



Exploration Lessons from the International Space Station

Background

The International Space Station is the world's preeminent orbital microgravity platform. For more than 20 years, scientists have used the space station to conduct research into biological, physical, biomedicine, materials, and Earth and space science. Technology demonstrations aboard the space station have advanced state-of-the-art applications with benefits both on Earth and in space. The space station's redundant systems enable the crew to test multiple environmental systems simultaneously, creating a unique testbed for life support and environmental technology that will enable future exploration. Sensors deployed on the space station have validated climate models and contributed to host of new information about Earth's changing climate, while space science instruments on the orbiting laboratory have advanced our knowledge of phenomena like neutron stars and dark matter.

International Space Station crews have also been part of a critical experiment, volunteering themselves as test subjects for research into human adaptation to microgravity. These long-duration demonstrations and experiments into the joint human-and-vehicle system are enabling future human exploration of the solar system. The station will operate through 2030, continuing to offer benefits to humanity while paving the way for commercial industry to meet NASA's needs in low-Earth orbit and beyond.

The International Space Station has five major goals and has realized significant advances in each:

- Enable deep space exploration.
- Conduct research to benefit humanity.
- Foster a U.S. commercial space industry.
- Lead and enable international collaboration.

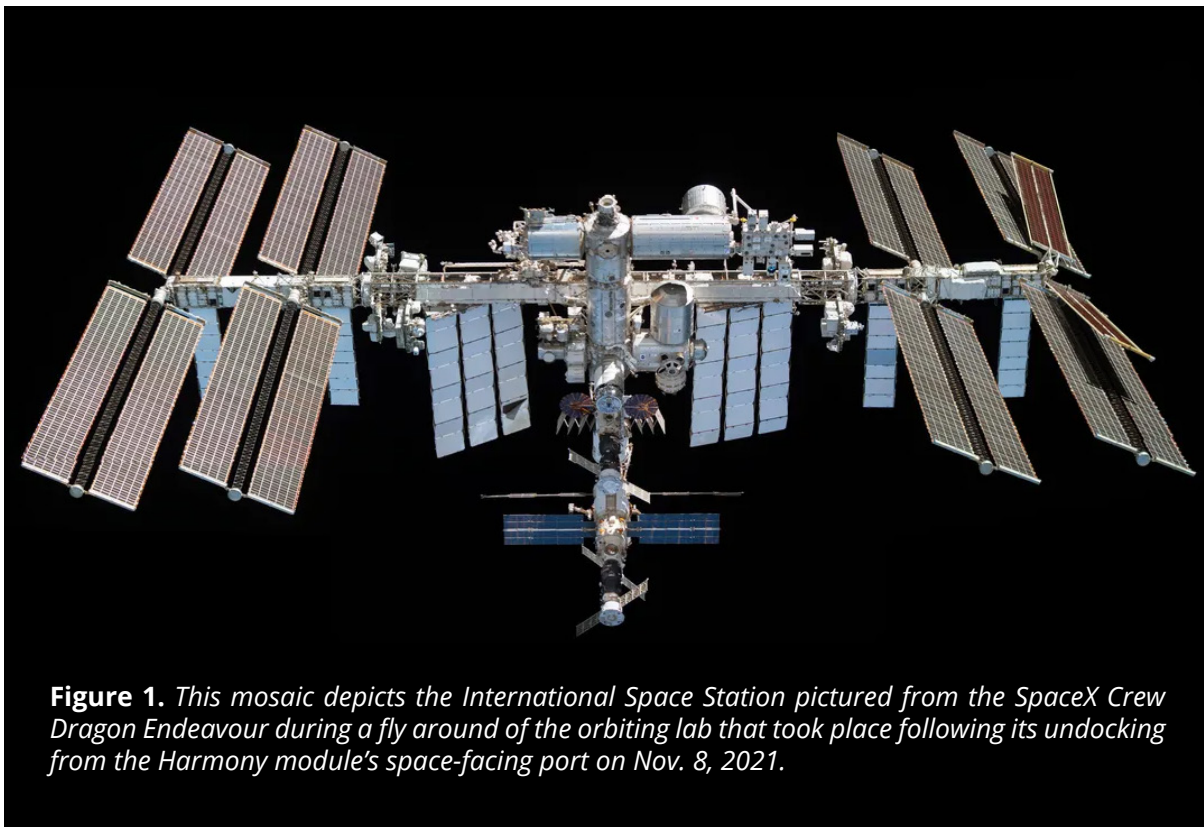


Figure 1. This mosaic depicts the International Space Station pictured from the SpaceX Crew Dragon Endeavour during a fly around of the orbiting lab that took place following its undocking from the Harmony module's space-facing port on Nov. 8, 2021.

The station's first decade was dedicated to on-orbit assembly. Its second was devoted to research and technology development and learning how to conduct these activities most effectively in space. The station is now in its third and most productive decade, continuing to advance research, create commercial value, and bolster global partnerships. During this period, NASA will test and validate exploration and human research technologies to support deep space exploration, continue to return medical and environmental benefits to humanity, and lay the groundwork for a commercial future in low-Earth orbit.

The space station offers a unique platform for demonstrating new technology in space, including the technologies needed for the Artemis missions to the Moon and future missions to Mars. Exploration-focused research and development on the station includes environmental control and life support systems (ECLSS), navigation, food storage systems, extravehicular activity (EVA) suits, and human research, among others. This white paper details how technology developed on the station and lessons learned from station operations enable future exploration missions.

Fly-Off Plans

The International Space Station program tracks the key technologies and human health mitigations needed for deep space exploration through a series of "fly-off" plans. These plans ensure that NASA completes all research that must be done in the low-Earth orbit environment before the end of the station's operational life, planned for 2030. The plans also account for technology demonstrations that may be started on the space station but concluded on commercial low-Earth orbit destinations after the station's retirement.

Environmental Control and Life Support Systems

Since 2009, the regenerative ECLSS aboard the International Space Station has been tested and upgraded into the Exploration ECLSS, intended to support long-duration missions beyond low-Earth orbit. The system-level redundancy of the U.S. and Russian segments, which can maintain critical functions in the event of failures, make the station an ideal testbed for this upgraded system.

The initial ECLSS was an open-loop, non-regenerative system. The Exploration ECLSS is a regenerative air and water system. Ongoing upgrades will continue to improve reclamation of water and air and overall system reliability.

The Water Recovery System provides clean water for astronaut use by recycling urine; cabin humidity condensate from crew sweat, respiration, and hygiene; and water recovered from the Air Revitalization System. The Urine Processor Assembly, part of the Water Recovery

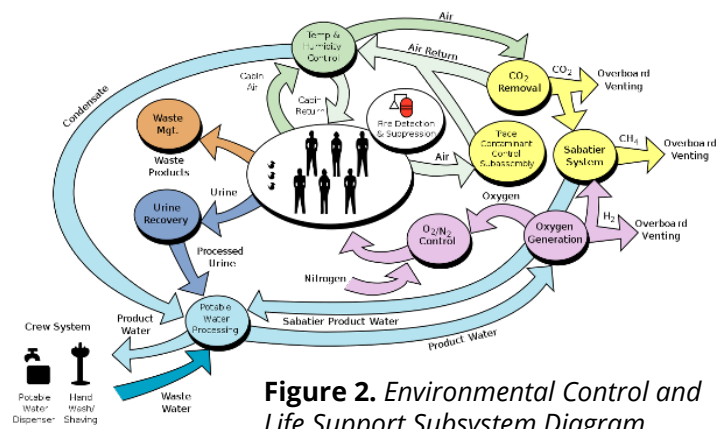


Figure 2. Environmental Control and Life Support Subsystem Diagram

System, was designed for 85 percent water recovery from crew urine. Over the last year, that performance has improved to 87 percent thanks to analysis that showed there was still a margin against calcium sulfate precipitation.

The combined water recycling system on the International Space Station has now reached a theoretical 98 percent, Mars-class efficiency thanks to another new device being tested on board — the Brine Processor Assembly, which demonstrates the ability to recover additional water from crew urine and reduce water waste. Special membranes in the system retain contaminants and pass water vapor into the cabin's atmosphere, where it is captured and delivered to a water processing system.

The Air Revitalization System has also evolved, with additional upgrades planned to launch in the near term. A new generation Carbon Dioxide Removal Assembly, known as the 4-bed CO2 scrubber, has demonstrated improved performance and reliability over its predecessor. This improved performance has enabled lower carbon dioxide levels, improving crew health, and has reduced crew time for maintenance.

The original Oxygen Generation Assembly is also being upgraded into the Advanced Oxygen Generation Assembly, which will fly to the space station in FY25. This new system will feature a more robust cell stack design that reduces mass and maintenance of replacement parts, which NASA estimates will save hundreds of pounds in spares for future long-duration missions.

A redesigned Sabatier carbon dioxide reduction system, which produces methane from CO2 and hydrogen, will also fly to the station in FY25. This will be a redesigned reflight of a previous Sabatier system that failed because of catalyst bed contamination and degradation.

When integrated together, the Exploration ECLSS air systems will recover approximately 50 percent of the oxygen from carbon dioxide. In addition, NASA has been working on advanced carbon dioxide reduction technologies that will potentially recover more than 75

percent of oxygen from carbon dioxide. Those technology demonstrations are planned for late in the decade, either on the space station or follow-on commercial low-Earth orbit destinations.

Equally important — if not more important than ECLSS loop closure — is ECLSS system reliability. One of the major lessons learned from ECLSS on the space station is that no matter how much systems are ground tested, new issues are discovered when they are integrated in the space environment. Even after operating regenerative ECLSS for over 14 years, NASA is still learning.

While the proximity of low-Earth orbit enables relatively easy launch of replacement components, long-duration missions beyond low-Earth orbit must have either a highly reliable ECLSS or the ability to launch with thousands of pounds of spare parts. The ECLSS evolution and testing that has occurred and is still planned on the space station has already improved system reliability, measured in spares mass required for a Mars mission, by more than 35 percent. Additional testing on the orbiting laboratory, coupled with ground testing, will continue to improve our understanding of these systems and their reliability.

Navigation

The Orion spacecraft uses an optical navigation system called OpNav to voyage to and from the Moon. OpNav uses images of the Moon and Earth, looking at their sizes and positions to determine Orion's angle and distance from these bodies, to keep Orion on course. The system also can help Orion autonomously return home if the spacecraft loses communication with Earth.

The International Space Station is demonstrating the effectiveness of this approach by testing OpNav. The station investigation uses two cameras mounted on a plate and offset by about 20 degrees. The plate is installed in the station's cupola, a seven-windowed observation module, with the cameras pointing out one of the windows. One camera captures images of stars and the other takes photos of specified views of the Moon. OpNav software then analyzes these images and determine the station's position in space. Since the station's position is always known, and the time at which a particular photo was taken is also known, NASA engineers can compare the OpNav algorithm results with the actual location to judge the system's accuracy.

The Sextant Navigation for Exploration Missions focuses on stability and star sighting opportunities in microgravity. Astronauts have demonstrated that the handheld sextant intended for use on future Orion exploration missions can successfully be used as a backup navigation capability in a microgravity environment.

Another, more modern sextant technology on the space station is also contributing to future navigation capabilities. The external Neutron-star Interior

Composition Explorer (NICER) external payload studies the composition of neutron stars and pulsars deep in the universe, adding to humanity's understanding of astrophysics. The Station Explorer for X-ray Timing and Navigation Technology (SEXTANT), a NICER experiment, detected pulsars' repeated, consistent flashes of radiation to demonstrate X-ray navigation for the first time in space. X-ray navigation uses the specific timing of pulsars to determine position, just as a GPS receiver on Earth uses the timing supplied by GPS satellites. When developed to an operational capability, X-ray navigation could allow precision navigation anywhere in the solar system.

Food Storage Systems

The eXposed Root On-Orbit Test System (XROOTS) experiment uses aeroponic and hydroponic systems to grow fresh food without space-consuming growth media. XROOTS grows plants in the microgravity environment and evaluates nutrient delivery and recovery techniques over the course of a full plant growth cycle, from germination to maturity. The system uses multiple independent growth chambers in parallel to evaluate alternative methods and configurations; the results could lead to large-scale food production systems. This would offer reductions in the weight requirements for such systems and fresh food produced in-situ, allowing more room for other valuable cargo.



Figure 3. Astronaut Frank Rubio checks tomato plants growing inside the International Space Station for the XROOTS space botany study.

Extravehicular Activities

Extravehicular activities, or spacewalks, have been critical to the assembly and maintenance of the International Space Station. Similarly, spacewalks will be essential to establishing and expanding our presence in cislunar space and on the lunar surface. To date, NASA astronauts aboard the station have performed more than 85 spacewalks, contributing to our understanding of working outside in the vacuum of space.

As we look forward to cislunar and lunar exploration, the station is also playing an important role in demonstrating technologies that will enable astronauts to work outside the Gateway lunar space station and on the lunar surface. These efforts include testing active thermal control components and demonstrating the functionality of next-generation spacesuits, as well as determining whether crew members can complete certain suit maintenance tasks in microgravity that would otherwise require returning parts of the suit to the ground for evaluation and testing.

Human Research

Crew health and performance are critical to successful human exploration beyond low-Earth orbit. NASA's Human Research Program investigates and mitigates the biggest risks to human health and performance, providing essential countermeasures and technologies for human space exploration using the International Space Station's unique capabilities. Those risks include physiological effects from radiation, microgravity, and planetary environments, as well as unique challenges in medical treatment, human factors, and behavioral health support. The Human Research Program is responsible for understanding and mitigating these risks to astronaut health and performance to ensure crew members remain healthy and productive during long-term missions beyond low-Earth orbit.

Key Take-Aways

For more than 20 years, scientists have used the International Space Station to conduct research into biological, physical, biomedicine, materials, and Earth and space science.

The International Space Station offers a unique platform for demonstrating new technology in space, including the technologies needed for the Artemis missions to the Moon and future missions to Mars.

Crew members aboard the International Space Stations have been a critical part of the experiments, volunteering as test subjects for research into human adaptation to microgravity.

Exploration-focused research and development on the space station includes navigation, environmental control and life support systems, food storage systems, extravehicular activities, spacesuits, and human research.