

Three astronaut silhouettes are shown against a white background. The left silhouette is filled with a blue-toned space scene featuring a rocket launch and a planet. The middle silhouette is filled with a dark space scene showing a planet and a lunar surface. The right silhouette is filled with a red-toned space scene showing a planet and a lunar surface. A dark blue horizontal bar is overlaid across the center of the silhouettes, containing the title text.

Exploration Lessons From The International Space Station



Enable Deep Space Exploration

Validate Exploration Technologies and Reduce Human Health Risks

Conduct Research to Benefit Humanity

Life-saving medical research & applications, understanding climate change, sharing discoveries with all

Enable International Collaboration

Maintain & expand international partnerships, set norms & standards

Foster Commercial Space Industry

In partnership with Commercial LEO Office

Incubate in-space manufacturing, support commercial LEO facilities and customers

Inspire Humankind

Broaden reach of space benefits, engage public, create diverse future STEM workforce

Provide National Human Space Flight Infrastructure

Ensure continuous human presence in LEO - no gap; provide destination for crew & cargo transportation

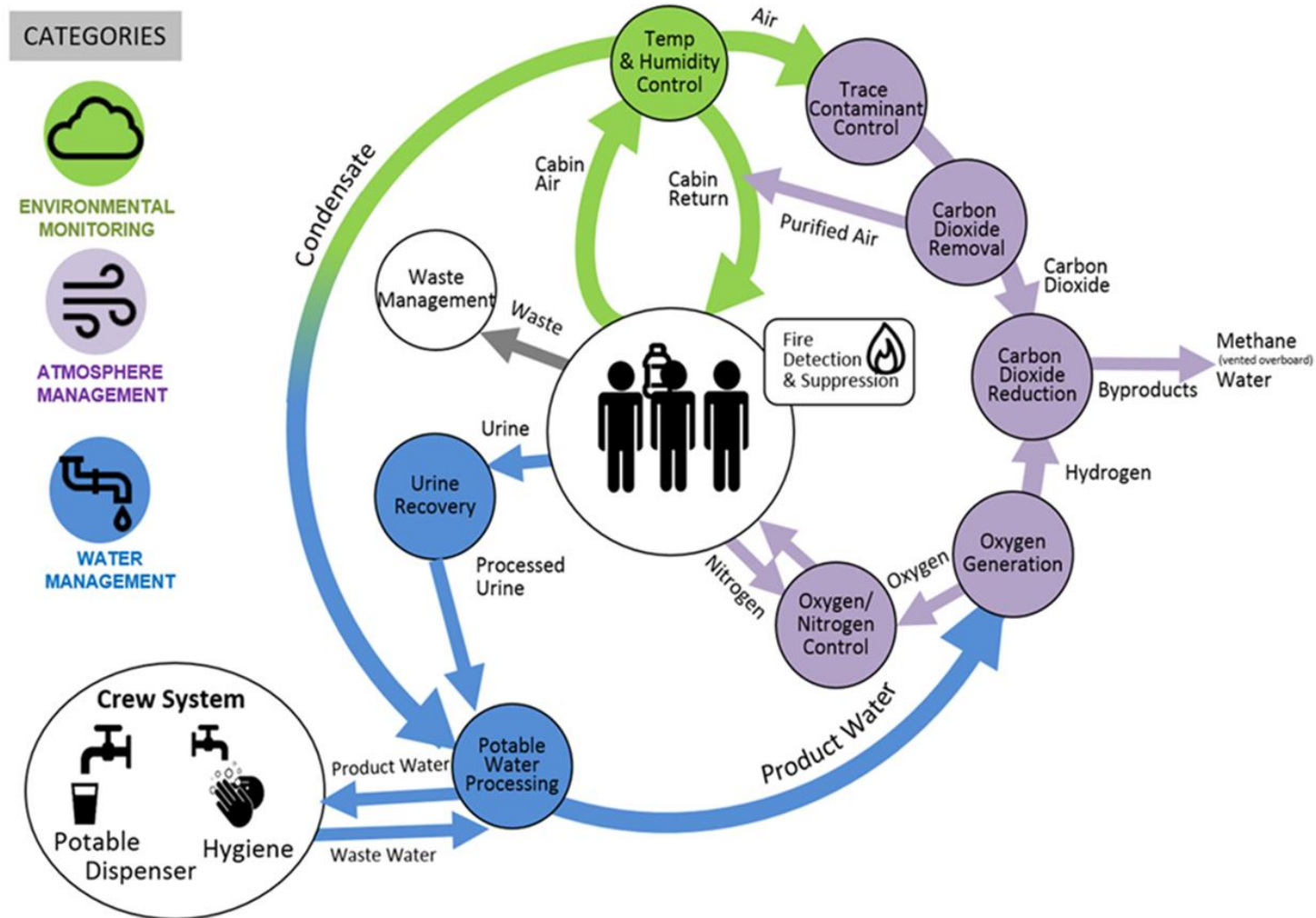
ISS Exploration Lessons Learned



- Fly-Off Plans
- Environmental Control and Life Support Systems
- Navigation
- Food Storage Systems
- Extravehicular Activities
- Human Research



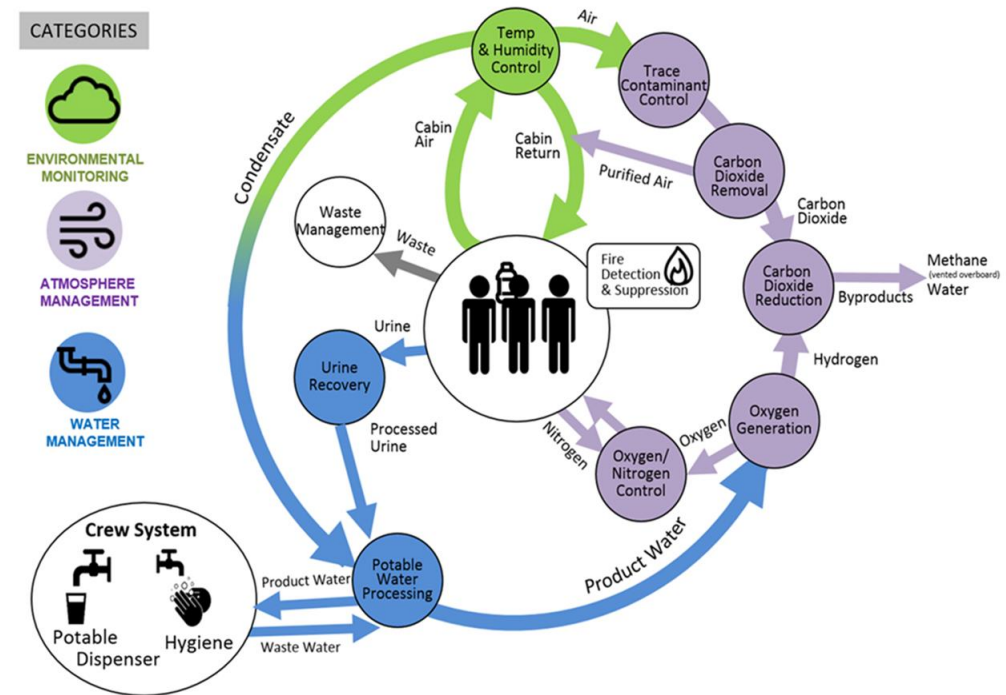
Environmental Control and Life Support Systems



Environmental Control and Life Support Systems



- Water Recovery System
 - Recycles urine, cabin humidity (crew respiration, sweat, hygiene)
 - Up to 98% Mars-class water recycling has been achieved
- Air Revitalization System
 - Next generation 4-bed CO2 scrubber
 - Lower CO2 levels improves crew health
 - Advanced Oxygen Generation Assembly will launch in 2024
 - CO2 reduction assembly to be added in 2025, completing the air string



- Orion uses an optical navigation system called OpNav
 - OpNav has been installed in the ISS cupola, using two cameras and an algorithm to demonstrate the system's accuracy in a real-world environment
- Neutron-star Interior Composition Explorer (NICER) studies neutron stars and pulsars for SMD's Astrophysics Division
 - Using the NICER payload, the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) uses pulsar's radiation flashes to determine position in space, similar to GPS

Commercial Partnerships



External Facilities

Earth observation:
Teledyne Brown
Engineering
MUSES

Payload testing:
Nanoracks NREP

Materials exposure/testing: Aegis
Aerospace MISSE-FF

**Manufacturing
facility:**
Redwire's AMF

Tissue printing:
Redwire's BFF

Payload deployment:
Craig Technologies SSIKLOPS
Nanoracks Kaber

**Payload deployment &
transfer:**
Nanoracks BISHOP Airlock

Station interface:
Nanoracks Nanode

Real-time analysis:
Nanoracks Plate Reader

**Incubator &
Atmospheric Control:** BioServe's
SABL

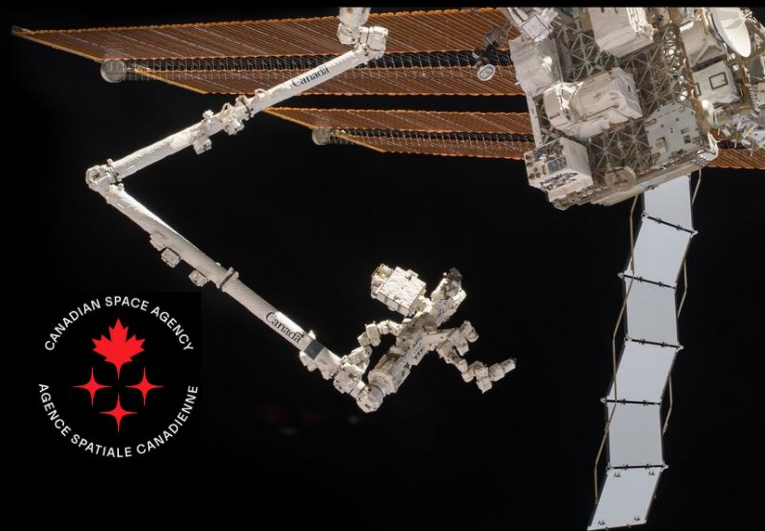
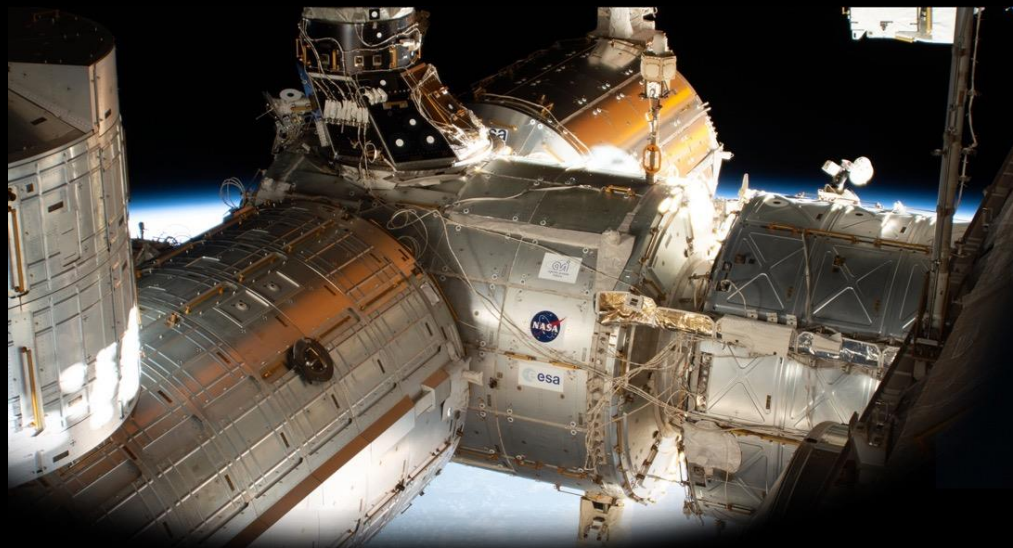
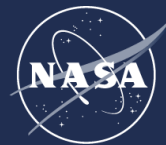
Temperature control:
BioServe's SALI

Biological & physical lab hardware:
Space Tango TangoLabs
Redwire's ADSEP

**Research platform
hardware:**
Redwire's MVP

Internal Facilities

International Partnerships



International partnership is essential to space station operations and has created an infrastructure of cooperation that is the foundation for the future of human exploration.

Key Takeaways



- For more than 20 years, the ISS has provided a unique platform for conducting research in a variety of scientific fields
- The ISS also offers a platform for technology demonstrations in space, including those needed for future Moon and Mars missions



White Paper



National Aeronautics and Space Administration



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.

The 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.
- Inspire humankind.

white paper

2023 Moon to Mars Architecture

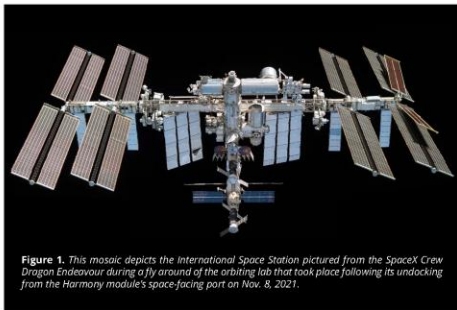


Figure 1. This mosaic depicts the International Space Station pictured from the SpaceX Crew Dragon Endeavour during a fly-around of the orbiting lab that took place following its undocking from the Harmony module's space-facing port on Nov. 6, 2021.

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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 activities most effectively in space. The station is in its third and most productive decade, continuing to advance research, create commercial value, and bolster international partnerships. During this period, NASA will test and demonstrate exploration and human research technologies that support deep space exploration, continue to realize environmental and human health benefits to humanity, and the groundwork for a commercial future in low-Earth orbit.

The space station offers a unique platform for prototyping 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), radiation, food storage systems, extravehicular activity (EVA) suits, and human research, among others. This paper details how technology developed on the station and lessons learned from station operations will inform future exploration missions.

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 can be done in the low-Earth orbit environment before the end of the station's operational life, planned for 2030. Plans also account for technology demonstrations that may be started on the space station but concluded at commercial low-Earth orbit destinations after the station's retirement.

Environmental Control and Support Systems

In 2009, the regenerative ECLSS aboard the International Space Station has been tested and validated into the Exploration ECLSS, intended to support long-duration missions beyond low-Earth orbit. 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 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

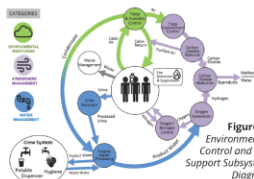


Figure 2. Environmental Control and Life Support Subsystem Diagram

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.

The proximity of low-Earth orbit enables relatively frequent 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 kinds of spare parts. The ECLSS evolution and testing has occurred and is still planned on the space station — already improved system reliability, measured in less mass required for a Mars mission, by more than 10 percent. Additional testing on the orbiting laboratory, paired with ground testing, will continue to improve our understanding of these systems and their reliability.

Navigation

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 in these bodies, to keep Orion on course. The system can help Orion autonomously return home if the crew loses communication with Earth.

The International Space Station is demonstrating the tightness 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 area, with the cameras pointing out one of the cupola's 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 Moon's position in space. Since the station's position is also known, and the time at which a particular photo is taken is also known, NASA engineers can compare OpNav algorithm results with the actual location to test the system's accuracy.

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

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

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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 building and expanding our presence in cis-lunar space and on the lunar surface. To date, NASA astronauts and the station have performed more than 85 spacewalks, contributing to our understanding of working side in the vacuum of space.

We look forward to cis-lunar 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. Efforts include testing active thermal control components and demonstrating the functionality of next-generation spacesuits, as well as determining whether crew members can conduct long-term missions in microgravity during parts of their testing.



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