumor drugs[10, 11], and high quality protein crystal growth. [1, 12] Many research topics that are initially basic or applied may eventually evolve into industrially relevant processes and/or products on ISS.

Education and Outreach The scientific and engineering accomplishments of the ISS provide an opportunity to educate and inspire students of all ages in their studies of science, technology, engineering and math (STEM). Experiments conducted on the ISS offer many levels of student participation; from developing hardware, software, or procedures to the execution of experiments using ground control to the analysis of samples [13].

INTERNATIONAL COLLABORATION

The International Partners from Canada, Europe, Japan, Russia and the United States have worked together to develop and implement engineering designs, assembly, on orbit operations and scientific research plans. This unprecedented global partnership has succeeded through many challenges including financial difficulties and transportation concerns.

The partnership is not limited to engineering successes; it also includes collaboration on many ISS research projects. Frequently, scientists from different countries work together on a single experiment. One such experiment is the International *Caenorhabditis elegans* Experiment: Physiological Study of Nematode Worms in Weightlessness (*ICE-First*[i]). Investigators from Canada, France, Japan, and the United States worked together to study effects of the spaceflight environment on living systems. Each of the investigator teams studied a different aspect of effects which included radiobiology, muscle protein changes, ageing, apoptosis, radiation effects on living organisms, and Deoxyribonucleic Acid (DNA) damage and repair.

The ISS partner agencies have a joint database containing summaries of the research conducted on the ISS. In this library, experiments are tracked from the beginning until the final results paper is published. Each summary contains information on the science of the experiment, how the crew conducts the experiment, where on ISS does the experiment take place, references such as published results and publications related to the research, and investigator information.[14]

REALIZED POTENTIAL

Scientific research began on the ISS before the first permanent crew lived aboard. Even though the primary focus during this time was on the construction of the ISS, nearly half of the experiments conducted have been completed. As the focus of the ISS changes from assembly to utilization, the throughput of the experiments is accelerating and the number of experiments completed in a short timeframe is expected to increase. After activities are completed on ISS, it often takes 3-5 years for all the analyses to be completed and results to be published.[15] Here we highlight recent investigations and remarkable results of ISS research during the assembly years.

Physical and Material Sciences The ESA-sponsored investigation, Simulation of Geophysical Fluid Flow under Microgravity (*Geoflow*. Principal Investigator: C. Egbers, Brandenburg University of Technology, Cottbus, Germany), uses a model of the Earth's crust and liquid core comprised of silicone oil (incompressible fluid) to evaluate fluid behavior under different conditions (Figure 2). Potential applications for this research include improvements to a variety of engineering applications, such as spherical gyroscopes and bearings, centrifugal pumps and high-performance heat exchangers.

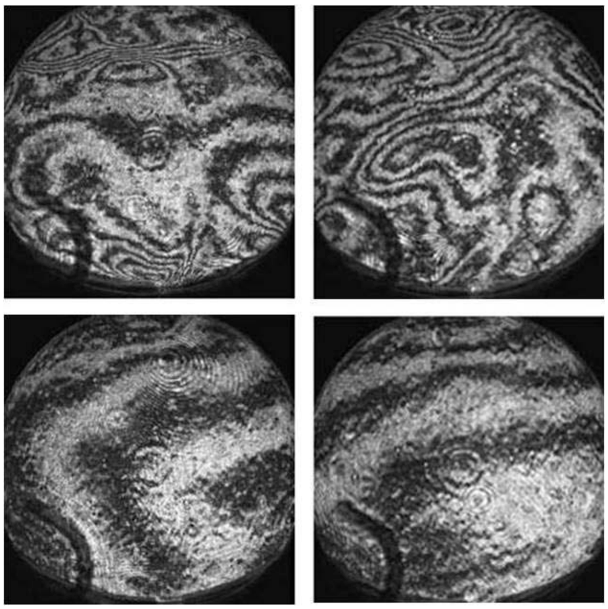

Figure 2: The interferograms shown above are from the Geoflow experiment, which is a model of Earth's crust and liquid core. Here, a viscous incompressible fluid (silicone oil) is used to understand fluid under different conditions. Applications include flow in the atmosphere and oceans, and movement of Earth's mantle on a global scale, as well as other astrophysical and geophysical problems. Results from Geoflow will also be useful for making improvements in a variety of engineering applications, such as spherical gyroscopes and bearings, centrifugal pumps, and high-performance heat exchangers. Image courtesy of Professor C. Egbers, BTU Cottbus.

One of the first experiments conducted on the ISS was the Dusty and Liquid Plasma Crystals in Conditions of Microgravity (*Plasma Crystal*. Principal Investigator: V. Fortov, Director Joint Institute for High Temperature, Russian Academy of Science, Russia). This investigation studied complex plasma, a low-temperature gaseous mixture of ionized gas, neutral gas, and micron-sized particles. The microgravity environment of the ISS provided the specific conditions necessary to develop larger three-dimensional plasma crystals in a weaker electric field when compared to crystals produced on Earth; which revealed the unique structural details of the crystals. This successful experiment has led to additional experiments such as the ESA sponsored Plasma Crystal Research on the ISS (*PK-3 Plus*. Principal Investigator: H. Thomas, Ph.D. Max Planck Institute for Extraterrestrial Physics, Garching, Germany).[16]

Biological Research Recent studies such as the Effect of Spaceflight on Microbial Gene Expression and Virulence (*Microbe* Principal Investigator: C. Nickerson, Arizona State University, Tempe, Arizona) and Microbial Drug Resistance and Virulence (*MDRV* Principal Investigator[ii]: D. Niesel, University of Texas Medical Branch, Galveston, Texas), have shown an increase in microbial virulence in some species when activated in microgravity. Through this body of research, the scientists have identified the controlling gene responsible for the increased virulence *Salmonella typhimurium*. [4, 17]

Human Health The training methods developed by the Advanced Diagnostic Ultrasound in Microgravity (*ADUM*. Principal Investigator: S. Dulchavsky, Henry Ford Health System, Detroit, Michigan) investigation have been incorporated by the American College of Surgeons Committee on Education into a computer-based program to teach ultrasound to surgeons. The remote guidance techniques developed were used by the United States Olympic committee to provide care during the Olympic Games. [1] (Figure 3)

Figure 3: (*Left*) Utilizing the ADUM protocols, ISS Expedition Commander Leroy Chiao performs an ultrasound examination of the eye on Flight Engineer Salizhan Sharipov. (*Right*) Mountain climber performs a comprehensive chest ultrasound examination at the Advanced Base Camp on Mt Everest. The operator, who had never used ultrasound equipment, was guided remotely over the internet using a satellite phone. Image provided courtesy of Scott A. Dulchavsky, M.D., Ph.D., Henry Ford Health System, Detroit, Michigan.

Human Performance The Perceptual Motor Deficits in Space (*PMDIS*. Principal Investigator: B. Fowler, York University, Downsview, Ontario, Canada) experiment sought to identify the root causes of the decline in perceptual-motor coordination (e.g. fine hand-eye coordination) that is observed during the period of adaptation to spaceflight. This experiment took place on ISS using shuttle crew as subjects. Dr. Fowler concluded that cognitive overload and stress-related factors drove the perceptual motor deficits, rather than physiological changes to the vestibular system induced by microgravity. These results have strong implications for training and operational strategies.[18]

Earth and Space Observations Mounted externally on the ISS is the JAXA sponsored experiment Monitor of All-sky X-ray Image (*MAXI* Principal Investigator: M. Matsuoka, Institute of Space and Astronautical Science (ISAS) ISS Science Project Office, Japan Aerospace Exploration Agency, Tsukuba, Japan). This investigation uses highly sensitive X-ray slit cameras to monitor over 1,000 sources of X-rays in space over an energy range of 0.5 to 30 keV. The slit cameras scan the sky through the entire 96 minute orbit of the ISS. The cameras determine the direction of X-ray sources within the narrow field of view of the slit that is orthogonally oriented to a one-dimensional position-sensitive X-ray detector. As an X-ray source moves according to the motion of the International Space Station, another position of the X-ray source is determined when the sources are captured by the collimated field of view of the camera.

Technology Development The need to monitor the presence and colonization of microbes on ISS has also led to the use of advanced molecular technologies to better understand the types of organisms the crew could encounter, the sources, and the risks. The Surface, Water and Air Biocharacterization (*SWAB.* Principal Investigator: D. Pierson, Johnson Space Center, Houston, Texas) experiment provided a method of on-orbit microbial analysis that could detect far more types of harmful microorganisms than standard ISS culture testing, including *Legionella* (the bacterium which causes Legionnaires' disease) and *Cryptosporidium* (a parasite common in contaminated water). A different microbial monitoring study employs the hardware Lab-on-a-Chip Application Development-Portable Test System (*LOCAD-PTS.* Principal investigator: N. Wainwright, Charles River Endosafe, Charleston, South Carolina), which is a handheld device that enables astronauts to perform microfluidic tests for endotoxins, glucan, and lipoteichoic acid on an interchangeable thumb-sized cartridge with a press of a button.[19] Real-time data analysis using microfluidics offers a drastic reduction in time for detection of fungi as well as gram negative and gram positive bacteria (minutes versus days), thus demonstrating the advantages of compact, user-friendly hardware that has the potential to provide astronauts with information to make autonomous decisions on contamination issues and mitigate risks to their health.

Commercial Development The Japan Aerospace Exploration Agency - High Quality Protein Crystallization Project (*JAXA-GCF*. Principal Investigator: H. Tanaka, Japan Space Forum, Tokyo, Japan) which was supported by Roscosmos for launch and recovery examined protein crystal growth in microgravity of the HQL-79 (human hematopoietic prostaglandin D2 synthase inhibitor) protein. This protein is a candidate treatment in inhibiting the effects of Duchenne's muscular dystrophy. The crystals grown in microgravity allowed researchers to more accurately determine the three-dimensional structure of HQL-79 which led to the development of a more potent form of the protein (Figure 4). [1][16]

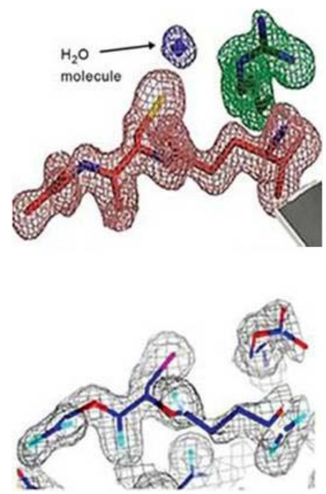

Figure 4 : Electron Density Maps of HQL-79 crystals grown in space show a more detailed three-dimensional structure (top) as compared to those grown on Earth (bottom), which also uncovered the presence of a newly identified water molecule. Figures courtesy of Yoshihiro Urade.

Education and Outreach As part of the educational activities associated with the first Canadian ISS Expedition crewmember, Robert Thirsk, 1.85 million students participated in hands-on learning activities related to ISS science. Thirsk participated in five classes from space with nearly 24,000 students attending. CSA in conjunction with the International Space University conducted an experiment on optical illusions in space with Thirsk.[1]

FUTURE EXPERIMENTS

The Alpha Magnetic Spectrometer-02 (*AMS-02*. Principal Spokesperson S. Ting, CERN, Geneva and Massachusetts Institute of Technology, Cambridge, Massachusetts) is scheduled to launch to the ISS in early 2011. The AMS-02 (Figure 5) is a state-of-the-art particle physics detector that uses the environment of space to search for antimatter, dark matter and measuring cosmic rays. By detecting and characterizing high-energy cosmic rays that are produced by highly energetic events such as supernovae explosions, it is expected that AMS-02 will advance knowledge of the universe and lead to increased understanding of the universe's origin.[1, 20]

Figure 5: The AMS-02 state-of-the-art particle physics detector. Image courtesy of the Massachusetts Institute of Technology, Cambridge, MA.

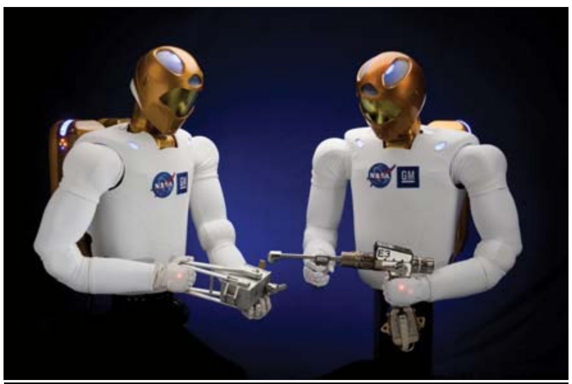

Figure 6: Robonaut2, the next generation of dexterous humanoid robots, was designed through a joint venture between NASA and General Motors.

A technology development to watch is the Advanced robotic technology such as Robonaut (*Robonaut* Principal Investigator: M. Diftler, Johnson Space Center, Houston, Texas) scheduled for testing on the ISS in late 2010/early 2011. Robonaut (Figure 6) is a robotic torso with movable hands and arms plus two high image cameras for eyes. This dexterous robot is designed to perform tasks that assist the human crewmembers. For the initial testing, Robonaut will manipulate switches, remove dust covers and install handrails. Once the technology is demonstrated, more difficult tasks will be scheduled.

CONCLUSION

The dawning of a new era of scientific research on the ISS is upon us as we move from the assembly phase to the utilization phase. Even though research has been conducted throughout the assembly phase, the future will see an intensified research effort as this orbiting laboratory reaches its full potential. As we begin the 21st century, the ISS represents an extraordinary leap forward in space technology and the future potential of research and development is as least as great as the engineering achievements already achieved.

The ISS not only represents broad perspectives for a new future in scientific discoveries, it is a community of international collaborators who have overcome financial, technical and political challenges to assemble one of the greatest engineering accomplishments. This partnership continues to reach for extraordinary achievements in science and technology – the future of the ISS will benefit mankind on Earth and future space exploration.

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[i] Principal Investigators for the ICE-First experiment include: N. Buckley, Canadian Space Agency, Ottawa, Ontario, Canada; A. Rose, Ph.D., University of British Columbia, Vancouver, British Columbia, Canada;C. Conley, Ph.D., Ames Research Center, Moffett Field, CA; L. Segalat, Universite Lyon, Villeurbanne, France ; H. Kagawa, Japanese eXploration Agency, Tsukuba City, Japan; N. Ishioka, Japanese eXploration Agency, Tsukuba City, Japan; S. Kim, Ph.D., Stanford University, Stanford, CA; S. Honda, Japanese eXploration Agency, Tsukuba City, Japan; Y. Honda, Japanese eXploration Agency, Tsukuba City, Japan; B. Girten, Ph.D., Ames Research Center, Moffett Field, CA; A. Higashitani, Ph.D., Tohoku University, Sendai, Japan; A. Higashitani, Ph.D. Iwate University, Morioka, Japan

[ii] Additional Principal Investigators for the MDRV experiment include: M. McGinnis, Ph.D., University of Texas Medical Branch, Galveston, TX; B. Pyle, Ph.D., Montana State University, Bozeman, MT; C. Nickerson Ph.D., Arizona State University, Tempe, AZ