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EXPANDED BENEFITS FOR HUMANITY FROM THE INTERNATIONAL SPACE STATION

International Space Station Program Science Forum*[1]

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In 2012, the International Space Station (ISS) [See Figure 1] partnership published the updated *International Space Station Benefits for Humanity*, 2nd edition [1], a compilation of stories about the many benefits being realized in the areas of human health, Earth observations and disaster response, and global education. This compilation has recently been revised to include updated statistics on the impacts of the benefits, and new benefits that have developed since the first publication. Two new sections have also been added to the book, economic development of space and innovative technology. This paper will summarize the updates on behalf of the ISS Program Science Forum, made up of senior science representatives across the international partnership.

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[1] Including the section editors and contributors for the *International Space Station Benefits for Humanity*, 2nd edition including Hasbrook, P., Ruttley, T., Alleyne, C., Evans, C., Stefanov, W., Read, M., Costello, K., Hornyak, D., Thumm, Anderson, S., Byerly, J., Buck, J., Cohen, L., Chicoine, R., Giguère, C., Istasse, E., Hatton, J., Ngo-Anh, J., Savage, J., Weems, J., Kamigaichi, S., Umemura, S., Oikawa, K., Watanabe, H., Fujimoto, N., Koyama, M., Miyagawa, Y., Aiba, T., Ogawa, S., Ikeda, T., Lavrenko, E., Zhukova, N., Biryukova, N., Belakovskiy, M., Kussmaul, A., Sabbagh, J., Galoforo, G.

Fig 1: The International Space Station (Image credit: NASA)

The new section on "Economic Development of Space" highlights case studies from public-private partnerships that are leading to a new economy in low earth orbit (LEO). Businesses provide both transportation to the ISS as well as some research facilities and services. These relationships promote a paradigm shift of government-funded, contractor-provided goods and services to commercially-provided goods purchased by government agencies. Other examples include commercial firms spending research and development dollars to conduct investigations on ISS and commercial service providers selling services directly to ISS users. This section provides examples of ISS as a test bed for new business relationships, and illustrates successful partnerships.

The second new section, Innovative Technology, merges technology demonstration and physical science findings that promise to return Earth benefits through continued research. Robotic refueling concepts for life extensions of costly satellites in geo-synchronous orbit have applications to robotics in industry on Earth. Flame behavior experiments reveal insight into how fuel burns in microgravity leading to the possibility of improving engine efficiency on Earth. Nanostructures and smart fluids are examples of materials improvements that are being developed using data from ISS.

The publication also expands the benefits of research results in human health, environmental change and disaster response and in education activities developed to capture student imaginations in support of science, technology, engineering and mathematics, or STEM, education internationally. Applications to human health of the knowledge gained on ISS continues to grow and improve healthcare technologies and our understanding of human physiology. Distinct benefits return to Earth from the only orbiting multi-disciplinary laboratory of its kind. The ISS is a stepping stone for future space exploration by providing findings that develop LEO and improve life on our planet.

I. INTRODUCTION

In the second edition of the *International Space Station Benefits for Humanity*, we share the successes of the International Space Station (ISS). The ISS is a unique scientific platform that has existed since 1998 and has enabled over 2,400 researchers in 83 countries and areas to conduct more than 1,700 experiments in microgravity through just September 2014, and the research continues.

Since November 2, 2000, the ISS has maintained a continuous human presence in space. Even before it was habitable, the research began on the only orbiting laboratory of its kind. In 2011, when ISS assembly was complete, the focus shifted to fully utilizing the lab for continued scientific research, technology development, space exploration, commerce, and education.

The tremendous value of the ISS began through the engineering achievement evolving over a decade. Components were built in various countries around the world—all without the benefit of prior ground testing—allowing us to learn a vast amount about construction and about how humans and spacecraft systems function in orbit. This testament to the international achievement exemplifies cultural harmonization through cooperative teamwork leading to an international partnership that has continued to flourish and foster international cooperation. While each ISS partner has distinct agency goals for research conducted, a unified goal exists to extend the knowledge gleaned to benefit all humankind.

In the first edition of the book released in 2012, the scientific, technological and educational accomplishments of ISS research that impact life on Earth were summarized through a compilation of stories. The many benefits being realized were primarily in the areas of human health, Earth observations and disaster response, and global education. [See Figure 2.]

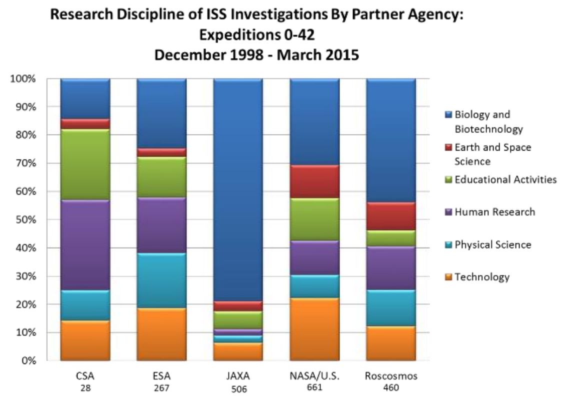

Fig 2: Research Discipline of ISS Investigations By Partner Agency: Expeditions 0-42, December 1998 – March 2015. (Data under review.)

This second edition [See Figure 3] includes updated statistics on the impacts of those benefits as well as new benefits that have developed since the first publication. In addition, two new sections have been added to the book: Economic Development of Space and Innovative Technology.

Economic Development of Space highlights case studies from public-private partnerships that are leading to a new economy in low-Earth orbit (LEO). Businesses provide both transportation to the ISS as well as some research facilities and services. These relationships promote a paradigm shift of government-funded, contractor-provided goods and services to commercially-provided goods purchased by government agencies. Other examples include commercial firms spending their research and development dollars to conduct investigations on ISS and commercial service providers selling services directly to ISS users. This section provides examples of the use of ISS as a test bed for new business relationships and illustrates successful partnerships.

The second new section, Innovative Technology, merges technology demonstration and physical science findings that promise to return Earth benefits through continued research. Examples include robotic refueling concepts for life extensions of costly satellites in geo-synchronous orbit that have applications to the robotics industry on Earth, flame behavior experiments that reveal insight into how fuel burns in microgravity leading to the possibility of improving engine efficiency on Earth, and nanostructures and smart fluids examples of materials improvements that are being developed using data from ISS.

Fig 3: *International Space Station Benefits for Humanity 2nd Edition* Front Cover (Image credit: NASA)

The publication also expands the benefits of international research results in human health, environmental change and disaster response. It provides examples of education activities developed to capture student imaginations in support of science, technology, engineering and mathematics, or STEM, education. Applications to human health of the knowledge gained on ISS continue to grow and improve healthcare technologies and our understanding of human physiology.

The ISS is a stepping stone for future space exploration, as the only orbiting multi-disciplinary laboratory of its kind, returning research results that develop LEO and improve life on our planet. The goal of the publication is to serve as a source of pride for those who read it and learn of the unique shared laboratory orbiting our planet that provides ground for the development of critical technologies and ways to keep humans healthy in space. The NASA ISS Program identifies annually, key discoveries stemming from ISS research. These achievements are honored at the American Astronautical Society (AAS) ISS Research and Development Conference [See Table 1]. This year, researchers were recognized in the areas of innovation and for compelling results. Our publication provides an overview of the updates in benefits summarized previously, and outline details of some of the newly developed benefits described for the first time.

ISS Research Award	Research	Recipient(s)
Innovation in Biology and Medicine	Image-Guided Autonomous Robot (IGAR)	Dr. Mehran Anvari
Innovation in Commercialization	CASIS Protein Crystal Growth-3	Paul Reichert
Innovation in Technology Demonstration	3-D Printing in Zero-G Technology	Jason Dunn
Compelling Results	Transgenic Arabidopsis Gene Expression System - Intracellular	Dr. Robert Ferl Dr. Anna-Lisa Paul
Compelling Results	Constrained Vapor Bubble Experiment	Dr. Joel Plawsky Dr. Peter Wayner
Compelling Results	NanoRacks-CellBox Effect of Microgravity on Human Thyroid	Dr. Daniela Grimm

Table 1: International Space Station (ISS) Research Award Recipient List from the 4th Annual American Astronautical Society (AAS) ISS Research and Development Conference

II. HUMAN HEALTH

The International Space Station (ISS) is a unique laboratory for performing investigations that affect human health both in space and on Earth. During its time in orbit, the space station has enabled research that is providing a better understanding of many aspects of human health including aging, trauma, disease and environmental impacts. Driven by the need to support astronaut health, several biological and human physiological investigations have yielded important results that can also be of benefit on Earth. These results include new ways to mitigate bone loss, insights into bacterial behavior, and innovative techniques for improving wound-healing. Advances in telemedicine, disease models, psychological stress response systems, nutrition, and cell behavior are just a few more examples of the benefits that have been gained from applying studies in orbit to human health back on Earth.

II.1 Health Technology

Research on ISS has allowed for innovations in surgical performance through the world's first robotic technology capable of performing surgery inside MRI machines [2]. This technology is making difficult brain tumor surgeries easier and impossible surgeries possible. Soon, medical technology stemming from space station robotics will enter clinical trials for use in the early diagnosis and treatment of breast cancer by providing increased access, precision and dexterity resulting in highly accurate and minimally invasive procedures. [See Figure 4.] In addition, the development of an advanced technology solution for pediatric surgery is in the design stages. In common laser surgeries to correct eyesight, a new technology developed on ISS is now used on Earth to track the patient's eye and precisely direct a laser scalpel. Thermal regulation research on ISS has also led to the use of sensor technology for monitoring during surgery.

Fig 4: Medical team prepares for SYMBIS Surgical System use in the operating room. (Image credit: University of Calgary)

When medical facilities are not readily available such as in remote and underdeveloped regions of the world, ultrasound units are used in conjunction with protocols for performing complex procedures rapidly with remote expert guidance and training [3]. These telemedicine and remote guidance techniques empower local healthcare providers and provide patients with access to more timely and diagnostic care, thereby making the healthcare system more efficient.

A lightweight, easy-to-use device to measure nitric oxide in air exhaled by astronauts on ISS is used to study possible airway inflammation before health problems are encountered [4]. This device is now used at some health centers to monitor levels of asthma control leading to more accurate medication dosing, reduced attacks, and improved quality of life.

The study of plasmas (which are charged gases that can permeate many materials and spread evenly and quickly), reveals that they support the disinfecting of chronic wounds [5], the neutralization of bacteria, the boosting of tumor inactivation, and even the jumpstarting plant growth.

II.2 Preventing Bone Loss

The common problem of bone loss in the elderly is also observed in astronauts when they are in space. Ongoing studies on ISS indicate a reduction in bone loss and renal stone risk through use of a bisphosphonate and exercise to increase bone load and muscle training, and in a well-balanced, low-sodium diet [6]. In promoting the health of the elderly at risk of osteoporosis, improved scanning technologies are under development to provide a reference technique to enable the early detection of osteoporosis and in the development of more effective countermeasures to its effects [7].

II.3 Immune Defenses

Virtually the entire population is infected with one of eight herpes viruses, four of which reactivate and appear in body fluids in response to the stress of spaceflight [8]. A patent-pending device designed for use in either a doctor's office or on a spacecraft allow for the rapid detection of one of these viruses [VZV, See Figure 5], which can lead to earlier treatment and prevent the onset of painful shingles [9]. Microgravity studies on ISS help researchers pinpoint genetic triggers for immune responses in T-cells leading to future medical treatments on Earth for immunosuppression [10]. Determining the changes that occur to the immune system in space is providing the means to develop targeted countermeasures to adverse effects in space, as well as providing additional information for targeted treatments on Earth for the development of pharmaceuticals that can suppress immune response to help manage autoimmune diseases or organ transplants [11].

II.4 Developing New Therapies

Studying the unique and complicated structures of proteins in the human body leads to the development of medical treatments. Microgravity allows unique conditions for growth of protein crystals where there is no gravity or convection to disrupt their growth [12]. The protein expressed in certain muscle fibers of patients with Duchenne's Muscular Dystrophy, which affects 1 in 3,500 boys, has been successfully crystallized in space [Figure 6] revealing a new inhibitor several hundred times stronger than the prototype inhibitor [13].

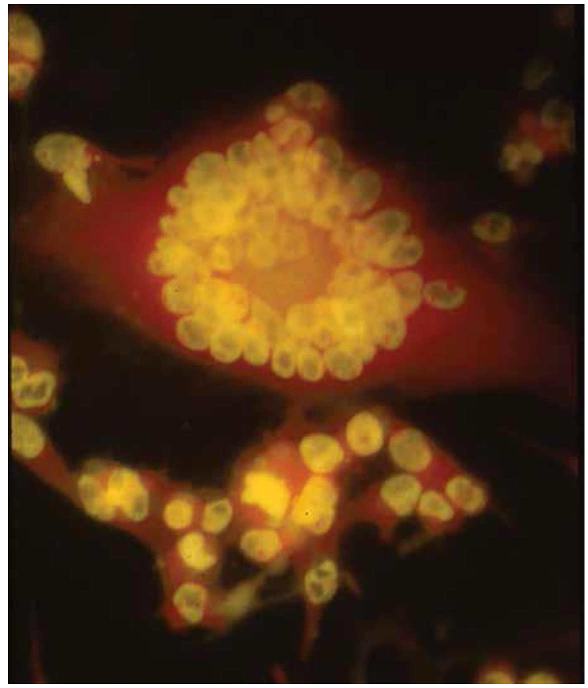

Fig 5: Varicella zoster-infected MeWo cells showing typical herpes virus-induced, multinucleated giant cells. Cultures are stained with acrydine orange to identify RNA (red) in the cytoplasm. (Image credit: NASA)

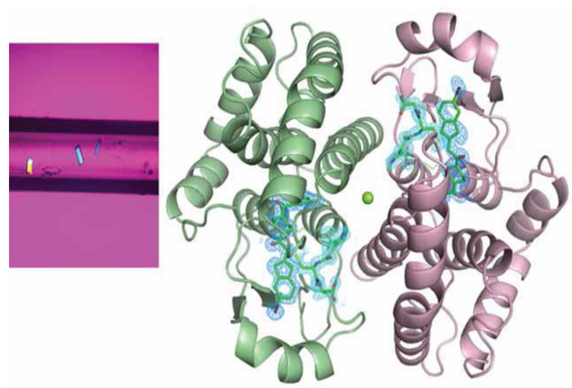

Fig 6: High-quality crystals of H-PGDS-Inhibitor complexes. The detailed structure of muscular dystrophy related-protein became clear through a space experiment. (Image credit: Osaka Bioscience Institute/Tsukuba University/Maruwa Foods and Biosciences, Inc./JAXA)

Microencapsulation is the process by which tiny, liquid-filled, biodegradable micro-balloons are created containing specific combinations of concentrated anti-tumor drugs. The goal is to deliver this medication using specialized needles to specific treatment sites within a cancer patient. The microgravity environment, where density differences do not cause layering of the medication, has allowed for the development of devices on Earth to create these microcapsules and devices that will aid in the drug delivery using this technology [14]. Progress continues towards clinical studies in cancer patients one day in the future.

Ongoing research of gravitational unloading supported by dry immersion technology allows for a broad spectrum of possible clinical applications [15] such as the early diagnosis of slow-developing neurological disorders, the combating of edema that responds poorly to medication, post-operative rehabilitation, sports medicine and rehabilitation for premature babies.

II.5 Food and the Environment

Microbiology is a vitally important area, not only within human spaceflight but also for humans on Earth. Microorganisms such as bacteria, archea, fungi and algae have a detrimental or a beneficial impact on our daily lives. This research has far-reaching effects feeding into many different areas of biotechnology as microorganisms have a role in food spoilage, waste and sewage treatment and processing, nutrient cycling and exchange, pollution control, and in increased greenhouse gases.

Studying the effects of gravity on plants led to the development of an ethylene scrubber [16]. This technology is now used as an air purifier that destroys airborne bacteria, mold, fungi, viruses, and odors. The scrubber is used for food preservation in major supermarkets, high-end refrigerator technology, and in trucks that carry groceries to remote regions of countries such as India, Saudi Arabia and Kuwait to name a few. Even the health care industry benefits from the use of these units in clinics, operating rooms, neonatal wards and waiting rooms making these locations safer for their inhabitants.

Plant research in a space greenhouse [Figure 7**]** has allowed the study of root zone substrates in space allowing scientists to improve predictions of how artificial soils will behave when irrigated both in space and on Earth in experimental forests [17].

Fig 7: Astronaut Peggy Whitson with the ADVASC soybean plant growth experiment during Expedition 5. (Image credit: NASA)

II.6 Heart Health and Biorhythms

Studying spaceflight effects on the cardiovascular system has led to the creation of unique instruments that can be used on Earth for the detection of the earliest deviations in health status [18]. These technologies are now used to examine motor vehicle drivers and civil aviation pilots to evaluate risks and prevent accidents. Twenty-four-hour ECGs of astronauts were also analyzed to understand the space environment's effect on biological rhythm and cardiac autonomic nervous activity leading to recommendations for maintaining a well-balanced biological rhythm on Earth. One of these recommendations is maintenance of a regular sleep schedule [19]. In studying the sleep patterns of cosmonauts using a miniature device that fits in their pocket [Figure 8], information is recorded and sent to Earth for analysis of sleep quality. An Earth model of this device is

Fig 8: Crew member sets up the Sonocard device before sleep in spaceflight. (Image credit: Roscosmos)

placed under the pillow or mattress to record movements related to heart and breathing [20].

II.7 Improving Balance and Movement

A new technology developed to correct motor disturbances in weightlessness has been used to treat patients with cerebral palsy, stroke, spinal cord injuries, balance problems and motor decline due to aging [See Figure 9]. Assessment of eye movement reactions of cosmonauts preflight and postflight has led to faster and less expensive diagnoses and treatment of patients suffering from vertigo, dizziness and equilibrium disturbances [21]. A patented computerized, non-pharmacological method of preventing and correcting unfavorable perception and sensorimotor reactions is used to train patients and astronauts to acquire the ability to suppress vertigo, dizziness and equilibrium disturbances [22].

A system of hardware and software that collects information on body movements of astronauts on ISS has led to motor imagery protocols used in the research environment of a hospital in Rome in treatment of adult stroke patients and children with cerebral palsy [23]. Other body movement research on ISS lead to the development of a suit for astronauts to compensate for the lack of daily loading from gravity. The clinical version of this suit is used for the comprehensive and drug-free treatment of cerebral palsy in children in Russia [24]. Another clinical variation of this suit is used on patients who have suffered from stroke or brain trauma [25].[2]

Fig 9: The support unloading compensator. (Image credit: Institute of Biomedical Problems)

III. EARTH OBSERVATION AND DISASTER RESPONSE

The International Space Station (ISS) is a "global observation and diagnosis station." It promotes international Earth observations aimed at understanding and resolving the environmental issues of our home planet. A wide variety of Earth observation payloads can be attached to the exposed facilities on the station's exterior as well as in the Window Observational Research Facility located within the Destiny module. The presence of a human crew also provides a unique capability for real-time observation of the Earth, and "on the fly" data collection using hand-held digital cameras, and the astronauts may also provide input to ground personnel programming the station's automated Earth observation systems [26]. Several instruments are currently collecting data from ISS; in addition, some instruments have completed their data collection missions, with other remote sensing systems in development or proposed by researchers from the partner countries, NASA, academic institutions, and corporations. The existing international partnerships, fundamental to the ISS, facilitate data sharing that can benefit people around the world and promote international collaboration on other Earth observation activities. The space station contributes to humanity by collecting data on the global climate, environmental change, and natural hazards using its unique complement of crew-operated and automated Earth observation payloads. Subsections III.1 and III.2 provide insight into the two areas of this section.

III.1 Environmental Earth Observations

The space station offers a unique vantage for observing the Earth's ecosystems and atmosphere with hands-on and automated equipment. The size, power, and data transfer capabilities of the space station enable a wide range of sophisticated sensor systems including optical multispectral and hyperspectral imaging systems [See Figure 10] for examining the Earth's land surface and coastal oceans, as well as active radar and Light Detection and Ranging (LiDAR) systems useful for investigating sea surface

[2] Small studies based in the U.S. and Israel were not able to distinguish improvements from Adeli suit therapy with traditional physical therapy [27]. Therefore, this therapy has not been adopted in North America.

winds and atmospheric aerosol transportation patterns. Astronauts using hand-held digital cameras provide an additional imaging capability for obtaining both detailed images of the Earth surface as well as sweeping panoramic views of its atmosphere. This flexibility is an advantage over sensors on unmanned spacecraft, especially when unexpected natural events such as volcanic eruptions and earthquakes occur.

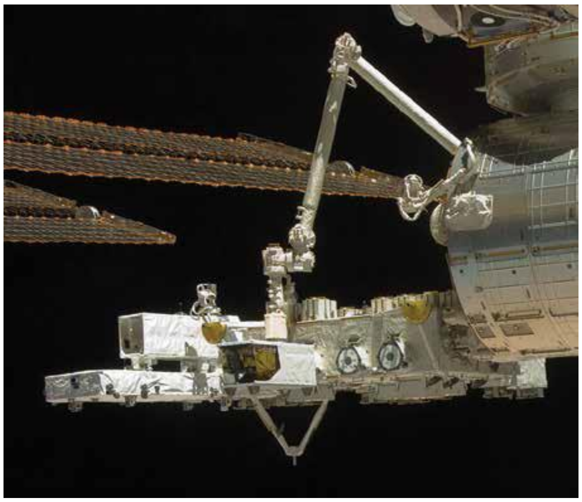

Fig 10: Hyperspectral Imager for Coastal Ocean being installed on the Japanese Experiment Module - Exposed Facility of the Kibo Laboratory, Sept. 23, 2009. (Image credit: NASA)

III.2 Disaster Response

Remotely sensed data acquired by orbital sensor systems has emerged as a vital tool to identify the extent of damage resulting from a natural disaster [Figure 11], as well as providing near-real time mapping support to response efforts on the ground and humanitarian aid efforts [28]. The ISS is a unique terrestrial remote-sensing platform for acquiring disaster-response imagery. Unlike automated remote-sensing platforms it has a human crew; is equipped with both internal and externally mounted still and video imaging systems; and has an inclined, low-Earth orbit that provides variable views and lighting (day and night) over 95 percent of the inhabited surface of the Earth. As such, it provides a useful complement to autonomous sensor systems in higher-altitude polar orbits for collecting imagery in support of disaster response [29].

Fig 11: Before and after images of flooding from two rivers inundating downtown Calgary. Canadian officials used the images to help in their disaster assessments and to improve their flood-mapping algorithms. (Image credits: left, Digital Globe; right, NASA/SERVIR)

IV. GLOBAL EDUCATION

The International Space Station (ISS) has a unique ability to capture the imaginations of both students and teachers worldwide. The presence of humans aboard the station provides a foundation for numerous educational activities aimed at capturing interest and motivating children towards the study of science, technology, engineering and mathematics (STEM). Projects such as the Amateur Radio on International Space Station (ARISS); Earth Knowledge Acquired by Middle School Students (EarthKAM) [See Figure 12]; and Synchronized Position Hold, Engage, Reorient Experimental Satellites (SPHERES) Zero Robotics competition, among others, have allowed for global student, teacher and public access to space through student image acquisition and radio contacts with crew members [30]. Projects like these and their accompanying educational materials are distributed to students around the world. Through the continued use of the station, we will challenge and inspire the next generation of scientists, engineers, writers, artists, politicians and explorers. Sections IV.I and IV.II describe global education endeavors in both inquiry-based learning environments as well as using ISS as a tool for inspiration.

Fig 12: ISS Chief Scientist Julie Robinson talks about ISS orbits with a student preparing a photo request for the EarthKAM camera. (Image credit: NASA)

<u>IV.1 Inquiry-based Learning</u>

From the launch of the first modules of ISS into orbit, students have been provided with a unique opportunity to get involved and participate in science and engineering projects. Many of these projects support inquiry-based learning—an approach to science education that allows students to ask questions, develop hypothesis-derived experiments, obtain supporting evidence, analyze data, and identify solutions or explanations [See Figure 13]. This approach to learning is well-published as one of the most effective ways to engage students to pursue careers in scientific and technology fields [31].

Fig 13: Grade 3 students measure their tomato plants as part of the Tomatosphere™ experiment. (Image credit: CSA/Tomatosphere™)

<u>IV.2 Inspiration</u>

Conducting education activities is not the reason the space station was built, but the presence of astronauts aboard the ISS serves as an inspiration to students and their teachers worldwide. Having the opportunity to connect with crew members real-time, either through "live" downlinks or simply speaking via a ham radio [See Figure 14], ignites the imagination of students about space exploration and its application to the fields of science, technology and engineering [32].

Fig 14: A student talks to a crew member aboard the International Space Station during an Amateur Radio on the International Space Station (ARISS) contact. (Image credit: ARISS)

<u>V. INNOVATIVE TECHNOLOGY</u>

In space, physical processes can be better understood with the control of external influences such as gravity. Technical innovations designed for space systems are tested on the International Space Station (ISS) before use in other spacecraft systems. While investigating how new technologies operate in space, unexpected discoveries are possible. Simplified physical systems can also be directly used to improve models of physical processes leading to new industrial techniques and materials.

The ISS provides the unique capability to perform long-duration experiments in the absence of gravity and in interaction with other spacecraft systems not available in any other laboratory. Additional insight comes from the presence of the ISS crew observing and interacting with these experiments and participating in the discovery process.

The ISS research portfolio includes many engineering and technology investigations designed to take advantage of these opportunities. Experiments investigating thermal processes, nanostructures, fluids and other physical characteristics are taking place to develop these technologies and provide new innovations in those fields. Additionally, advanced engineering activities operating in the space station infrastructure are proving next-generation space systems to increase capabilities and decrease risks to future missions. Emerging materials, technology and engineering research activities on the ISS are developing into benefits for economic development and quality of life.

V.1 Fluids and Clean Water

Whether in the vacuum of space or the relative comfort of the Earth's surface, access to clean water is essential for living organisms. The challenges of moving and processing fluids such as water using compact, reliable systems in the microgravity environment of space have led to advances in the way we purify water sources on the ground [33]. Testing methods developed to ensure water quality on the International Space Station (ISS) have led to advancements in water monitoring here on Earth [See Figure 15]. Investigations into the basic dynamics of how fluids move in space have also led to advances in medical diagnostic devices [34].

Fig 15: Girl at hydration station. (Image credit: Sinergia Systemas)

V.2 Materials

The ISS provides a unique laboratory environment for the testing of new materials. In microgravity, sedimentation and buoyancy-driven convection do not take place, thus allowing us to witness how materials change and develop over longer periods. This allows researchers to manipulate their materials in unique ways [Figure 16]. These opportunities are leading to a better understanding of how material processes work on Earth thereby enabling the manufacturing of new materials with well-defined structures, improved strength, and better function [35].

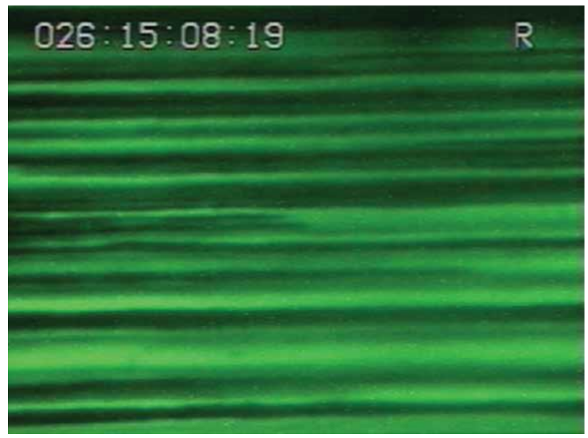

Fig 16: Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions science video image of aggregates (columns forming). (Image credit: NASA)

V.3 Satellites

The ISS offers a unique platform for access to LEO through its Japanese Experiment Module (JEM) airlock working in coordination with the JEM robotic arm. This small airlock allows small devices such as CubeSats to be deployed into LEO while making the trip up to space in the relative comfort of a pressurized cargo container. This can have many benefits in reducing the cost to small satellite operators specifically in the number of launch testing and redundancy requirements for the developer. Lower cost leads to more financial incentive to enable small operators to design and prove out their technology in space. [See Figure 17].

Fig 17: The Robotic Refueling Mission investigation (center, on platform) uses Canadarm2, the International Space Station's robot arm, and the Canadian Dextre robot (right) to demonstrate satellite-servicing tasks. (Image credit: NASA)

V.4 Transportation Technology

Combustion science is one of the longest running fields of research on the ISS. [See Figure 18.] There is a long running campaign to understand just how both simple and more complex fuels burn in space. Understanding this process in microgravity helps us refine combustion models on Earth where gravity and turbulent buoyancy-driven convection flows make this process too difficult to model. Recent observations on ISS have shown that a phenomenon known as "cool flames" can be witnessed in the combustion chambers in orbit to understand how lower temperature burning could have significant applications towards more efficient fuel use and new combustion engine designs in the future [36].

Fig 18: A burning heptane droplet during the Flame Extinguishing Experiments investigation on the International Space Station. (Image credit: NASA)

V.5 Robotics

Key to enhancing human spaceflight missions is the ability of robots to work alongside the human crew to perform necessary tasks more efficiently. These tasks include those that are monotonous or risky and impose on the available time astronauts have to focus on science experiments. The ISS provides an excellent platform where these operational concepts and procedures can be developed, tested and evolved in an actual space environment while demonstrating robotic systems performance and reliability over the long duration [37]. The precision and reliability requirements for space robotics led to dual-purpose technologies and advanced robotic capabilities for use on Earth. [See Figure 19.]

Fig 19: The Robo-Glove was built through the continuing partnership between NASA and General Motors. It uses R2 technology to decrease fatigue and stress when a human grasps an object. (Image credit: NASA)

VI. ECONOMIC DEVELOPMENT OF SPACE

While the International Space Station (ISS) has proven its value as a platform for a broad waterfront of research disciplines as well as technology development, it also provides an ideal opportunity to test new business relationships. This allows an opportunity to shift from a paradigm of government-funded, contractor-provided goods and services to a commercially provided, government-as-a-customer approach.

This interest in promoting a more commercially oriented market in LEO is driven by several goals [38]. First, it can stimulate entirely new markets not achievable in the past. Second, it creates new stakeholders in spaceflight and represents great economic opportunity. Third, it ensures strong industrial capability not only for future spaceflight but also for the many related industries. Finally, and perhaps most importantly, it allows cross-pollination of ideas, processes, and best practices, as a foundation for economic development.

From commercial firms spending some of their research and development funds to conduct research on the space station, to commercial service providers selling unique services to users of the orbiting lab, the beginnings of a new economy in LEO are starting to emerge.

VI.1 Commercial Service Providers

Evolution of the space station as a laboratory in the vanguard of research in microgravity relies on a new and growing number of commercial service providers [See Figures 20 and 21]. Rather than follow the traditional model of government-funded, contractor-provided hardware or capability, a number of firms are entering a new phase of development of LEO—

Fig 20: SpaceX's Dragon capsule as it approaches the ISS, Oct. 25, 2014. (Image credit: NASA)

Fig 21: Orbital's Cygnus vehicle about to be berthed to the International Space Station, July 16, 2014. (Image credit: NASA)

establishing a market. In this model, commercial firms develop capabilities that are then offered to government users and also marketed widely to potential new users of the ISS as a research platform [39]. The space station gains important new (or updated) capability, while the service provider gains a new market in which to offer its services.

VI.2 Commercial Research

The unique environment of microgravity provides opportunities for many types of commercially-viable research. Using model organisms (such as rodents or flatworms) to help understand terrestrial concerns such as:

- bone loss [40]
- muscle wasting [41]
- performing materials research on colloids to develop products that are more uniform and have a longer shelf life [42],
- growing larger protein crystals on the space station [See Figure 22] to help develop monoclonal antibodies [1]
- using the station as a launchpad for a flock of Earth-observing satellites [1]

  are just a few examples of the diverse research interests of the corporate world and how they intersect with the ISS.

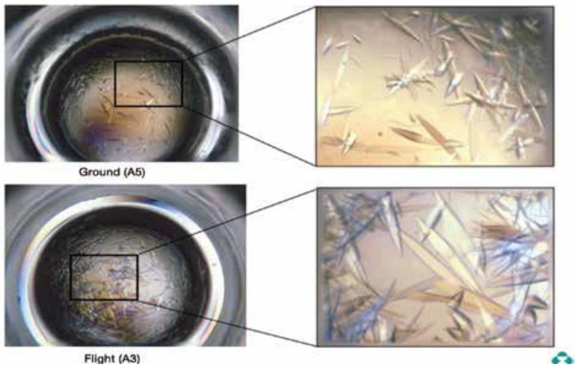

Fig 22: The difference between protein crystals grown on the ground (top) versus in microgravity (bottom). (Image credit: Merck)

VII. CONCLUSION

The International Space Station (ISS) is a unique scientific platform enabling researchers from all over the world to put their talents to work on innovative experiments that could not be done anywhere else. Although each space station partner has distinct agency goals for station research, each partner shares a unified goal to extend the resulting knowledge for the betterment of humanity. We may not know yet what will be the most important discovery gained from the space station, but as exemplified in the *International Space Station Benefits for Humanity 2nd Edition*, we clearly already have some amazing breakthroughs.

In the areas of human health, innovative technology, education and observations of Earth from space, there are already demonstrated benefits to people back on Earth. Lives have been saved, station-generated images assist with disaster relief, new materials improve products, and education programs inspire future scientists, engineers and space explorers. Some benefits in this updated in the second edition have expanded in scope. In other cases, new benefits have developed.

Since the publication of the first edition, a new constituency has developed, one that is using the ISS in a totally different fashion—to develop a commercial market in low-Earth orbit. From pharmaceutical companies conducting commercially-funded research on ISS, to private firms offering unique research capabilities and other services, to commercial cargo and crew, the ISS is proving itself to be just as adaptable to new business relationships as it has been for a broad diversity in research disciplines.

Our book summarizes the scientific, technological and educational accomplishments of research on the space station that have had and will continue to have an impact to life on Earth. All serve as examples of the space station's potential as a groundbreaking research facility. Through advancing the state of scientific knowledge of our planet, looking after our health, developing advanced technologies and providing a space platform that inspires and educates the science and technology leaders of tomorrow, these benefits will drive the legacy of the space station as its research strengthens economies and enhances the quality of life here on Earth for all people.

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