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NASA's Management of the International Space Station and Efforts to Commercialize Low Earth Orbit

November 30, 2021

Report No. IG-22-005

Office of Inspector General

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RESULTS IN BRIEF

NASA's Management of the International Space Station and Efforts to Commercialize Low Earth Orbit

November 30, 2021 IG-22-005 (A-21-003-00)

WHY WE PERFORMED THIS AUDIT

Astronauts have lived and worked onboard the International Space Station (ISS or Station) orbiting roughly 250 miles above the Earth's surface for more than 20 years. The ISS costs about $3 billion a year, roughly a third of NASA's annual human space flight budget, and while current plans call for the Station's retirement in 2024, an extension to 2030 is likely.

Anticipating its retirement, NASA has committed to replacing the ISS with one or more commercially owned and operated space destinations. In the fiscal year (FY) that ended September 30, 2021, Congress authorized $17 million to that end—a fraction of the $150 million the Agency said it needed. NASA's plans for long-term, deep space human exploration missions depend on continuous access to a research laboratory in low Earth orbit. In fact, the Artemis mission, aimed at returning humans to the Moon and ultimately landing astronauts on Mars, is not feasible without continued human health research and technology demonstrations being conducted on the ISS and its eventual replacement. As long as humans intend to travel in space, NASA expects research and testing will be needed in the microgravity environment of low Earth orbit.

In this audit, we examined the costs associated with the Station's continued use and maintenance, risks to its structure, NASA's utilization of the ISS, and the Agency's plans for commercialization of low Earth orbit. Most of our work focused on the ISS Program office at NASA Headquarters and Johnson Space Center. We interviewed officials from the Program Office, the Commercial Low Earth Orbit Development Program, the ISS National Laboratory, and private industry space firms. In addition, we reviewed ISS analyses, assessments, hazard reports, risk assessments, and structural health and life extension reports among other documents.

WHAT WE FOUND

While overall ISS operations and maintenance costs remained steady at about $1.1 billion a year from FY 2016 through 2020, systems maintenance and upgrade costs trended upward 35 percent in the same 5-year period, rising to approximately $169 million in FY 2020 due primarily to upgrades. Meanwhile, NASA and Roscosmos are investigating the cause and long-term impacts of cracks and leaks that were recently discovered in the Station's Service Module Transfer Tunnel, which connects the Service Module to one of eight docking ports on the Station. Causes being explored include structural fatigue, internal damage, external damage, and material defects. Notably, based on the models NASA used to assess the structure, the cracks should not have occurred, suggesting the possibility of an earlier-than-projected obsolescence for at least one element of the Station. Ultimately, whether in response to an emergency or at the end of its useful service life, NASA and its partners will need to decommission and deorbit the ISS—a technically complex and costly operation requiring international participation and a critical decision on timing.

In reviewing NASA's planned research onboard the ISS, we found that research needed for long-duration missions to the Moon and Mars will not be complete by 2030. NASA uses the ISS microgravity and harsh space environment to study the human health risks of deep space travel and to demonstrate key technologies for crewed missions to the Moon and Mars. Under the Agency's current plans, both health risk mitigation and technology demonstrations will not be complete by 2030—the expected retirement date of the ISS. Consequently, a substantial gap between the Station's retirement and the introduction of a new, commercial destination in low Earth orbit would force NASA to accept a higher level of health risk or delay start dates for long-duration, deep space human exploration missions.

Given the Station's inevitable retirement and NASA's continuing need for low Earth orbit research, the success of the Agency's Plan for Commercial Low Earth Orbit Development is crucial to avoid a gap in low Earth orbit access. NASA's plan to close that gap is for one or more commercial low Earth orbit destinations to be operational by 2028, which would allow a two-year overlap with the ISS before its anticipated retirement in 2030. The Agency's Plan for Commercial Low Earth Orbit Development, published in 2019, identifies five steps in the near-term and also outlines mid- and long-term objectives. We found that the Agency's near-term actions show promise, with NASA's recent efforts resulting in market interest and growth, especially for private astronaut missions. However, NASA faces significant challenges with fully executing the plan in time to meet its 2028 goal and avoid a gap in availability of a low Earth orbit destination. Challenges of commercialization include limited market demand, inadequate funding, unreliable cost estimates, and still-evolving requirements. The risk of deep space human exploration missions will increase significantly if NASA is not able to conduct the required microgravity health research and technology demonstrations on a habitable space destination in low Earth orbit. Furthermore, without a destination the nascent low Earth orbit commercial space economy would likely collapse, causing cascading impacts to commercial space transportation capabilities, in-space manufacturing, and microgravity research.

WHAT WE RECOMMENDED

In order to mitigate risks to the Station's structural integrity, we recommended that the Associate Administrator for the Space Operations Mission Directorate ensure the risks associated with cracks and leaks in the Service Module Transfer Tunnel are identified and mitigated prior to agreeing to an ISS life extension.

We provided a draft of this report to NASA management, who partially concurred with our recommendation. In its response, the Agency agreed that it is essential to complete ongoing work to assess the risks with the cracks and leaks along with Roscosmos' plans to locate and repair leak locations in the Service Module Transfer Tunnel. However, NASA does not agree that this work must be completed prior to agreeing to an ISS life extension. We acknowledge that ongoing work to assess, repair, and monitor the leaks is needed, and in our judgment the Agency's ongoing and planned efforts are responsive to the intent of our recommendation. The recommendation will be closed upon completion and verification of the proposed corrective actions. That said, we will continue to monitor NASA's efforts to manage the issues associated with the Service Module Transfer Tunnel and any impacts these issues may have on the integrity of the ISS.

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Acronyms

CASIS	Center for Advancement of Science in Space
CIPHER	Complement of Integrated Protocols for Human Exploration Research
ECLSS	Environmental Control and Life Support Systems
ESA	European Space Agency
FY	fiscal year
HRP	Human Research Program
ISS	International Space Station
OIG	Office of Inspector General

INTRODUCTION

Orbiting roughly 250 miles above the Earth's surface, the International Space Station (ISS or Station) has allowed humans to live and work in space for more than 20 years. With an annual operating cost of approximately $3 billion, NASA's outpost in low Earth orbit consumes about one third of its annual human space flight budget. While current plans call for the Station's retirement in 2024, an extension of ISS operations to 2030 is likely.[1] In the long term, NASA has committed to replacing the Station with one or more commercially owned and operated space destinations. In fiscal year (FY) 2021, Congress authorized $17 million for NASA to develop a commercial low Earth orbit destination—a fraction of the $150 million the Agency said it needed. NASA's plans for long-term, deep space human exploration missions depend on the Agency having continuous access to a research laboratory in low Earth orbit.[2] In fact, the Artemis mission, aimed at returning humans to the Moon and ultimately landing astronauts on Mars, is not feasible without continued human health research and technology demonstrations on the ISS and its eventual replacement. For as long as humans intend to travel in space, NASA expects research and testing will be needed in the microgravity environment of low Earth orbit.

The Station was designed with a life expectancy of 15 years with a safety factor of two, meaning it could last 30 years after the 1998 launch of its first segments. The Boeing Corporation (Boeing) has certified the U.S. portions of the Station's structure through 2028 (30 years), and NASA is optimistic that the Station's life can be extended to 2030; however, the structure cannot endure the long-term effects of the harsh space environment forever. Ionizing radiation, extreme temperature changes, structural loading events such as docking and undocking of vehicles, and the hazards of micrometeoroids and orbital debris all wear on the Station's structure and will lead to its inevitable decommissioning and deorbit. Moreover, NASA engineers are reviewing whether recently discovered air leaks require updated analysis of the structural longevity of other segments because the leaks were caused by cracks that models suggest should not exist. As it thinks through the timing of the Station's eventual decommissioning, a significant question facing NASA is whether one or more commercial destinations will be available in time to avoid a gap in access to low Earth orbit.[3]

In this audit, we examined the costs associated with the Station's continued use and maintenance, risks to its structure, NASA's utilization of the ISS, and the Agency's plans for commercialization of low Earth orbit. See Appendix A for details of our scope and methodology.

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[1] The United States Innovation and Competition Act of 2021 (S.1260), a bill approved by the Senate in June 2021, includes a provision that NASA continue ISS operations through September 30, 2030.

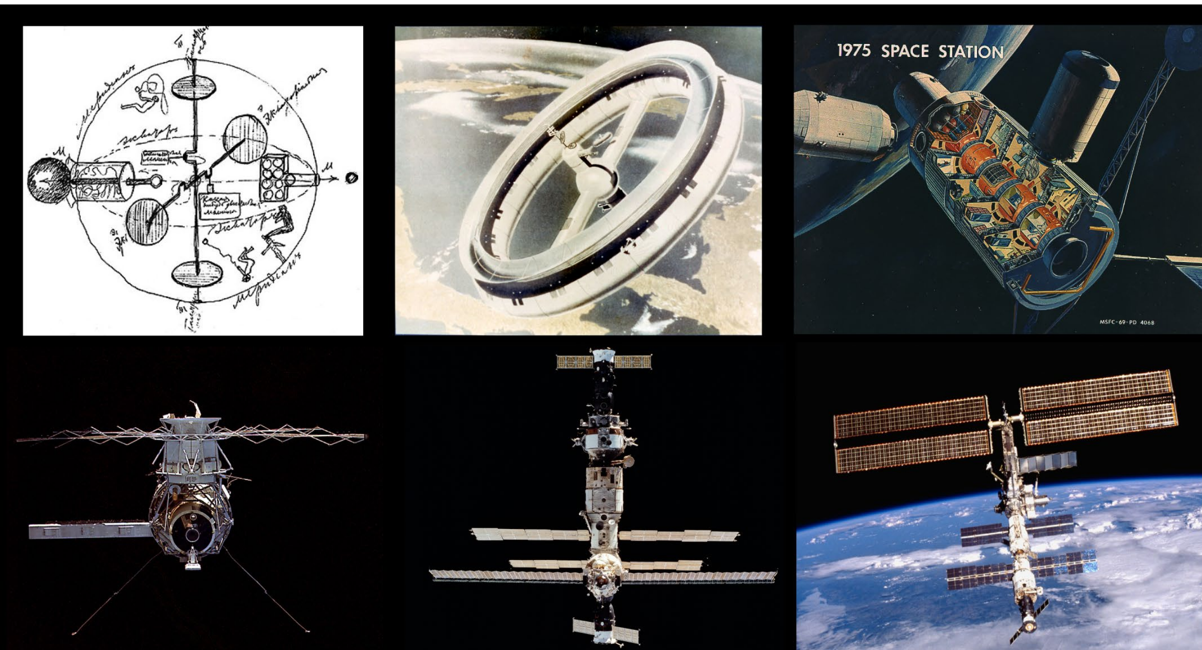
[2] For the purposes of this report, long-duration missions are 30 days or more while deep space missions are any mission beyond low Earth orbit that exposes astronauts to the full effects of the harsh space environment. The latter would include both missions to the Moon and Mars.

[3] Between the end of the U.S. Space Shuttle program in 2011 and the first commercial crew mission in November 2020, NASA faced a 9-year transportation gap where it was forced to pay premium costs to Russia for crew transportation to and from the Station.

Background

Human endeavors toward permanently inhabiting low Earth orbit have been building for more than a century (see Figure 1). As early as 1883, Russian space visionary Konstantin E. Tsiolkovsky published sketches of a spaceship orbiting Earth. In the 1950s, Wernher von Braun developed a concept of a large, wheel-shaped space station, slowly rotating to provide artificial gravity to its occupants.[4] While the von Braun concept did not come to fruition, the Soviet Salyut 1 and the American Skylab space stations were in orbit with crew onboard by the early 1970s.

Figure 1: Space Station Concepts



Top row, left to right:
1883 Russian physicist Konstantin Tsiolkovsky imagined a spaceship with gyroscopes, an airlock, and a propulsion system.
1952 An early space station concept, based on a rotating wheel that would provide artificial gravity, attributed to Wernher von Braun
1969 A 12-person space station concept by engineers at Marshall Space Flight Center and the McDonnel Douglas Corporation
Bottom row, left to right:
1973 Skylab, the first U.S. space station, hosted three crewed astronaut missions
1986 The Russian Mir Space Station stayed in orbit for 15 years and served as the first, longterm microgravity research platform
2001 The ISS under construction, photographed by departing crew aboard the Shuttle Orbiter Discovery

Source: NASA.

In 1984, President Ronald Reagan directed NASA to invite other nations to join in developing a permanently crewed space station within a decade. However, it was not until 1998 that representatives from the United States, Russia, Japan, Canada, and the European Space Agency (ESA) met and signed an agreement to form a partnership to develop the ISS.[5] In-orbit construction of the Station began in

[4] Dr. Wernher von Braun (1912–1977) was a rocket developer and the chief architect of the Saturn V rocket that first propelled Americans to the Moon in 1969. Von Braun served as director of NASA's Marshall Space Flight Center from July 1960 through January 1970.

[5] The countries that comprise the European Space Agency are Austria, Belgium, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxemburg, the Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland, and the United Kingdom.

November 1998 with the Russian Proton rocket and U.S. Space Shuttle delivering ISS modules. Over the next 13 years, NASA and its international partners constructed, launched, and completed in-space assembly of the Station by May 2011. The U.S. and Russia built the foundational elements of the ISS, while ESA and Japan produced elements that enhanced the Station's capabilities. For example, ESA and Japan furnished the Columbus module and Kibo experiment module, respectively, housing experiment racks and exterior payload platforms. Canada contributed robotic assets such as the Space Station Remote Manipulator System (Canadarm2) and the Special Purpose Dexterous Manipulator for hardware relocation and maintenance.

The completed Station includes living quarters and laboratories, exterior trusses for structural support, solar panels that provide power, and radiator panels that dissipate heat (see Figure 2). Altogether, the ISS—essentially a series of modules with connecting nodes—is 356 feet long, approximately the size of a football field, with eight miles of wire connecting its electrical power system. The Station is powered by nearly an acre of solar panels, and its internal pressurized volume is equal to that of a Boeing 747. On board, more than 50 computers control the Station's systems, which rely on 1.5 million lines of flight software code.

Figure 2: ISS as it appeared in 2018

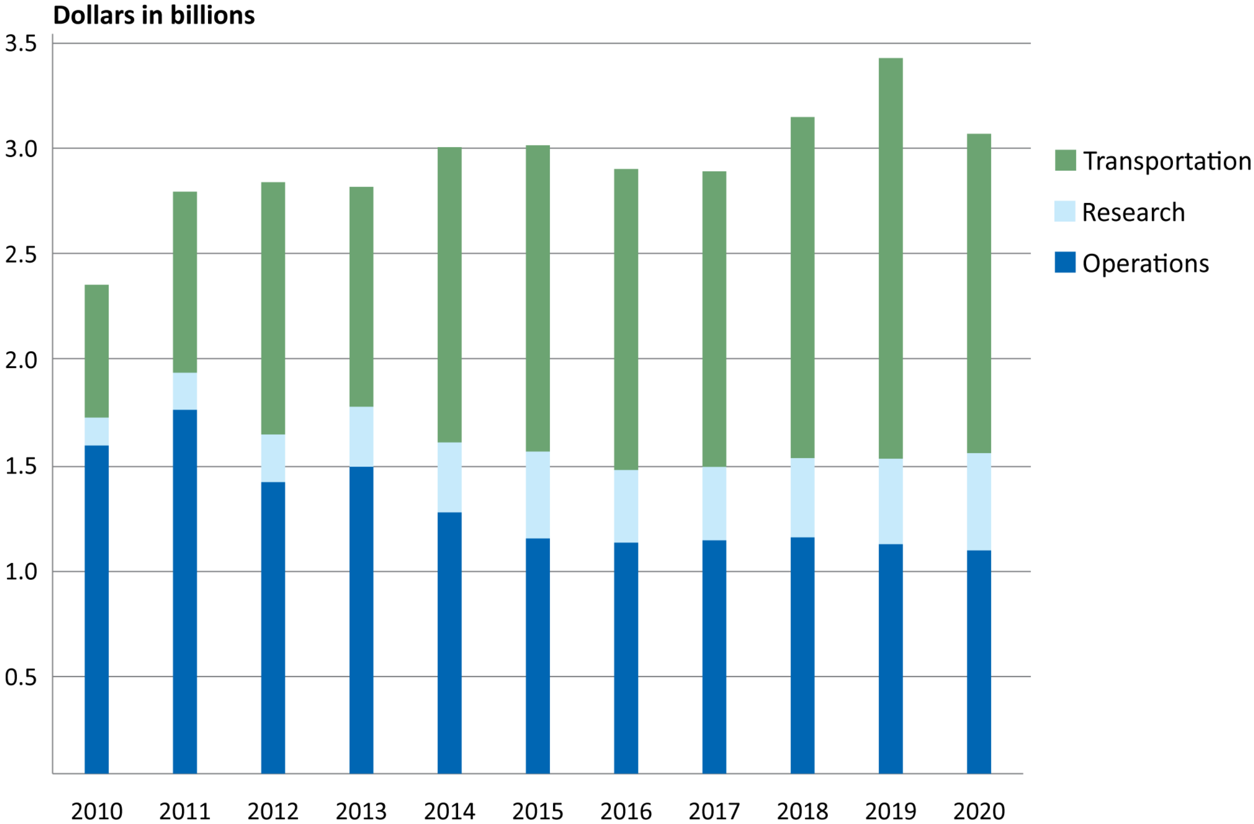
Source: NASA.

Costs

Over the last decade, NASA has spent between $2 to $4 billion a year on the ISS, including operations and maintenance, research activities, and transportation costs (see Figure 3). Operations costs are driven largely by the ISS Program Office's $19.6 billion, 26-year contract with Boeing for sustaining engineering of the U.S. segment. This contract includes original design, development, test, and evaluation of the Station as well as spares, subsystem management, modifications, repairs, and life extension analysis. Research costs include labor costs of staff at NASA and the Center for Advancement of Science in Space (CASIS), grants issued by CASIS to outside researchers, and the Multi-User System and Support budget which includes hardware, software, and mission integration and operation costs associated with conducting biological and physical science both on the ground and on the Station.[6] Transportation costs have fluctuated over time, but since 2014 have accounted for the majority of overall Station costs. The main variable in transportation has been what vehicles are available to transport cargo and crew to the ISS. The Agency has relied on Space Exploration Technologies Corporation (SpaceX) and Orbital ATK (now Northrop Grumman) to resupply the Station since the first commercial cargo mission in 2012. NASA used the Space Shuttle in conjunction with the Russian Soyuz for crew transportation until the Shuttle's retirement in 2011, then began exclusively purchasing seats on the Russian Soyuz for crew transportation through 2020. In 2014, NASA awarded contracts to Boeing and SpaceX, valued at $7.1 billion as of October 2021, for commercial crew transportation. SpaceX flew its first certified crewed mission to the Station in November 2020 while Boeing has encountered numerous delays and technical issues and has yet to fly its first crewed mission. The ISS Program Office expects annual operating costs to remain stable at $3.2 billion until the Station nears the end of its life and NASA begins to spend less on repairs, spare equipment, and transportation.

[6] The Center for the Advancement of Science in Space (CASIS) is a non-profit organization that manages the International Space Station U.S. National Laboratory, a U.S. government-funded laboratory with principal research facilities located in the U.S. Orbital Segment of the ISS.

Figure 3: NASA's Annual ISS Costs, Fiscal Years 2010 to 2020



Source: NASA.

Operational Life

The ISS was initially scheduled to retire in 2015, but its life was extended by Congress through 2024 with a further extension to 2030 pending congressional approval.[7] Any extension of operations past 2024 would also require support from NASA's international partners, whose continued participation hinges on issues that range from the state of international politics to budget constraints and differing space exploration goals. Most importantly, extending the life of the Station beyond 2024 will depend on the structural integrity of the Station itself. Boeing has certified the U.S. portions of the structure through 2028, and NASA is optimistic that it can last until 2030; however, the Station's structure is not immune to the harsh environment of space, and it will inevitably need to be decommissioned and deorbited.

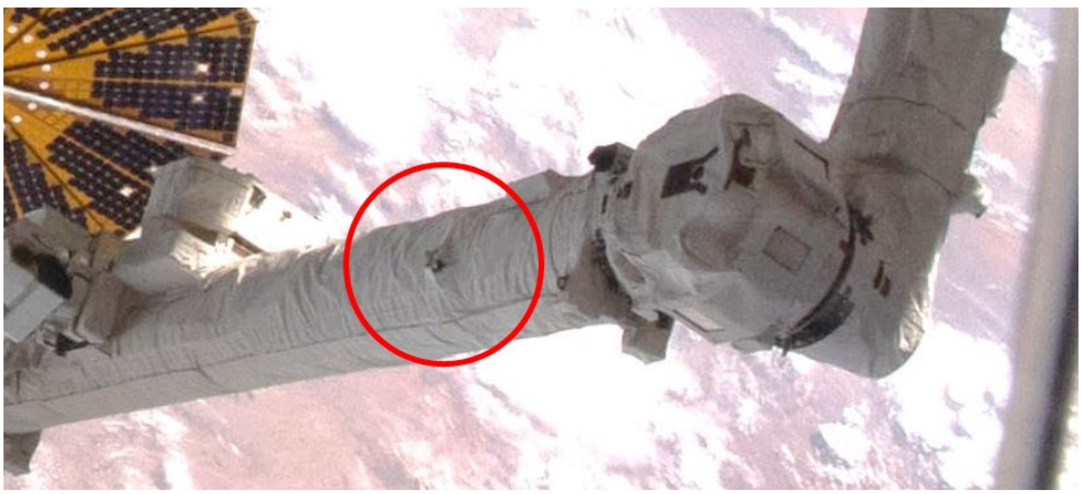
Recent events highlight some of the risks associated with the harsh space environment, which require continuous assessment of the Station's operational performance. For example, in September 2019 NASA began tracking an increase in its atmosphere leakage rate, which up to that point had been stable for years. The Station's crew isolated the source of the leak to the ISS Service Module Transfer Tunnel

[7] S.1260.

where they discovered a 22 mm-long crack on the starboard side of the hull.[8] In March 2021, crew repaired the crack and applied sealant to a second suspected leak site. This resulted in a reduced leakage rate; however, the rate remained two times higher than normal, indicating that additional leaks exist. In the near-term, the increased leakage rate requires NASA and Roscosmos to resupply additional air and nitrogen to maintain cabin pressure within the module. In the long-term, there is a risk that fractures can grow and lead to structural failure. NASA and Roscosmos continue to investigate the cause of the leaks and potential structural impacts.

Meanwhile, in May 2021 NASA identified a hole on the Canadarm2, which was hit by either a micrometeoroid or orbital debris, also known as "space junk" (see Figure 4). On-orbit inspections revealed that the damage would have no impact on the arm's operations through the end of the Station's certified life. The Canadarm2 is used to conduct regular maintenance checks and operations on the outside of the Station; move supplies, equipment, and astronauts conducting spacewalks; and capture visiting vehicles to connect them to the Station. In January 2021, we reported that the growing volume of orbital debris threatens the loss of important space-based applications, and remediation is needed to stabilize the orbital debris environment.[9] At the time of our report issuance, NASA was assessing the risks to ISS operations from a new cloud of orbital debris stemming from a Russian military anti-satellite test on November 15, 2021.

Figure 4: Canadarm2 Orbital Debris Strike, May 2021



Source: Canadian Space Agency.

Further, the ISS experienced loss of attitude control on two separate occasions in 2021.[10] First, in July 2021 the ISS experienced an abrupt and unexpected loss of attitude control after Russia docked its new Multi-Purpose Laboratory Module. The new module inadvertently fired its thrusters for a period of 10 minutes, resulting in the Station becoming inverted and losing satellite communications for several minutes on two separate occasions. NASA declared a spacecraft emergency in order to maintain primary control of satellite communications during the incident. Mission Control-Moscow activated the

[8] The Service Module Transfer Tunnel is one of three pressurized compartments of the Service Module, an area in which the crew lives and works.

[9] NASA OIG, *NASA's Efforts to Mitigate the Risks Posed by Orbital Debris* (IG-21-011, January 27, 2021).

[10] The attitude is the orientation of the ISS with respect to Earth and the Sun, which is important for maintaining communications, microgravity, power, and thermal levels on the Station.

Service Module thrusters to slow the rotation and then used the docked Russian Progress cargo vehicle to provide additional stabilization, recovering the Station's attitude approximately one hour after the initial loss of control.[11] After the event, NASA assessed the inadvertent thruster firing anomaly data and determined that there was no structural damage or long-term concern. In a separate occasion in October 2021 Russian flight controllers conducted a scheduled thruster firing test on the Soyuz spacecraft that unexpectedly continued after the end of the test window, resulting in another loss of attitude control. Within 30 minutes, flight controllers regained attitude control of the Station, and NASA and Roscosmos are collaborating to understand the cause.

While NASA determined that these events do not pose an immediate threat to the Station's operational longevity, the Agency and its partners will eventually need to decommission and deorbit the ISS either in response to an emergency or at the end of its useful service life. Deorbiting the ISS will require extensive cooperation between NASA and Russian officials to dispose of the Station via controlled, destructive, and safe reentry into the Earth's atmosphere. NASA estimates it will take approximately three years to deorbit the Station from current operational altitudes; the deorbit timeframe drops to six months in the event of an emergency. During initial descent, the Station will gradually decay to a lower altitude, and normal operations will be able to continue until it gets too low—approximately 155 miles above the Earth's surface—for vehicles to dock. Prior to the final deorbit sequence, all crew onboard will return to Earth, and needed equipment and experiments will either return to Earth or be transferred to a new, commercial destination in low Earth orbit. Final deorbit will be accomplished by computer systems executed by Mission Control-Moscow. During descent through the Earth's atmosphere, the ISS will burn, break up, and vaporize into fragments. Ground level environmental impacts are projected to be small because any toxic liquids or materials are expected to burn up during the reentry process. Surviving fragments of the Station's structure, however, will have sufficient kinetic energy to cause damage to people and structures, including ships. For this reason, the strategy is for the Station to enter the atmosphere at a precise latitude and longitude in order to position the debris footprint over an uninhabited region, preferably in the South Pacific Ocean.

Utilization

Early Shuttle missions to the Station focused on its construction until completion in May 2011, with focus then shifting toward using the ISS as a laboratory to fulfill the third prong of NASA's purpose for the ISS—to establish the United States as a leader in space, connect international partners, and conduct microgravity and observational research in low Earth orbit.

Since 2000, the ISS has housed scientific research and technology development efforts for more than 4,200 researchers in 108 countries. NASA's ISS Research Integration Office manages placement of research onboard the Station with the goal of ensuring that the laboratory is used to the greatest extent possible. In total, 13 NASA offices place research and coordinate demonstrations on the Station, including the Human Research Program (HRP) and the Technology Demonstrations office, which use the Station as an experimentation platform to enable long-duration human spaceflight. Other NASA users of the Station include the Advanced Exploration Systems Division, which tests advanced life support systems for lunar habitats; Biological and Physical Science Division, which studies the effects of weightlessness on biological and physical systems as well as the behavior of fluids and combustion in

[11] Mission Control-Moscow operates the ISS Russian segment, which houses many of the Station's propulsion and avionics systems.

microgravity; and the Earth Science Division, which collects Earth observation data, capturing the changes in our planet's systems.

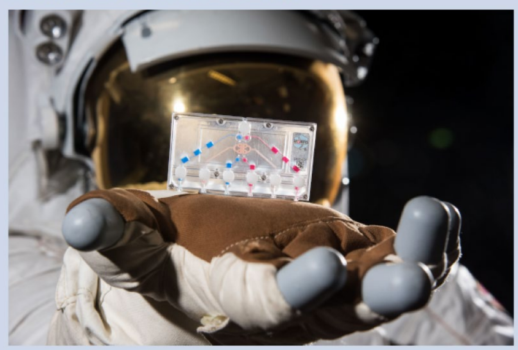
In addition to NASA users, 50 percent of the U.S. segment's research capacity is allocated to private, academic, and other government agency partners. The ISS National Laboratory, managed by CASIS, solicits and vets proposals and schedules non-NASA research on the Station, with the ultimate goal of fostering a sustainable and scalable low Earth orbit research and manufacturing economy. In August 2011, NASA signed a 10-year, $136 million cooperative agreement with CASIS to manage all non-NASA research on the ISS. In July 2017, NASA extended the cooperative agreement to September 2024 and added another $60 million to the agreement. CASIS funds research grants to help researchers integrate their investigations into the microgravity environment and pays for the staff to manage the ISS National Laboratory, while NASA funds the cost of access to the ISS including the cost of transporting the research materials to and from the Station, mission integration and operations including the use of onboard facilities, and crew time.

ISS research activities by NASA and its partners have delivered benefits in human health, Earth observations and disaster response, innovative technology, global education, and the economic development of space. For example, the world's first robot capable of performing surgery, the neuroArm, was based on the Canadarm2, and the use of the Station's advanced water filtration and purification systems provide clean water technology for at-risk areas across the world. In addition, technology used to freeze dry fruit, electrolytic silver iodizer for pool water purification, and development of wireless headsets all are products of in-space technology.

Enabling Deep Space Exploration

Understanding and mitigating risks to astronaut health and performance for long-duration spaceflight continues to be a top priority for the ISS, and multiple NASA offices have a role in developing procedures, medications, devices, and other strategies for mitigating risks to spaceflight crew. The risks NASA is focused on have evolved since our 2018 report on this topic, as priorities in space travel have shifted and technology has advanced.[12] To track progress on mitigating health risks such as space radiation exposure, sensorimotor alterations, and cardiac rhythm problems, NASA created an "Integrated Path to Risk Reduction" in 2014. The latest Integrated Path to Risk Reduction, issued in June 2021, lists 16 outstanding human health risks that require mitigation, 12 of which require the ISS for testing. Each outstanding human health risk relates specifically to long-duration missions of 30 or more days or long-distance travel to the Moon or Mars. NASA has implemented countermeasures allowing it to accept the human health risks of short-distance trips to low Earth orbit destinations such as the ISS. After the ISS is retired, NASA plans to continue its human health risk research on alternative platforms

Human Health Research



Tissue chips—which contain human cells in a 3D matrix, representing functions of an organ—have been sent to station, seeking to better understand the impact of microgravity on human health.
Source: NASA.

[12] NASA OIG, *NASA's Management and Utilization of the International Space Station* (IG-18-021, July 30, 2018).

such as a commercial low Earth orbit destination, commercial spaceflight missions to low Earth orbit, and platforms on or near the Moon.

NASA also uses the Station to demonstrate new technologies needed for missions to the Moon or Mars. In 2013, the Agency created 14 System Maturation Teams to work on new technologies for propulsion, life support, and other elements required for human travel to the Moon and Mars. In 2020, NASA created the Capability Integration office to integrate capability needs across the organization and prioritize its technology development investments. The ISS Program coordinates with Capability Integration to perform technology demonstrations, including upgrades to the Station's water system and Brine Processor Assembly, air systems, and communication and navigation systems. NASA uses its Technology Demonstration Fly-Off Plan to track funding, scheduling, and progress of the demonstrations that require microgravity testing on a crewed low Earth orbit platform. The most recent update to the Fly-Off Plan in June 2021 documents 27 technology demonstrations that are either currently flying on the ISS or in development through 2032. Should NASA require a microgravity environment for technology demonstrations beyond the expected life of the ISS, it plans to transition testing to a commercial low Earth orbit destination.

Efforts to Commercialize Low Earth Orbit

The U.S. has long sought to establish a marketplace and stimulate a national economy for space products. The Commercial Space Launch Act of 1984 helped pave the way for commercial development of space by encouraging the private sector to provide launch vehicles and associated launch services.[13] While the focus at the time was satellite launches, the legislation eventually enabled NASA's Commercial Orbital Transportation Systems Program for commercial cargo resupply services to the ISS and NASA's Commercial Crew Program for crewed flights to the ISS. Commercial transportation, however, represents just one piece of what could eventually become a thriving commercial low Earth orbit economy. To that end, NASA is currently engaged in a number of commercialization initiatives in pursuit of its goal of becoming one of many customers that purchases time and resources on a commercial low Earth orbit destination.

CASIS Demand Stimulation

As we first reported in 2013, CASIS has continuously struggled to foster a market for commercial and non-government research onboard the Station.[14] In a 2018 follow-up report, we found that CASIS underperformed on tasks such as recruiting National Laboratory users and failed to meet a majority of the goals and expectations set out by NASA including fully utilizing its allocated crew time; for NASA's part, we found that it failed to actively oversee CASIS' performance, contributing to the organization's inability to meet expectations.[15] NASA established an Independent Review Team in 2019 to evaluate CASIS' management of the National Laboratory, which found overarching issues with the organization's structure, integration with the scientific community, and NASA's oversight.[16] In response to the Independent Review Team's findings and recommendations, NASA and CASIS implemented a six-point plan that includes a reorganization of CASIS' structure, the development of a User Advisory Committee,

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[13] Commercial Space Launch Act of 1984, Pub. L. No. 98-575, §3 (1983).

[14] NASA OIG, *NASA's Efforts to Maximize Research on the International Space Station* (IG-13-019, July 8, 2013).

[15] NASA OIG, *NASA's Management of the Center for the Advancement of Science in Space* (IG-18-010, January 11, 2018).

[16] International Space Station Cooperative Agreement Independent Review Team, *Final Report to NASA* (February 4, 2020).

and establishment of a NASA Program Executive who will work with CASIS to ensure they maximize the benefit of the ISS National Laboratory for the remainder of its time in orbit by enabling diverse, high quality research. At this point, it is too early to tell whether these efforts have improved outcomes. Nonetheless, because CASIS's initial efforts to develop a sustainable and scalable commercial marketplace for research and manufacturing in low Earth orbit have not yet resulted in self-sustained demand, in 2019 NASA proceeded to develop its own plan. Importantly, NASA's plan went beyond the scope of CASIS's cooperative agreement to expand the scope of opportunities to include marketing and tourism on the ISS.

NASA's Plan for Commercial Low Earth Orbit Development

In pursuit of its goal of creating a low Earth orbit commercial economy where NASA is one of many customers, in 2019 the Agency announced a plan for commercial low Earth orbit development, focused on near-term actions that include:

1. Establishing an ISS commercial use and pricing policy
2. Enabling private astronaut missions
3. Initiating a process for developing commercial low Earth orbit destinations
4. Seeking out opportunities to stimulate sustainable demand
5. Quantifying NASA's long-term needs for activities in low Earth orbit

Figure 5 shows NASA's near-term, mid-term, and long-term commercialization goals. To develop its new commercialization plan, the Agency relied on market studies that offered recommendations on how to best stimulate demand for a low Earth orbit destination. The studies found the most promising areas to stimulate demand are in-space manufacturing of unique materials or products; video products for entertainment including films, documentaries, and sporting events; sponsorship and marketing; accommodations for space tourism; in-space assembly and servicing of large structures and satellites; and transportation of people and cargo to and from low Earth orbit.

Figure 5: NASA's Vision for Economic Development in Low-Earth Orbit as of January 2020

Source: NASA.

Emerging Commercial Marketplace

Creating a new commercial market where there once was only government demand is an arduous challenge; nonetheless, the low Earth orbit marketplace is slowly beginning to take shape. The number of private companies interested in traveling to space has increased over the past 20 years, with growth in industries such as information technology hardware, telecommunications, aerospace, and defense. As of 2020, the private space industry generated revenues of approximately $350 billion a year and it is expected to generate revenue of more than $1 trillion in 2040, the bulk of which would come from telecommunications.[17] This projected growth would be due, in part, to the development of reusable commercial launch vehicles that enable more affordable, reliable access to space. Also, space tourism has come to the fore since both Virgin Galactic and Blue Origin successfully launched vehicles to a suborbital level in July 2021, and SpaceX successfully completed a commercial mission to low Earth orbit in September 2021.[18]

[17] Morgan Stanley, *Space: Investing in the Final Frontier* (July 24, 2020). The Federal Communications Commission licenses and regulates telecommunications per the *Communications Act of 1934*, 47 U.S.C. §151.

[18] The Federal Aviation Administration establishes requirements for human space flight as required by the *Commercial Space Launch Amendments Act of 2004*, Pub. L. No. 108-492 (2004), including rules on crew qualifications and training, and informed consent for crew and space flight participants (14 CFR Parts 401, 415, 431, 435, 440, and 460 (2006)).

ISS Requires Costly Maintenance and Upgrades While the Cause of Leaks in the Service Module Transfer Tunnel Remains Unknown

Although NASA and Roscosmos independently certified the structural life of the U.S. segment of the ISS to 2028 and Russian segment to 2024, the ISS is entering its third decade of use, and continued Station operation requires costly maintenance and system upgrades. At the same time, discovery of multiple cracks and leaks in the Station's Service Module Transfer Tunnel over the past year that structural life assessment models say should not exist suggest the possibility of an earlier-than-projected obsolescence for the Transfer Tunnel and potential concerns about other segments. Lastly, whether in response to an emergency or at the end of its useful service life, NASA and its partners will ultimately decommission and deorbit the ISS—a technically complex and costly operation requiring international participation and a critical decision on timing.

ISS Requires Costly Maintenance and Systems Upgrades

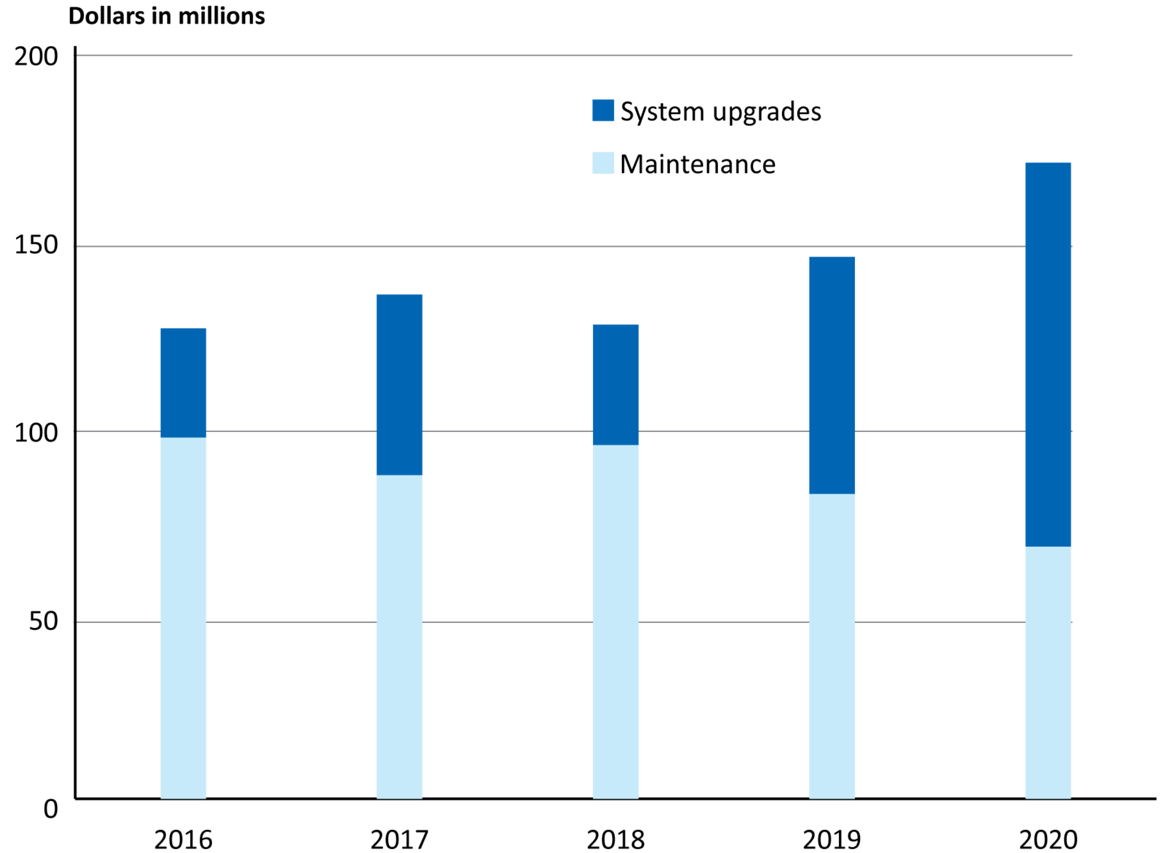
Continued preventive and corrective maintenance of the ISS structure and systems is required to safely operate this unique platform in the harsh space environment.[19] Station maintenance involves keeping items and equipment in an operational condition through installation, inspection, repair, servicing, removal, and replacement. Support teams continuously monitor and plan to resupply consumables such as oxygen, water, fuel, and hundreds of unique replacement parts for the Station's complex flight systems. In addition, ground teams continually monitor ISS performance and communicate with the crew to address mechanical failures when they occur. Resolving unexpected problems can be challenging and often requires the crew to make repairs in space with the aid of teams on Earth.

While overall system operations and maintenance costs remained steady at about $1.1 billion a year from FY 2016 through 2020, systems maintenance and upgrade costs trended upward 35 percent in the same 5-year period, rising to approximately $169 million in FY 2020 due to significant system upgrades such as replacing nickel-hydrogen batteries with more efficient lithium-ion batteries (see Figure 6).[20]

[19] Preventive maintenance includes inspection, servicing, and any other routine actions needed to ensure continuing proper operation of the hardware or system. Corrective maintenance involves repairing or replacing equipment that has failed or is otherwise no longer operating within specification.

[20] Systems maintenance costs include user, corrective, and preventative work to preserve the function of the ISS vehicle and facilities held within, including acquisition and deployment of space hardware components for ISS maintenance and repair. Upgrade costs include improvements to vehicle hardware and software to support enhanced mission objectives, such as increased vehicle performance, and greater research utilization and commercial capability.

Figure 6: ISS Systems Maintenance and Upgrade Costs, Fiscal Years 2016 – 2020



Source: NASA.

NASA and Roscosmos Continue to Investigate the Cause and Long-Term Impacts of Recently Discovered Leaks in the Station's Service Module Transfer Tunnel

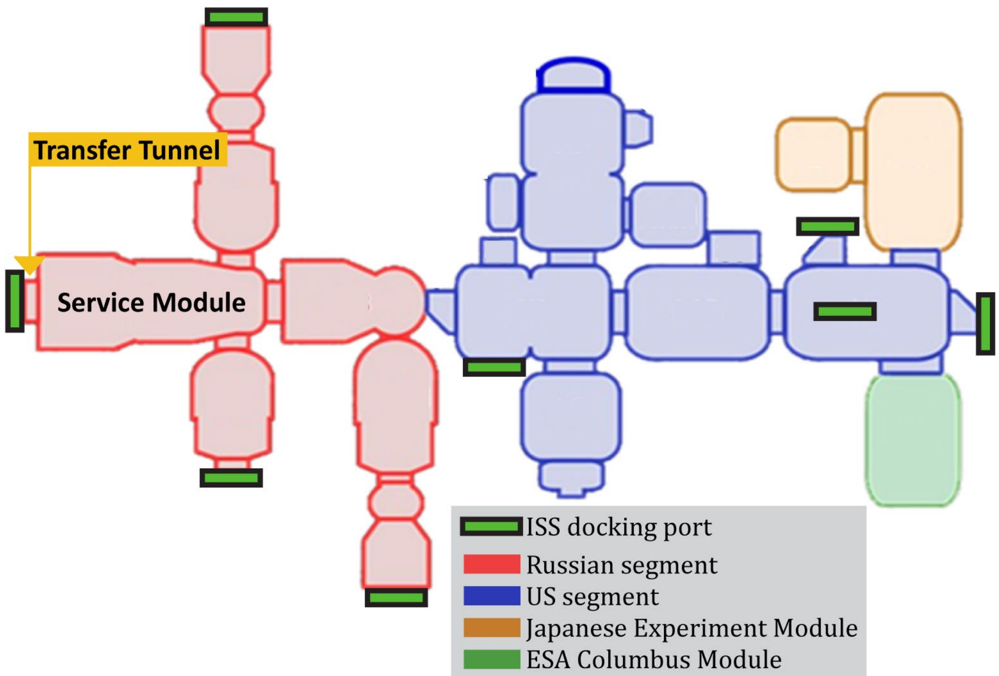
The Service Module—the third oldest module on the Station—was the first Russian contribution to the ISS and serves as the structural and functional center of the Russian segment.[21] The Service Module Transfer Tunnel, which connects the rear docking port to the Service Module (see Figure 7), is currently the source of multiple cabin air leaks of unknown cause, some of which have yet to be located.[22] The ISS leaks cabin air as part of its normal operations; structures, systems functions, docking and undocking events, and extravehicular activities all contribute to normal leakage. NASA continuously monitors the leakage rate to ensure a habitable atmosphere for the crew. Prior to identification of the leaks, the Station's atmosphere leakage rate was stable at about 0.6 pounds mass air/day. Although there is no formal leakage rate standard, long-term leakage statistics establish 0.6 pounds mass air/day as the

[21] The Service Module launched on July 12, 2000.

[22] Four docking ports on the Russian segment enable spacecraft to attach to the Station. The U.S. segment also has four docking ports.

accepted rate. Large deviations from the normal leakage rate represent an anomaly that requires investigation and potential corrective action.

Figure 7: Location of the Service Module Transfer Tunnel and Docking Ports on the ISS



Source: NASA.

In September 2019, NASA observed a doubling of cabin air leakage to about 1.2 pounds mass air/day. A year later the leak rate increased again to about 3 pounds mass air/day, and crew isolated the source of the leak to a crack in the Service Module Transfer Tunnel. Since discovery of this fracture in October 2020, NASA and Roscosmos have identified three leak sources and sealed two of the areas resulting in a reduction of the overall ISS leak rate to about 1.7 pounds mass air/day. However, the repairs did not completely mitigate the leak rate as it remains nearly two times higher than the normal rate of about 0.6 pounds mass air/day. This elevated rate suggests that additional undiscovered leaks may still exist in the Service Module Transfer Tunnel. The foremost concern is the Station's ability to maintain a habitable atmosphere to protect the crew. Beyond that, leaks cause the ISS to consume more resources in order to maintain adequate interior cabin pressure.[23] To date, ISS teams have not observed any indications that crack growth is continuing towards a catastrophic failure; however, cracks can grow over time increasing risk. Thus, without identifying all leak locations it will be difficult for NASA and Roscosmos to properly assess the long-term structural integrity of the Service Module.

While NASA and Roscosmos have not identified the cause of the structural cracks and leaks in the Service Module Transfer Tunnel, they believe a micrometeoroid or orbital debris strike is highly unlikely. Potential causes of the cracks and leaks being explored include fatigue, internal damage, external damage, and material defects. The identified cracks are in what NASA and Roscosmos consider a very low stress area of the hull. Notably, based on the models and design mission dynamic loads NASA used to characterize the structure, the cracks should not have occurred. NASA uses tools such as fracture

[23] Maintaining additional consumables—such as filters and gas—also impacts storage, upmass, and downmass cargo space.

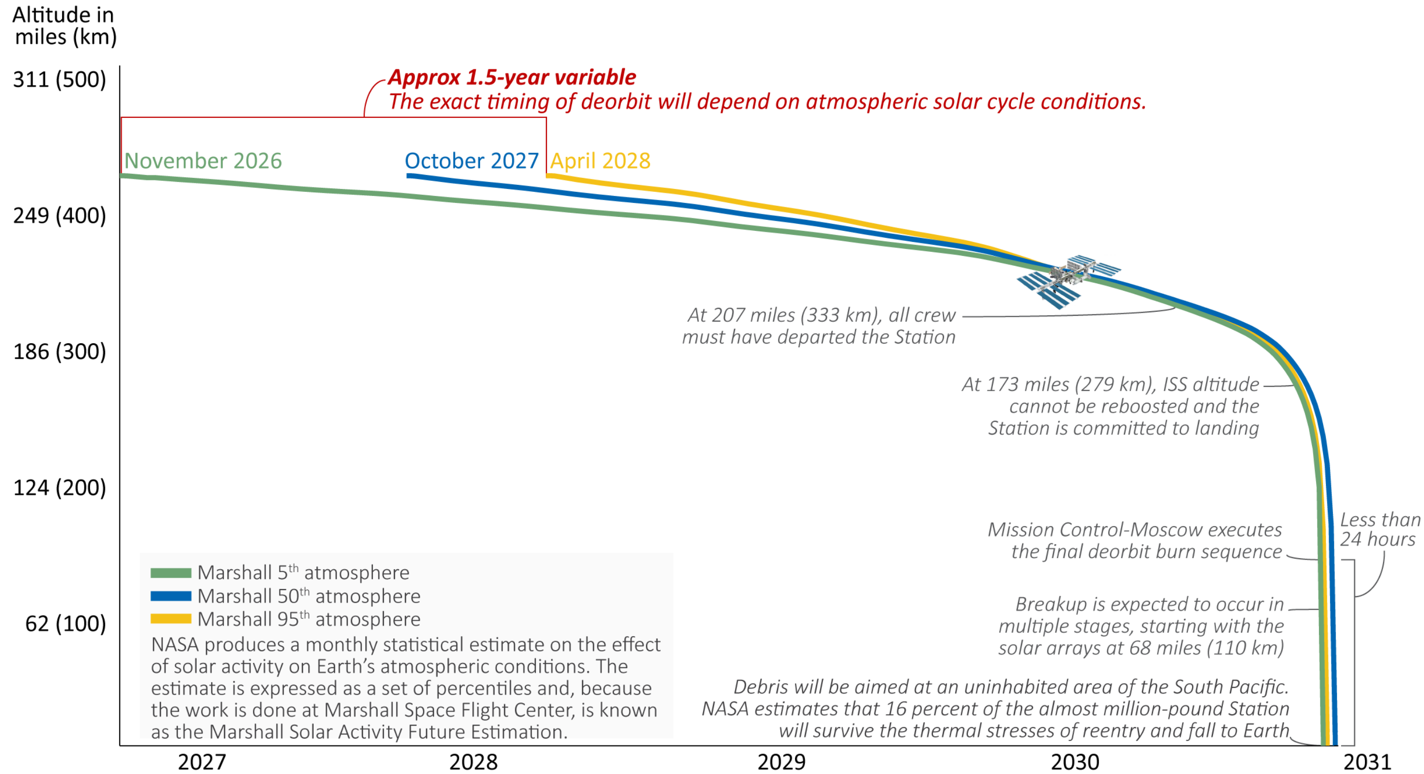
analyses, dynamic loads, materials, and stress testing to evaluate the structural life of modules. With uncertainty surrounding the cause, NASA engineers are partnering with Roscosmos to perform additional ground-based tests and analysis to better understand the cracks' causal factors. As needed, this analysis will be used to update the analytical framework used to assess the life of the Service Module Transfer Tunnel and the Service Module as a whole. NASA engineers are also reviewing whether the analysis of other segments may need to be updated based on these observations because until the root cause of the cracks is identified the situation raises potential implications for the Station's long-term structural health. At the time of our report, NASA officials stated that their review had yet to identify any problems with the analytical assumptions NASA uses to analyze other segments of the ISS. In the event that NASA and Roscosmos determine that the structural integrity of the Service Module Transfer Tunnel is at risk, NASA believes the tunnel can be safely closed and isolated from the rest of the ISS. While permanently closing off the tunnel would result in the loss of one of the four docking ports on the Russian segment, officials said continued ISS structural integrity and functionality can be maintained with the seven ports that would remain.

Deorbiting the Station will be Complex, Costly, and Time Intensive

It is likely that within the next decade NASA and its international partners will decide to decommission and deorbit the ISS either at the end of its useful service life or in response to an emergency. The overall cost to deorbit the structure is estimated at $1 billion, and the plan is for each international partner to contribute to the cost. The final cost for each partner will be determined through negotiations and bartering.

In the event of a planned deorbit, the Station will begin gradually decreasing its altitude several years prior to reentry. For example, using a hypothetical reentry date of December 2030, the ISS would likely begin altitude degradation between November 2026 and April 2028, depending on atmospheric conditions that will affect the amount of drag on the Station (see Figure 8). NASA expects that current ISS fuel and oxidizer tanks will be sufficient to provide the propellant required to perform a planned targeted reentry. In the event of an emergency in which the ISS cannot be recovered after experiencing a critical anomaly or devastating micrometeoroid or orbital debris strike, the deorbit timeframe would shrink to approximately six months.

Figure 8: Hypothetical ISS Deorbit and Re-entry Scenarios Targeting Late 2030



Source: NASA.

In both planned and emergency deorbit scenarios, toward the end of the deorbit maneuver Mission Control-Moscow will attempt a controlled, destructive reentry into the Earth's atmosphere where the Station will use its thrusters to position the spacecraft at a steep angle to confine the debris field to a targeted area. In 2018, we reported that NASA and its international partners did not have the capability to ensure a targeted reentry of the ISS because they were still developing the hardware and software necessary to enable a controlled deorbit of the Station under various deorbit scenarios. In addition, the Agency needed to develop options for obtaining supplemental emergency deorbit propellant.[24] NASA has since resolved these issues by working with Roscosmos to complete hardware and software work and by modifying its contract with Boeing to allow Northrop Grumman's Cygnus cargo resupply spacecraft to perform operational re-boosts of the ISS beginning in 2022, thereby preserving propellant resources on the Station.

[24] IG-18-021.

Research Needed for Long-Duration Missions to the Moon and Mars Will Not be Complete by 2030

NASA uses the microgravity testing environment offered by the ISS to research the human health risks of deep space travel and to demonstrate key technologies for crewed missions to the Moon and Mars. We found that, under NASA's current plans, both health risk mitigation and technology demonstrations will not be complete by 2030—the expected retirement date of the ISS. A substantial gap between the Station's retirement and the introduction of a new, commercial destination in low Earth orbit would force NASA to accept a higher level of health risk or delay start dates for long-duration, deep space human exploration missions.

Most Human Health Risks Requiring Microgravity Testing Will Not be Mitigated by 2030

Returning humans to the Moon and eventually landing astronauts on Mars will pose a complex set of challenges due to the hazardous conditions passengers face during long-duration, deep space missions. Possible adverse health outcomes for astronauts include increased risk for cancer and cardiovascular disease as well as adverse cognitive or behavioral conditions that can lead to mental disorders.

To reduce these risks, the Human Research Program (HRP) studies the hazards of radiation, isolation and confinement, distance from Earth, lack of gravity, and hostile closed environments. HRP utilizes various research platforms such as ground-based analogs, laboratories, and the ISS to provide insight into how the human mind and body might respond during extended forays into space. HRP tailors its mitigation plans to address the most strenuous environments that astronauts are expected to face—long-duration missions to the Moon and Mars. While NASA tests its mitigation strategies using various platforms to address each human spaceflight risk before deploying to the ISS, most risks require testing in a microgravity environment to ensure the effectiveness of planned mitigation solutions.

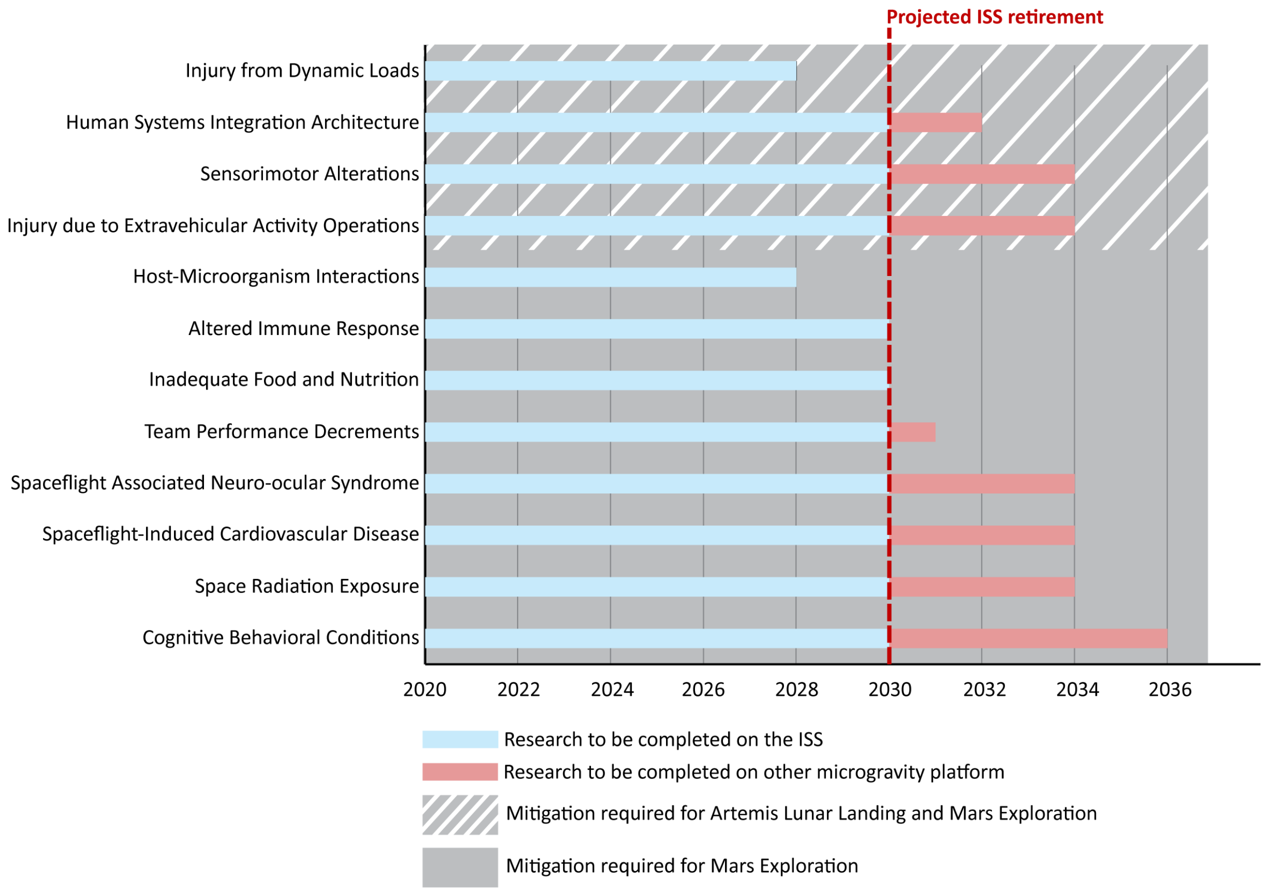
The ISS offers an optimal testing environment because, unlike ground-based testing, the Station is subject to the combined impacts of radiation, weightlessness, isolation, and a closed environment similar to what astronauts will face on long-duration missions—these hazards cannot be replicated in combination on Earth.

Health Risk Mitigation Plans

The HRP Integrated Path to Risk Reduction tracks the risks that require mitigation for deep-space travel, including those that require a microgravity testing environment. As of June 2021, 8 of the 12 critical human health risks—including those pertaining to vision, sensory and motor functions, cognitive behavioral health, and cancer-causing radiation—require the ISS for testing and will not be mitigated to an acceptable level for long-duration, deep space travel by 2030 (the expected retirement date of the

ISS) (see Figure 9). Microgravity research that is not completed by 2030 would shift, according to NASA's plans that are in development, to alternative platforms such as a commercial destination in low Earth orbit, the Lunar Gateway, the Human Landing System, and the surface of the Moon.[25] If none of these destinations are available in time to complete this critical research, the Agency will have to accept a higher level of health risk for deep space missions or delay those missions until adequate mitigation strategies are developed.

Figure 9: NASA's Schedule for Low Earth Orbit Research to Mitigate Human Health Risks for Exploration Missions (as of June 2021)



Source: OIG presentation of NASA information.
Note: See Appendix B for descriptions of the health risks.

Four human health risks—human systems integration architecture, sensorimotor alterations, injury from dynamic loads, and injury due to extravehicular activity operations—require mitigation for short-duration Artemis missions to the lunar surface (see Appendix B for descriptions of health risks). The Agency is developing plans to mitigate risks in time to return astronauts to the Moon; however, plans to mitigate risks related to human systems integration architecture, injury due to extravehicular activity operations, and sensorimotor alterations face delays because critical systems such as the Human Landing System and the Exploration Extravehicular Mobility Unit are still in development, and astronauts

[25] The Lunar Gateway will be a small space station orbiting the Moon and will provide a staging location for additional lunar missions and future deep space operations. The Human Landing System will be a spacecraft designed to ferry astronauts back and forth from lunar orbit to the surface of the Moon.

need to be able to train using these systems in order to fully characterize and mitigate the health risks related to using them.[26] According to Agency officials, NASA may accept some risks for early, short-duration lunar missions.

Changes in the Health Risk Mitigation Timeline

NASA's current health risk reduction schedule pushes mitigation timelines for deep space missions significantly farther into the future than previously planned. For example, in 2018 we reported that the Agency was on track to complete most ISS research to enable deep space exploration by 2024.[27] However, it was not until September 2020, when the Agency issued its Artemis Plan outlining the programs, projects, and plans for its Artemis missions, that NASA began to fully define human requirements for deep space exploration, including the location, duration, and types of activities that astronauts would be expected to perform. According to NASA officials, defining these activities shifted the risk level and timeframe for mitigation of several human health risks.

With the Artemis missions, NASA plans to return humans to the Moon as a precursor to sending astronauts to Mars. According to Agency officials, the March 2019 White House directive to accelerate the Artemis timetable by four years in order to land on the Moon by the end of 2024, followed by the September 2020 announcement of the Artemis Plan further defining what that mission would entail, dramatically shifted the scope of necessary health risk mitigation work and timeframe for completion.[28] The landing site at the Moon's South Pole as well as the types and durations of astronaut activities that will be required necessitated a reevaluation of health risks. For almost 20 years, astronauts have been traveling exclusively to the ISS. Traveling to the Moon and Mars exposes astronauts to different risks than those faced on the ISS, including more radiation, more frequent shifts between weightlessness and gravity, increased frequency of extravehicular activities on the surface of the Moon and Mars, and delayed communications with ground support on Earth.

In addition to the scope and timeline changes for health risk mitigation required by the Artemis mission, limited transportation capabilities prior to the first successful commercial crew flight in 2020 delayed execution of several one-year ISS missions NASA needs to test the effects of human exposure to long-duration space missions. For example, NASA developed a Complement of Integrated Protocols for Human Exploration Research (CIPHER) experiment that will address a number of human health risks by tracking ISS crews on 30-day, six-month, and one-year missions. The goal is to have results for 10 subjects for each category of mission duration completed by the early 2030s. Scientists will extrapolate data from the CIPHER missions to estimate the impact of three-year missions to Mars. NASA plans to fly the first six-month CIPHER subjects to the ISS in September 2022.

[26] The Exploration Extravehicular Mobility Unit is NASA's new spacesuit that will be worn on Artemis missions and ISS spacewalks.

[27] IG-18-021.

[28] In August 2021, we reported that NASA's next-generation spacesuits will not be ready for flight until April 2025 at the earliest, meaning that a lunar landing in late 2024 as the Agency currently plans is not feasible (IG-21-025). In addition, in a November 2021 report we found that although the Agency continues to aim for a late 2024 landing on the Moon, its own schedule risk analyses shows that 2026 is more likely (NASA OIG, *NASA's Management of the Artemis Missions* (IG-22-003, November 15, 2021).

Critical Technology Development Requiring Microgravity Testing Will Not Be Complete by 2030

NASA also uses the Station's microgravity test environment to demonstrate the safety and operational status of key technologies needed for human exploration missions to the Moon and Mars. For example, the Agency is upgrading numerous components of the ISS Environmental Control and Life Support System (ECLSS), which provides astronauts with clean air and water as well as comfortable temperature and humidity levels in the spacecraft. The ECLSS upgrades will allow NASA to test and demonstrate the improved technologies ahead of long-duration missions to Mars.

In general, technology development progresses through stages: idea inception and initial formulation; proof-of-concept testing; demonstration of mature technologies in relevant environments; and infusion of the technology into future missions. During the demonstration phase, the technology needs to run in a relevant environment—like the ISS—so data on its operational status can be gathered. Ground-based, simulated space environments, such as vacuum, thermal-vacuum, and vibration environments, can be used for some testing. However, certain technologies require testing in a microgravity environment, especially complex fluid and gas systems that are part of crew life support. Moreover, previous integrated testing of these systems on the ISS revealed problems that were not discovered in ground-based testing alone.

Exploration Extravehicular Mobility Unit Prototype

Before the first woman and next man land on the lunar South Pole, NASA will test new space suits on the ISS.

Source: NASA.

Technology Demonstration Timeline

NASA's Technology Demonstration Fly-Off Plan tracks funding, scheduling, and progress of technology demonstrations that require microgravity testing on a crewed low Earth orbit platform. As of June 2021, 27 technology demonstrations for Mars missions require a microgravity test environment—8 of those demonstrations are individual components of the ECLSS, which will be integrated into a single system for testing on the ISS by 2026. ECLSS and three other technologies—plant production, food system supporting health and performance, and radiation shielding—will need to be tested in microgravity after 2030, when the ISS is expected to retire.[29] Should NASA require a microgravity environment for technology demonstrations beyond the life of the ISS, it plans to transition the testing to a commercial low Earth orbit destination. In the case of a gap in availability, NASA may have to postpone a Mars mission or accept higher risk. The only technology that requires time on the ISS for NASA's return to the Moon is spacesuit testing for extravehicular activities,

[29] Plant production aims to deliver nutritious, reliable food to the crew while also requiring the least possible amount of storage space. Food system supporting health and performance testing tracks crew food intake against known successful health and performance outcomes. Radiation shielding mitigates space radiation risks for crew and vehicle systems by using lightweight, integrated, and multifunctional materials and technology to provide protection from solar particle events.

which is anticipated to be complete in 2027. In August 2021, we reported that NASA's next-generation spacesuits will not be ready for flight until April 2025 at the earliest.[30]

Like its health research plans, NASA's current technology demonstration plan pushes testing timelines significantly farther into the future than it had in the past. For example, in 2018 we reported that the Agency was on track to complete most microgravity testing needed to enable deep space exploration by 2024.[31] According to Agency officials, the timeline changes were primarily due to unanticipated technical challenges and the time needed to develop clear technical specifications and negotiate well-designed contracts to mature these complex technologies. In addition, since March 2020 the COVID-19 pandemic has created some unplanned schedule slips due to its impact on NASA operations.

[30] IG-21-025.

[31] IG-18-021.

NASA's Commercialization Plans Show Promise but Must Overcome Significant Challenges to Avoid a Gap in a Low Earth Orbit Destination

NASA's plan is for one or more commercial low Earth orbit destinations to be operational by 2028, which would allow a two-year overlap with the ISS before its anticipated retirement in 2030. The Agency's Plan for Commercial low Earth orbit Development, published in 2019, identifies five steps in the near-term and also outlines mid- and long-term objectives. We found that the Agency's near-term actions show promise, with its activities to date resulting in market interest and growth, especially for private astronaut missions. However, NASA faces significant challenges with fully executing the plan in time to meet its 2028 goal and avoid a gap in availability of a low Earth orbit destination. If there is no habitable commercial destination in low Earth orbit after the ISS is decommissioned, NASA will be unable to conduct microgravity health research and technology demonstrations needed for long-duration human exploration missions to the Moon and Mars, significantly increasing the risk of—or delaying—those missions.

NASA's Near-term Actions for Commercial Low Earth Orbit Development Show Promise

We found that NASA's Plan for Commercial low Earth orbit Development is comprehensive and targeted to the most promising areas of market growth based on the Agency's sponsored market research studies. In addition, NASA has taken steps to execute all five of the plan's near-term actions. NASA's market research studies found the most promising areas to stimulate demand include sponsorship and marketing; accommodations for space tourism; video products for entertainment use including films, documentaries, and sporting events; and in-space manufacturing of unique materials or products. Three out of five of NASA's near-term actions address these promising areas. The other two near-term actions relate specifically to the development and NASA's use of commercial low Earth orbit destinations.

Skincare in Space

With the ISS now open for commercial activity, New York-based Estée Lauder paid to have one of its products photographed in low Earth orbit.
Source: Estée Lauder.

The five near-term actions in NASA's Plan for Commercial low Earth orbit Development, and what the Agency is doing to address them, are as follows:

Commercial Use and Pricing Policy. In June 2019, NASA established a commercial and marketing pricing policy to expand commercial use of the Station beyond activities that had been allowed under the CASIS requirements of utilizing microgravity for research that benefits life on Earth.

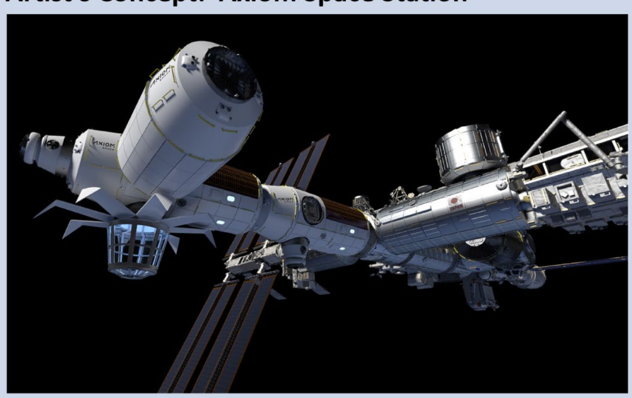
From June 2019 to June 2021, NASA approved 11 of 16 requests for commercial and marketing activities onboard the ISS. Approved activities included product launches, video demonstrations, and promotions. For example, in 2019 Adidas sneakers were launched to the ISS to be tested and photographed in microgravity, and similarly in 2020 Estée Lauder skincare products were photographed in space for a marketing campaign.

Private Astronaut Missions. NASA announced opportunities for private astronaut missions to the ISS in June 2019, and the Agency plans to allow up to two missions per year based on ISS availability. Allowing private astronauts onboard the Station extends the opportunity to travel into low Earth orbit to a broader range of candidates. As of August 2021, NASA had approved one of seven proposals for private astronaut missions: an Axiom Space launch of a private astronaut crew of four on the first private astronaut mission to the ISS in February 2022. In response to demand outpacing ISS availability, in June 2021 NASA issued its first annual call for proposals under which it plans to select up to two private astronaut missions to launch to the Station between fall 2022 and the end of 2023. The volume of interest in private astronaut missions for tourism and entertainment validates market projections that commercial spaceflight will be the chief revenue generator in the low Earth orbit economy. Furthering market growth, in July 2021 Virgin Galactic and Blue Origin both launched private citizens on brief suborbital trips to the edge of space, and in September 2021 SpaceX launched four private citizens on a three-day trip to low Earth orbit.[32] The future cost for private citizens to purchase these various space travel opportunities remains unclear given that Virgin Galactic's tickets have a starting price of $450,000, Blue Origin has not opened public ticket sales, and SpaceX did not disclose the cost of its civilian low Earth orbit mission.

Procurement Process for Commercial Destinations. NASA announced its Commercial Low Earth Orbit Destination procurement strategy in March 2021 to fund a portion of initial development costs and ultimately purchase services on one or more commercial low Earth orbit destinations—potential replacements, essentially, for the ISS. In the development phase, the strategy emphasizes public-private partnerships, similar to how the Agency managed its Commercial Crew Program. Forty-nine commercial entities expressed interest in this initiative by attending an industry briefing in March 2021, and in August 2021, companies submitted proposals to build low Earth orbit destinations.

As a separate initiative to develop a commercial destination in low Earth orbit, in 2020 NASA awarded Axiom Space a firm-fixed price contract valued at up to $140 million over 7 years to provide at least one habitable commercial module to attach to the ISS beginning late 2024. The ultimate intent of this project is for Axiom to launch a node module, research and manufacturing facility, crew habitat, and large-windowed Earth observatory to form a new, "Axiom Segment"

Artist's Concept: Axiom Space Station



The proposed station by Houston-based Axiom Space will be used for microgravity research, critical space-environment materials testing, and astronaut accommodation.

Source: Axiom Space.

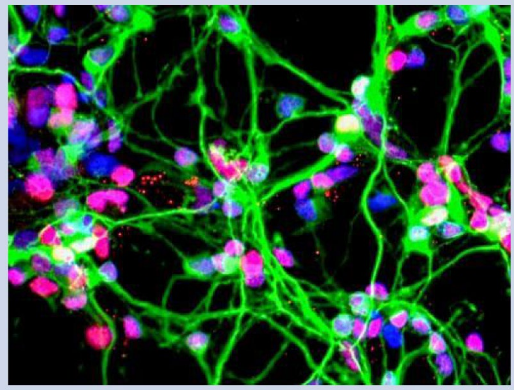
[32] A suborbital flight must travel at least 62 miles (100 km) from Earth's surface to reach the edge of space and achieve weightlessness. In contrast, spacecraft that operate in low Earth orbit maintain an altitude between 99 and 621 miles (160-1,000 km) from the Earth's surface.

of the Station.[33] By 2028, Axiom plans to launch a platform to provide power and cooling to its segment, allowing the Axiom Segment to detach and continue as a free-flying, commercial destination once the ISS is deorbited.

In the second phase of NASA's commercial destination procurement strategy, once the destination concepts mature the Agency intends to acquire services from one or more viable commercial destinations through an openly competitive solicitation.

Stimulating Sustainable Demand. NASA awarded seven companies a combined $38.8 million in contracts starting in 2017 to encourage U.S. industry to develop sustainable, scalable, and profitable non-NASA demand for services and products in low Earth orbit. Referred to as In Space Production Applications, these contracts fund commercial studies, hardware development, and flight demonstrations on the ISS to assess potential growth of a low Earth orbit economy and provide seed money to industries with the most potential to bring their products to market, including in-space manufacturing and regenerative medicine. Companies such as Techshot and Space Tango are employing tissue engineering and regenerative medicine research for higher-accuracy drug testing and advanced research in organ growth to address the shortage of organs for transplantation. Two additional companies—Redwire and Fiber Optic Manufacturing in Space Incorporated—are working on in-orbit production of a new type of fiber optics that, when manufactured in microgravity, may be capable of performing many times more efficiently than traditional fiber optic cables.

Examining Causes of Major Diseases



A current experiment on the ISS considers the effects of microgravity on 3D models of Parkinson's Disease and Multiple Sclerosis

Source: NASA.

Quantifying NASA's Long-term Needs in Low Earth Orbit. NASA continues to refine, quantify, and publicize services that it intends to purchase on future low Earth orbit destinations by issuing white papers and announcements, and the Agency's specifications have become more detailed over time. Recently, NASA provided an improved level of detail describing the facilities and features needed to support operations, research, and development in low Earth orbit beyond the lifetime of the Station, and the Agency has quantified the type and amount of services that it intends to purchase on such a destination. In May 2021, NASA announced what it calls "stretch goals"—a sort of wish list—for ancillary services that go beyond its primary goals for the commercial low Earth orbit destination. The stretch goals include the capability to perform missions that simulate deep space transportation conditions by isolating the crew from other astronauts and the capability to perform artificial gravity research to simulate Moon or Mars surface gravity.[34]

[33] Modules called "nodes" connect parts of the Station to each other. Axiom's node module would connect the Axiom segment to the U.S. segment of the ISS.

[34] Commercial Low Earth Orbit Destinations Announcement, 80JSC021CLD, July 12, 2021.

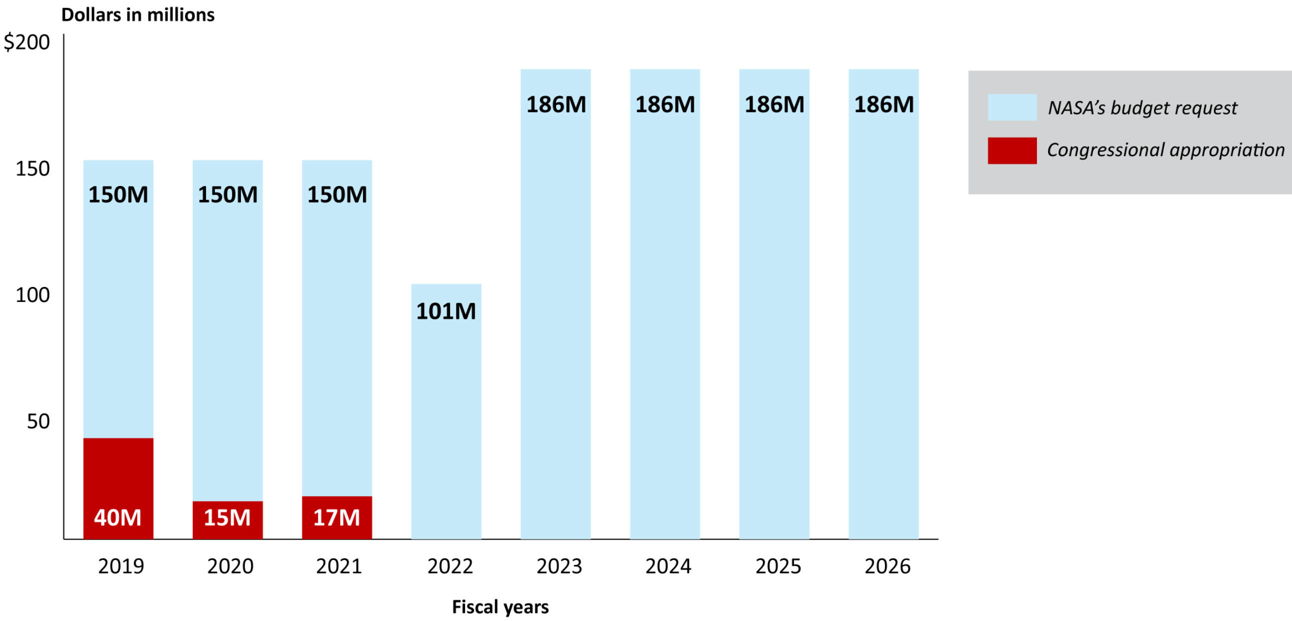
NASA's Plans for Commercial Low Earth Orbit Development Face Significant Challenges

While NASA's recent efforts to facilitate commercial low Earth orbit development show promise, we identified several interrelated challenges that may hinder the Agency's plans. These challenges increase the risk that, for an undetermined period of time, NASA may not have access to a habitable destination in low Earth orbit. An inability to conduct microgravity health research and technology demonstrations required for human missions to the Moon and Mars—including testing the new spacesuit for the planned Artemis mission to land on the Moon—significantly increases the risk or the potential delay of those missions. Furthermore, absent a stable low Earth orbit destination, commercial activities in low Earth orbit would likely collapse or be significantly reduced to taking place on a small, commercial spacecraft that offers limited time and space for such research.

Robust Market for Low-Earth Orbit Yet to Materialize. While the volume of interest in private astronaut missions has exceeded NASA's expectations, significant demand for commercial activity in other sectors of the nascent economy—such as in-space manufacturing and marketing products for sale on Earth—has yet to materialize. Over the last 10 years, efforts by CASIS to develop a commercial market have not yet resulted in self-sustained demand. In order to support and accelerate CASIS's efforts to spur growth, in 2017 NASA began to award seed money to industries that market studies determined to have the most potential to bring their in-space manufactured products to market, and in 2019 NASA expanded the types of commerce allowed on the Station to include commercial and marketing activities on a reimbursable basis. Nonetheless, companies have yet to successfully develop a business case to bring in-space manufactured products to market on Earth, and companies utilized less than one percent of the allocated crew resources and cargo capability the Agency made available for purchase for commercial and marketing activities in 2020. Furthermore, it is too early to determine the extent to which private astronaut missions will make a sustaining contribution to a commercial market in low Earth orbit. However, unless overall commercial demand expands markedly, future low Earth orbit platforms will likely not be viable without continued significant Government support.

Funding for Destination Platform Is Inadequate for NASA to Meet 2028 Goal. NASA requested $150 million each year from Congress in FY 2019 through 2021 to fund commercial low Earth orbit development, but only received $40, $15, and $17 million in each of those three years, respectively (see Figure 10). This funding supports more than destination development—it covers all five pillars of the Agency's commercial low Earth development and program management costs. NASA's destination strategy starts with supporting development of a commercial destination, then moves on to the Agency being able to purchase services on a commercial destination by 2028. NASA projects the first phase alone to cost $300 to $400 million over a 6-year period (NASA has requested $845 million total for FY 2022 through 2026) to meet the 2028 goal for replacing the ISS with a commercial destination.

Figure 10: Funding Required to Help Develop a Commercial Replacement for the ISS



Source: OIG presentation of NASA information.

Note: Congressional appropriations for FY 2022 had not been finalized at the time of this report.

Notably, current funding levels have already slowed implementation of the Agency's destination procurement initiative by three years. According to Agency officials, NASA would have started destination procurements sooner and offered more early development funding if it had received its requested budget. In addition, commercial partners expressed concern over being able to provide operational destinations by 2028 with the small amount of early development funding NASA is offering.

Unreliable Cost Estimates. Scant precedent exists to inform NASA's path forward in developing and eventually purchasing services from a commercial low Earth orbit destination, a fact that makes it difficult for NASA to clearly and accurately articulate its budgetary needs. Several NASA-sponsored studies varied significantly in their costs for destination development, operation, and transportation, with estimates ranging from $5.1 to $37.5 billion over a 15-year period. According to Agency officials, until companies that submitted proposals in August 2021 begin to further define their designs, cost estimates will remain unreliable. NASA officials and commercial partners agree that without full development of technical capabilities and design maturations, estimates of the full development cost are hypothetical. For their part, commercial partners indicated that inadequate cost analysis could negatively impact business planning and financing efforts. Moving forward, more concrete cost estimates will be necessary as Agency officials work with Congress and other stakeholders to ensure the long-term commitment exists to adequately fund this complex effort. Further, without more reliable cost estimates, it will be difficult for Congress to fully evaluate the tradeoffs of the commercial approach versus continued extension of ISS operations.

Optimistic Development Schedule. NASA faces a narrow timeframe to transition to a commercial destination in 2028 to avoid a gap in low Earth orbit destinations at the anticipated end of the ISS's lifetime in 2030. The Agency projects that the first phase of its destination strategy will complete early design maturation in 2025. In our judgment, even if early design maturation is achieved in 2025—a challenging prospect in itself—a commercial platform is not likely to be ready until well after 2030. In comparison, the Commercial Crew Program did not fly its first crewed mission to the ISS until eight years after it completed early design maturation in 2012. We found that commercial partners agree that NASA's current timeframe to design and build a human-rated destination platform is unrealistic.

Evolving Requirements. NASA has taken steps to refine and quantify its long-term low Earth orbit needs. However, according to private industry officials we spoke with, the Agency still has not provided sufficient information about its future requirements for companies to design and develop commercial destinations. The destination procurement strategy was not announced until two years after NASA first issued its plans for commercial low Earth orbit development, and several aspects of destination development requirements remain uncertain. NASA and its commercial partners will continue to refine their requirements as the destinations go through preliminary stages of design and development and potential customers, partnerships, and anticipated uses become more clearly defined. However, failure to provide enough information on requirements in a timely manner could result in additional development delays. This is especially the case with achieving human rating requirements, which are an integral part of all program activities, to include design and development, and which proved to be a significantly time-consuming part of the Commercial Crew Program's certification.[35]

[35] According to NASA Procedural Requirement 8705.2B, Human-Rating Requirements for Space Systems (May 6, 2008), human-rating is the certification granted to crewed space systems prior to the first crewed flight to ensure the system can safely carry astronauts by accommodating human needs, effectively utilizing human capabilities, controlling hazards with sufficient certainty to be considered safe for human operations, and providing the capability to safely recover from emergency situations.

CONCLUSION

While NASA is optimistic that the Station's life can be extended to 2030, the structure cannot endure the long-term effects of the harsh space environment forever. Ionizing radiation, extreme temperature changes, structural loading events such as docking and undocking of vehicles, and the hazards of micrometeoroids and orbital debris all wear on the Station's structure and will lead to its inevitable decommissioning and deorbit. Moreover, NASA and Roscosmos continue to investigate the cause of cracks in the Service Module Transfer Tunnel and their long-term impacts to the structural integrity of the tunnel and the Service Module as a whole.

NASA's future plans envision replacing the ISS with a commercial microgravity testing environment the Agency can use to develop strategies for mitigating the deep space travel risks to human health and to demonstrate key technologies for human missions to the Moon and Mars. Under the Agency's current projections, health risk mitigation and technology demonstration efforts for Mars missions will not be complete by 2030—the expected retirement date of the ISS. Meanwhile, the Agency's plans to mitigate outstanding health risks for short-duration lunar missions face delays because critical systems such as the Human Landing System and the Exploration Extravehicular Mobility Unit remain in development, and astronauts need to be able to train using these systems in order to fully characterize and mitigate associated risks.

Given the Station's inevitable retirement and NASA's continuing need for low Earth orbit research, the success of the Agency's Plan for Commercial Low Earth Orbit Development is crucial to avoid a gap in low Earth orbit access. NASA's plan is for one or more commercial low Earth orbit destinations to be operational by 2028, which would allow a two-year overlap with the ISS before its anticipated decommissioning in 2030. To its credit, we found that NASA's near-term actions show promise, and its economic demand stimulation activities to date have resulted in some market interest and growth, especially for private astronaut missions. However, the Agency faces significant challenges with executing its commercialization plan by 2028 or even 2030—meaning that without further extension of the ISS, a gap in availability of a low Earth orbit destination is likely. Challenges of commercialization include limited market demand, inadequate funding, unreliable cost estimates, and still-evolving requirements. The risk of deep space human exploration missions will increase significantly if NASA is not able to conduct the required microgravity health research and technology demonstrations on a habitable space destination in low Earth orbit. Furthermore, without a destination, the nascent low Earth orbit commercial space economy would likely collapse, with cascading impacts to commercial space transportation capabilities, in-space manufacturing, and microgravity research.

RECOMMENDATIONS, MANAGEMENT'S RESPONSE, AND OUR EVALUATION

To mitigate risks to the Station's structural integrity, the Associate Administrator for the Space Operations Mission Directorate should:

> Ensure the risks associated with cracks and leaks in the Service Module Transfer Tunnel are identified and mitigated prior to agreeing to an ISS life extension.

We provided a draft of this report to NASA management, who partially concurred with our recommendation. In its response, the Agency agreed that it is essential to complete ongoing work to assess the risks with the cracks and leaks along with Roscosmos' plans to locate and repair leak locations in the Service Module Transfer Tunnel. However, NASA does not agree that this work must be completed prior to agreeing to an ISS life extension. We acknowledge that ongoing work to assess, repair, and monitor the leaks is needed, and in our judgment the Agency's ongoing and planned efforts are responsive to the intent of our recommendation. The recommendation will be closed upon completion and verification of the proposed corrective actions. That said, we will continue to monitor NASA's efforts to manage the issues associated with the Service Module Transfer Tunnel and any associated impacts these issues may have on the integrity of the ISS.

Management's comments are reproduced in Appendix C. Technical comments provided by management and revisions to address them have been incorporated as appropriate.

Major contributors to this report include Ridge Bowman, Space Operations Director; Deanna Lee, Project Manager; Gina Davenport-Bartholomew; Anna David; Rachel Pierre; Dimitra Tsamis; Matt Ward; and Shani Dennis.

If you have questions about this report or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.

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Paul K. Martin
Inspector General

Appendix A: Scope and Methodology

We performed this audit from November 2020 through October 2021 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Our audit objective was to examine the costs associated with the Station's continued use and maintenance, risks to its structure, NASA's utilization of the ISS, and the Agency's plans for commercialization of low Earth orbit. To accomplish our objective, we performed the majority of our work with the ISS Program office at Headquarters and Johnson Space Center.

In order to accomplish our objectives and understand the Agency's use of the ISS, we conducted numerous interviews across multiple levels of the ISS Program Office. This included reviewing the critical research and demonstrations required for risk mitigation through the Human Research Program and the Technology Demonstrations office. We met with Agency officials and interviewed staff in the ISS Program Vehicle Office to determine the impacts of component failures on the integrity of the ISS vehicle. To understand the technical and safety threats to the ISS vehicle, we reviewed various analyses, assessments, hazard reports, risk assessments, and structural health and life extension reports. To understand deorbit planning efforts and the cost of maintaining and operating the ISS, we met with officials from the ISS Program Planning and Control office and analyzed the operating plans from the last 10 fiscal years. We reviewed documents and the cooperative agreement relating to the management of CASIS and interviewed the ISS National Laboratory liaison and ISS National Laboratory representatives.

To establish NASA's vision, infrastructure, and requirements for a commercial low Earth orbit economy, we met with the Commercial Low Earth Orbit Development Program and conducted structured interviews with executives from Axiom Space, Blue Origin, Boeing, Deloitte, KBR, Northrop Grumman, Sierra Nevada Corporation, Space Adventures, Virgin Galactic, SpaceX, and Shuttle IO. This sample of executives addressed the private industry's challenges and benefits to engaging with NASA to build a commercial low Earth economy and the impact of a potential gap in low Earth orbit on the marketplace.

We reviewed the following federal laws, regulations, policies, and guidance related to the ISS:

- National Aeronautics and Space Administration Authorization Act of 2020, H.R. 5666, 116th Congress (2020)
- National Aeronautics and Space Administration Transition Authorization Act of 2017, Pub. L. No. 115-10 (2017)
- National Aeronautics and Space Administration Authorization Act of 2010, Pub. L. No. 111-267 (2010)
- President Obama, National Space Policy of the United States of America (June 28, 2010)
- Commercial Space Launch Act of 1984, Pub. L. No. 98-575, §3 (1983)
- International Space Station Program Plan (October 2013)
- International Space Station Cooperative Agreement Independent Review Team, *Final Report to NASA* (February 4, 2020)

- Agreement Among the Government of Canada, Governments of Member States of the European Space Agency, the Government of Japan, the Government of the Russian Federation, and the Government of the United States of America Concerning Cooperation on the Civil International Space Station (January 29, 1998)
- NASA Plan for Commercial Low Earth Orbit Development, Summary and Near-Term Implementation Plans (June 7, 2019)
- Cooperative Agreement by the National Aeronautics and Space Administration (NASA) to the Center for the Advancement of Science in Space (CASIS) (2011)

Assessment of Data Reliability

We did not use computer-processed data to perform this audit.

Review of Internal Controls

We assessed internal controls and compliance with laws and regulations necessary to satisfy the audit objective. However, because our review was limited to these internal control components and underlying principles, it may not have disclosed all internal control deficiencies that may have existed at the time of this audit.

Prior Coverage

During the last 5 years, the NASA Office of Inspector General (OIG) and the Government Accountability Office (GAO) have issued several reports of significant relevance to the subject of this report; they can be accessed at https://oig.nasa.gov/audits/auditReports.html and https://www.gao.gov.

NASA Office of Inspector General

NASA's Management of the Artemis Missions (IG-22-003, November 15, 2021)

NASA's Development of Next-Generation Spacesuits (IG-21-025, August 10, 2021)

NASA's Efforts to Mitigate the Risks Posed by Orbital Debris (IG-21-011, January 27, 2021)

NASA's Management and Utilization of the International Space Station (IG-18-021, July 30, 2018)

NASA's Management of the Center for the Advancement of Science in Space (IG-18-010, January 11, 2018)

NASA's Management and Development of Spacesuits (IG-17-018, April 26, 2017)

NASA's Plans for Human Exploration Beyond Low Earth Orbit (IG-17-017, April 13, 2017)

Government Accountability Office

NASA Commercial Crew Program: Continued Delays Pose Risks for Uninterrupted Access to the International Space Station (GAO-18-317T, January 17, 2018)

NASA Commercial Crew Program: Schedule Pressure Increases as Contractors Delay Key Events (GAO-17-137, February 16, 2017)

Appendix B: Description of Human Health Risks

Health Risk	Description
Human Systems Integration Architecture	Human systems integration architecture risks relate to the crew being unable to adequately respond to critical malfunctions or perform safety critical procedures given the distance from Earth impacting real-time support from Mission Control and limited resupply and evacuation options.
Sensorimotor Alterations	Sensorimotor alterations risks relate to the effects of altered gravity on spatial orientation, postural control and locomotion, and manual and fine motor control.
Injury from Dynamic Loads	Injury from dynamic loads comes from dynamic phases of flight such as landing where dynamic loads are transferred to the crew via the vehicle.
Injury due to Extravehicular Activity Operations	Injury due to extravehicular activity operations stems from the demands of astronauts operating in a self-contained spacesuit in various gravity fields and system environments, creating a possibility that crew injury and compromised physiological and functional performance may occur.
Host-microorganism Interactions	Host-microorganism interactions refer to the risk that infectious disease will increase in prevalence or severity during spaceflight.
Altered Immune Response	Altered immune response risk involves changes to the immune system during spaceflight which leads to increased incidence of skin rashes and hypersensitivity reactions.
Inadequate Food and Nutrition	Inadequate food and nutrition can lead to decreased performance, crew illness, and long-term health effects.
Spaceflight Associated Neuro-ocular Syndrome	Spaceflight associated neuro-ocular syndrome is induced by the microgravity environment and causes intracranial pressure changes that can lead to vision alterations.
Team Performance Decrements	Team performance decrements refers to the risk that the conditions on space missions may lead to inadequate functioning within a team, such as poor cooperation, coordination, and communication, and the associated impact to performance and behavioral health.
Cognitive Behavioral Conditions	Cognitive behavioral conditions risks stem from exposure to extended durations of isolation and confinement, greater distances from Earth, and increased exposures to radiation and altered gravity, which could affect crew health and performance during the mission and lead to the development of psychiatric disorders.
Spaceflight-induced Cardiovascular Disease	Spaceflight-induced cardiovascular disease risk stems from the combined effects of weightlessness, radiation, psychological stress, and isolation on the cardiovascular health.
Space Radiation Exposure	Space radiation exposure stems from the exposure to radiation from the space environment and the possibility for increased cancer morbidity or mortality.

APPENDIX C: MANAGEMENT'S COMMENTS

National Aeronautics and
Space Administration

Mary W. Jackson NASA Headquarters
Washington, DC 20546-0001

November 23, 2021

Reply to Attn of: Space Operations Mission Directorate

TO: Assistant Inspector General for Audits

FROM: Associate Administrator for Space Operations

SUBJECT: Agency Response to OIG Draft Report, "NASA's Utilization of the International Space Station (ISS) and Commercialization of Low Earth Orbit" (A-21-003-00)

The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled, "NASA'S Utilization of the ISS Commercialization of Low Earth Orbit" (A-21-003-00), dated October 26, 2021.

In the draft report, the OIG makes one recommendation addressed to the Associate Administrator for Space Operations related to the structural life of the International Space Station (ISS).

Specifically, the OIG recommends the following:

Recommendation 1: In order to mitigate risks to the Station's structural integrity, ensure the risks associated with cracks and leaks in the Service Module Transfer Tunnel are identified and mitigated prior to agreeing to an ISS life extension.

Management's Response:

NASA partially concurs with the recommendation. NASA agrees it is essential to complete ongoing work to assess the risks with the cracks and leaks along with Roscosmos' plans to locate and repair leak locations in the Service Module Transfer Tunnel (PRK). However, NASA does not agree that this work must be completed prior to agreeing to an ISS life extension.

NASA specialists are continuing to work with Russian specialists to identify additional leak locations in the PRK and determine the root cause of the cracks/leaks. In early March 2021, the Russians repaired two leak locations, reducing the leak rate from 3.0 to 1.1 pounds air/day. Prior to 2019, the nominal ISS atmospheric leak rate was 0.6 pounds air/day, so this repair did not completely mitigate the leak, indicating an additional small crack in the PRK. With the PRK hatch closed (isolated from the rest of ISS), the ISS is very "tight," with a very small leak rate of 0.1 – 0.3 pounds air/day.

NASA and Roscosmos are working together to investigate the causal factors that may have contributed to the PRK leaks, including local stresses, material defects, environmental factors, and physical damage to the site (e.g. micrometeoroid/orbital debris strike). Ground testing that mimics the on-orbit repairs will include use of the PRK hull material and repaired hull samples. The tests will subject the materials to a range of different stress and environmental conditions. There are also plans to install additional sensors in the PRK to measure the local stress environment. The joint NASA/Russia test plans, analysis and on-board assessments will aid in determining causal factors. Findings from the investigation will be used to assess long-term PRK health and life extension. The Russians flew additional repair and troubleshooting hardware on the recent 79P Progress cargo flight, and will be working over the next month to identify the other leak locations. The strain gauges are tentatively scheduled for installation in February 2022. With the current schedule, preliminary results for the investigation will be available late March 2022.

The PRK is only used for certain operations when a vehicle is docked to the Service Module aft. When not in use, the PRK hatch is kept closed. If needed, the PRK could remain closed, with other ISS ports used for docking. There are no indications of leaks or cracks in other elements of the ISS. ISS has continuous insight into leak rates and can confirm that the PRK leak rates have been stable since the initial crack repairs.

NASA is working diligently with Roscosmos and the other partners to determine the root cause and repair the remaining PRK leaks, and NASA and our international partners are committed to resolving this issue to ensure the ISS is safe. Given the current and planned activities described above, NASA is confident in moving forward with plans to extend the ISS, noting that we will continue to monitor and evaluate ISS health as we go forward. In addition, clarity around the future of ISS is important to our international and commercial partners.

Estimated Completion Date: May 31, 2022

We have reviewed the draft report for information that should not be publicly released. As a result of this review, we have not identified any information that should not be publicly released.

Once again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Michelle Bascoe on (202) 358-1574.

KATHRYN LUEDERS

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Kathryn L. Lueders

Appendix D: Report Distribution

National Aeronautics and Space Administration

Administrator
Deputy Administrator
Associate Administrator
Chief of Staff
Chief Health and Medical Officer
Associate Administrator for the Space Operations Mission Directorate
Director, International Space Station
Program Manager, International Space Station

Non-NASA Organizations and Individuals

Office of Management and Budget
Deputy Associate Director, Energy and Space Programs Division

Government Accountability Office
Director, Contracting and National Security Acquisitions

Congressional Committees and Subcommittees, Chairman and Ranking Member

Senate Committee on Appropriations
Subcommittee on Commerce, Justice, Science, and Related Agencies

Senate Committee on Commerce, Science, and Transportation
Subcommittee on Space and Science

Senate Committee on Homeland Security and Governmental Affairs

House Committee on Appropriations
Subcommittee on Commerce, Justice, Science, and Related Agencies

House Committee on Oversight and Reform
Subcommittee on Government Operations

House Committee on Science, Space, and Technology
Subcommittee on Investigations and Oversight
Subcommittee on Space and Aeronautics

(Assignment No. A-21-003-00)