International Space Station Transition Report

pursuant to
Section 303(c)(2) of the NASA Transition Authorization Act of 2017 (P.L. 115-10)

January 2022

Table of Contents

1.0 THE INTERNATIONAL SPACE STATION: THE NEXT DECADE

This report responds to direction in the National Aeronautics and Space Administration Transition Authorization Act of 2017 (P.L. 115-10, hereafter "the Act"), Section 303(c)(1), to submit to Congress a report evaluating the International Space Station (ISS) as a platform for research, deep space exploration, and low-Earth orbit (LEO) spaceflight in partnership with its four international space agency partners, and the commercial space sector.

This report is an update to the "International Space Station Transition Report," dated March 30, 2018.[1] This version updates the plan to transition the LEO activities of United States Government agencies, ISS International Partners, ISS National Laboratory (ISSNL) users, researchers, industry, academia, and other ISS commercial partners off the ISS and onto Commercial LEO Destinations (CLDs) by 2030. It details the goals for the next decade of ISS operations leading to a smooth transition to commercial services, the steps being taken to develop both the supply and demand side of the LEO commercial economy, and the technical steps and budget required for ISS transition.

The ISS is the world's preeminent orbital microgravity research platform for research and development. For more than 20 years, scientists and researchers have used the ISS to conduct research into biological, physical, biomedicine, materials, and Earth and space science. Technology demonstrations and development aboard have advanced the state-of-the-art for applications with benefits both on Earth and in space. Climate sensors deployed on ISS have validated climate models and contributed a host of new information about Earth's changing climate environment, while space science instruments on ISS have advanced our knowledge of phenomena including neutron stars and dark matter. The ISS crew itself has been a critical part of the experiment as well, volunteering themselves as test subjects for research into human adaptation to living and working in microgravity. Without these long-duration demonstrations and experiments into the joint human-and-vehicle system, human exploration of the solar system will not be possible.

The ISS is now entering its third and most productive decade of utilization, including research advancement, commercial value, and global partnership. The first decade of ISS was dedicated to assembly, and the second was devoted to research and technology development and learning how to conduct these activities most effectively in space. The third decade is one in which NASA aims to verify exploration and human research technologies to support deep space exploration, continue to return medical and environmental benefits to humanity, continue to demonstrate U.S. leadership in LEO through international partnerships, and lay the groundwork for a commercial future in LEO.

Today, with commercial crew and cargo transportation systems online, the ISS is busier than ever. The ISSNL, responsible for utilizing 50 percent of NASA's resources aboard the ISS, hosts hundreds of experiments from other Government agencies, academia, and commercial users to return benefits to people and industry on the ground. Meanwhile, NASA's research and development activities aboard are advancing the technologies and procedures that will be necessary to send the first woman and first person of color to the Moon and the first humans to Mars.

The ISS is entering an era of robust commercial use, taking advantage of the utilities provided by the ISS to develop the capabilities industry needs to move from being dependent on NASA for space station utilization to providing the platform(s) the Agency will need to continue its mission in LEO after the lifetime of the ISS. Commercial crew and cargo transportation are well known examples of the commercial ecosystem supporting ISS, and today they provide the vital lifeline from Earth to the ISS. Perhaps less known are over 20 commercial facilities operating aboard ISS today – including a 3D

[1] https://www.nasa.gov/sites/default/files/atoms/files/iss_transition_report_180330.pdf

printer, a bioprinter, external Earth observation and materials platforms, and an airlock – that are available for use by both NASA and other paying customers. Commercial engagement is one step towards ensuring space continues to thrive beyond ISS. NASA awarded the use of an ISS docking port to Axiom Space, which plans to attach a series of commercial modules that will eventually detach to become a LEO free-flying destination.

NASA has also signed agreements with three U.S. companies (Blue Origin of Kent, Washington; Nanoracks LLC of Houston, Texas; and Northrop Grumman Systems Corporation of Dulles, Virginia) to develop commercial destinations in space that go directly to orbit, i.e., free-flyers. The awards, along with the Axiom concept, are the first part of a two-phase approach to ensure a seamless transition of activity from the ISS to commercial destinations. During this first phase, private industry, in coordination with NASA, will formulate and design CLD capabilities suitable for potential Government and private sector needs. The first phase is expected to continue through 2025. For the second phase of NASA's approach to a transition toward CLDs, the Agency intends to certify for NASA crew member use CLDs from these and potential other entrants, and ultimately, purchase services from destination providers for crew to use when available.

It is NASA's goal to be one of many customers of commercial LEO destination services, purchasing only the goods and services the Agency needs. CLDs, along with commercial crew and cargo transportation, will provide the backbone of the human LEO ecosystem after the ISS retires.

The ISS provides the United States with capabilities in space that are currently unmatched. NASA leads a team of five space agencies representing 15 countries, offering high-profile opportunities for U.S. leadership in civil and robotic spaceflight, along with other important priorities that accompany flying humans in space, such as space situational awareness, orbital debris mitigation, and spectrum management. At a time when other nations are seeking to expand their abilities to operate in space, the ISS remains the sole example of how an international team can productively and successfully cooperate over the course of decades in space. A major goal of NASA is to expand our international partnerships during and after the transition to CLDs.

The ISS has five major mission goals, each of which should realize significant advances in the next decade:

- Enable deep space exploration [Section 3.1];
- Conduct research to benefit humanity [Section 3.2];
- Foster a U.S. commercial space industry [Section 3.3];
- Lead and enable international collaboration [Section 3.4]; and
- Inspire humankind [Section 3.5].

The extension of ISS operations through 2030 is a decision that is intended to continue to return these benefits to the United States and to humanity as a whole, while preparing for a seamless transition of the suite of LEO mission capabilities to one or more commercially-owned and -operated LEO destinations that will follow after the ISS. The United States On-Orbit Segment (USOS) and Functional Cargo Block (FGB) life extension analyses for the time period through 2028 have been completed with no issues identified that would preclude extension through 2030. Roscosmos has formally completed extension analyses for the time period through 2024 and will begin work on analyzing extension through 2030. Indeed, the ISS itself has been recently upgraded with a new commercial airlock, a new Russian research and docking module, and several power systems upgrades that will operate for the life of the vehicle. While the ISS will not last forever, NASA expects to be able to operate it safely through 2030.

It is in the interests of the United States that a seamless transition be made from ISS to one or more future CLDs such that no gap in the Government's ability to use low Earth orbit space platforms is experienced. A gap could jeopardize the strong network of international partnerships that have matured over the last two decades. Operating ISS through 2030 gives NASA and our U.S. industry partners the time necessary to bring one or more CLDs online in the late 2020s, concurrent with ISS operations, to ensure these new capabilities can meet the needs of the Agency, its partners, and the Nation.

2.0 THE INTERNATIONAL SPACE STATION TRANSITION PLAN

If the priorities laid out above come to fruition, NASA envisions a bright future for the LEO economy. As described in recent testimony to Congress:

> By the early 2030s, NASA plans to purchase crew time for at least two – and possibly more – NASA crewmembers per year aboard commercial CLDs to continue basic microgravity research, applied biomedical research, and ongoing exploration technology development and human research, informed by the first several Artemis lunar landings. These activities could be supplemented by crew time purchased by NASA from a commercial provider using the provider's own private astronauts. The CLDs would be visited on a rotating basis by other private astronauts unaffiliated with the CLD provider, seeking either research time for their own experiments, or tourists looking to visit and experience space.
>
> After the end of the ISS, NASA plans to continue to provide support for research in LEO based on the successes and lessons learned of the ISS National Laboratory. We hope that our other U.S. Government partner agencies will join us in doing so. This will provide continuity for academia, research institutions, U.S. Government Agencies (including NASA), and developing industries to continue their work using the unique environment of LEO.[2]

NASA's goal is to partner with existing ISS International Partners, as well as new interested country partners in areas of mutual benefit, aboard U.S. CLDs, offering the international community access to the benefits of LEO through ongoing partnerships with the U.S.

NASA is already laying the foundation of this future. By extending the operation of ISS through 2030, we are giving U.S. private industry time to develop the capabilities and operational experience to operate in LEO and to deploy the platforms that will meet the needs of NASA and other users there. In January 2020, the Agency signed a contract with Axiom Space for the use of the forward Node 2 port on ISS, on which they will deploy a commercial module in the mid-2020s. This module will support private activities in LEO that could otherwise not be accomplished on the Government-owned ISS, testing technology and a business plan for commercial platform operations. Axiom plans to add more modules to this complex with the eventual aim of detaching from the ISS and becoming a free-flying destination in LEO.

To maintain competition for safe, reliable, and cost effective CLDs, NASA released a solicitation to stimulate U.S. private industry development of free-flying orbital destination capabilities and create a market environment in which those services are available to both Government and private-sector customers. After reviewing proposals received in August 2021, NASA announced three awards in December 2021 to advance designs for commercial free flyers. These awards, combined with the Axiom concept, support the goal of having at least one private entity that is ready to provide CLD services prior to ISS retirement so there is no gap in U.S. presence in LEO.

By engaging with industry early in the development phase of CLDs, NASA is helping to ensure that these commercial systems will be safe and will eventually meet the Agency's requirements. NASA will be able to transfer its knowledge and experience from over 20 years of ISS operations to the private sector, while the companies will be able to quickly mature innovative and cost-effective designs. This public-private partnership for the early phase of CLD development will leverage the strengths of both entities to produce safe, reliable, and cost effective CLDs.

---

[2] https://science.house.gov/imo/media/doc/Gatens%20Testimony.pdf

After Axiom, Blue Origin, Nanoracks, and Northrop Grumman have matured their designs and business models over the next 3-4 years, NASA intends to have a second phase of activity whereby the Agency contracts with one or more entities to certify their designs as safe and to purchase services from the CLD provider(s). This second phase, which will be a full and open competition, is similar to the Commercial Crew transportation Capabilities (CCtCap) contracts NASA awarded to SpaceX and Boeing for the Commercial Crew Program. Thus, the Agency is building on the successful legacy of our commercial crew and cargo programs that are currently delivering important research, supplies, and NASA and international partner astronauts to the ISS.

These activities will enable the development of commercially-owned and -operated LEO destinations that are safe, reliable, and cost-effective. With the introduction of CLDs, NASA expects to realize efficiencies from the use of innovative, efficient, and cost-effective platforms using a more commercial approach to meeting the Agency's needs in LEO. As commercial LEO destinations become available, NASA intends to implement an orderly transition from current ISS operations to these new CLDs. Transition of LEO operations to the private sector will yield efficiencies in the long term, enabling NASA to shift more financial and personnel resources toward deep space exploration objectives.

NASA is refining its "Forecasting Future NASA Demand in Low-Earth Orbit: Quantifying Demand"[3] white paper, which describes the Agency's anticipated service requirements for future CLD providers. These forecasts will include the anticipated NASA demand for crew accommodation, technology testing, human research, and science, as well as incorporate information the Agency has about the future needs of non-NASA U.S. entities and potential international partner users. The intent of this activity is to allow future CLD and launch providers to scale their activities to meet the future needs of NASA, while also allowing them to design for other users of the capabilities.

Given the unique barriers posed by space station operations and access to space, NASA and the ISSNL are partnering to support and incubate promising commercial in-space manufacturing applications, such as advanced materials, regenerative medicine, and tissue engineering through the ISSNL, with the goal of creating regular demand for future CLD services that, when combined with demand from NASA, can allow these CLDs to be financially self-sustaining. Other demand-enabling initiatives include allocating a portion of ISS resources for commercial use activities and private astronaut missions on a reimbursable basis.

As both the supply and demand activities mature through the mid-to-late 2020s, NASA will continue to assess readiness to transition to commercial services and destinations through a number of transition indicators, shown in Figure 1. While the top two indicators (CLD readiness and ISS health) are the most critical, the others are important signals to consider for a smooth transition that achieves national goals in LEO.

---

[3] https://www.nasa.gov/sites/default/files/atoms/files/forecasting_future_nasa_demand_in_low-earth_orbit_revision_two_-_quantifying_demand.pdf

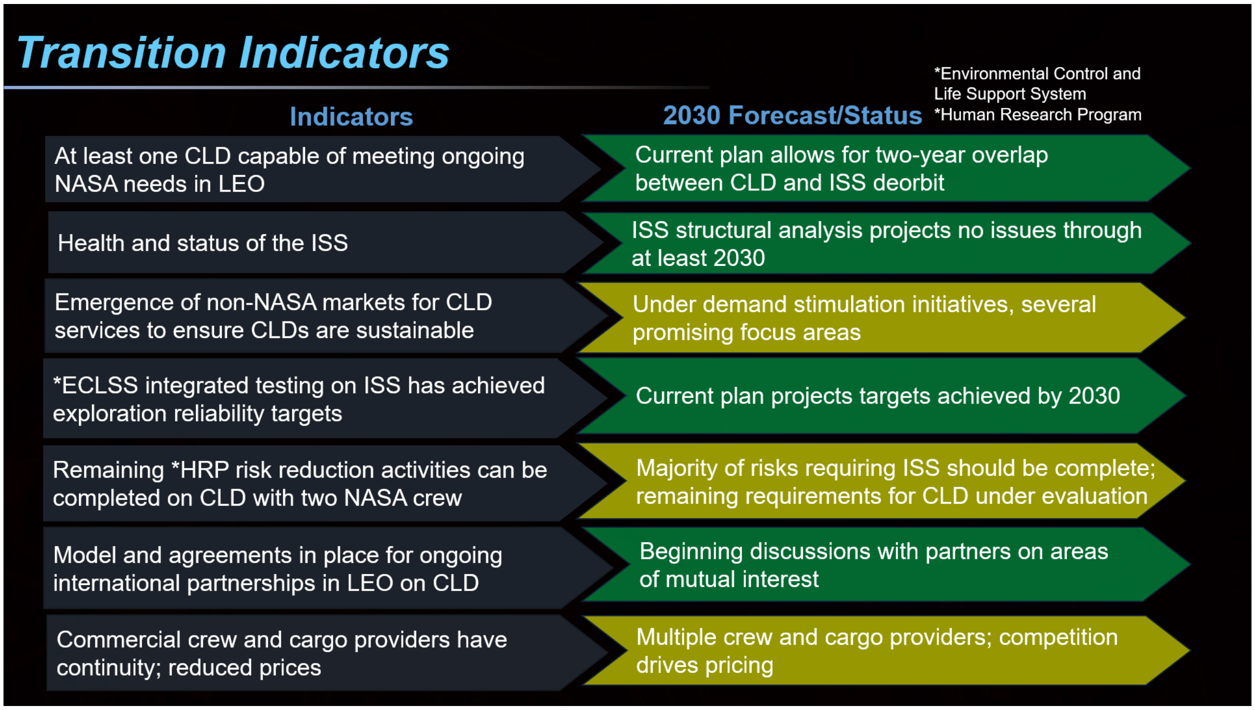

Figure 1. Transition Indicators.

Figure 2 further illustrates anticipated transition of current ISS users to future CLDs, describing the model for accommodating users currently on the ISS, and notional models for accommodation on a CLD. As NASA continues to engage these user communities, these models will be further clarified.

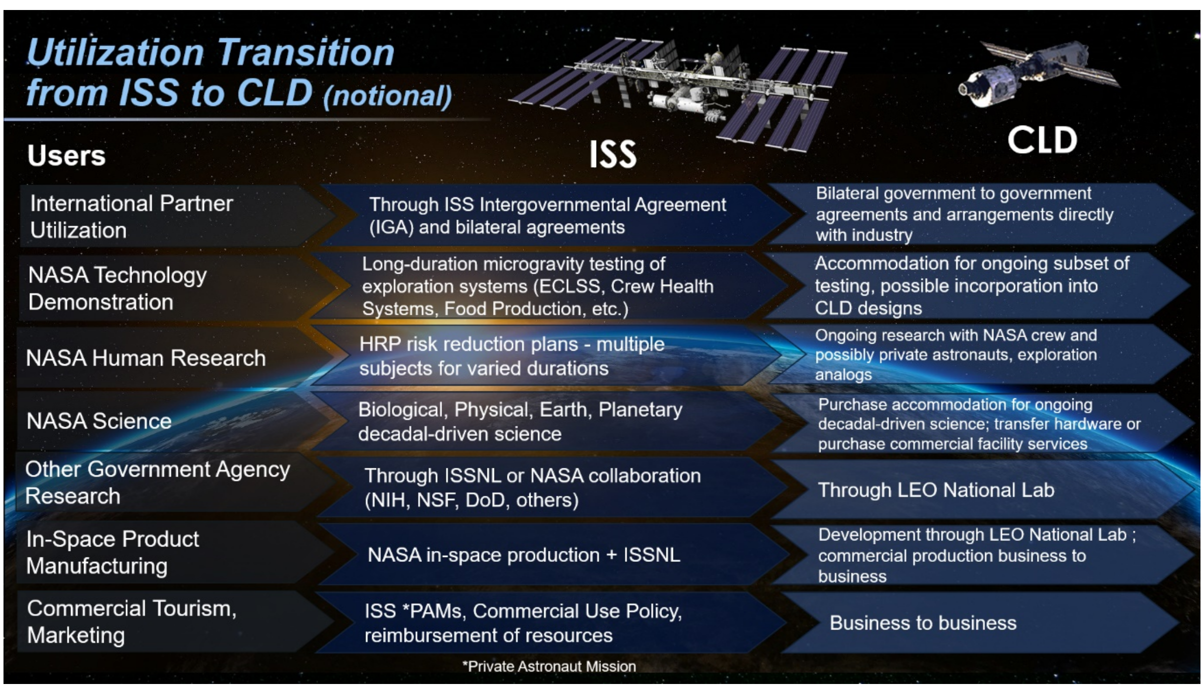

Figure 2. Utilization Transition from ISS to CLD (notional).

Over the next 5-7 years, NASA will enable these critical elements that support the CLDs and the user base for them in LEO and will ensure that the national capability provided by the ISS continues to be available for national use. There is a risk associated with relying on private companies to develop LEO destinations as well as to provide a national-lab-like facility; however, this same risk was present in relying on private companies to develop cargo and crew transportation to ISS as well as research capabilities that NASA uses today. The development of all of these commercial capabilities has returned significant benefits to the United States. The strategy NASA is employing allows for time to deploy these CLDs, while still allowing for overlap between ISS and CLDs. The Agency intends to collaborate with commercial and international partners towards a productive post-ISS future in LEO, ensuring continued growth, development, and U.S. leadership of this critical domain.

2.1 ISS Transition Budget Planning

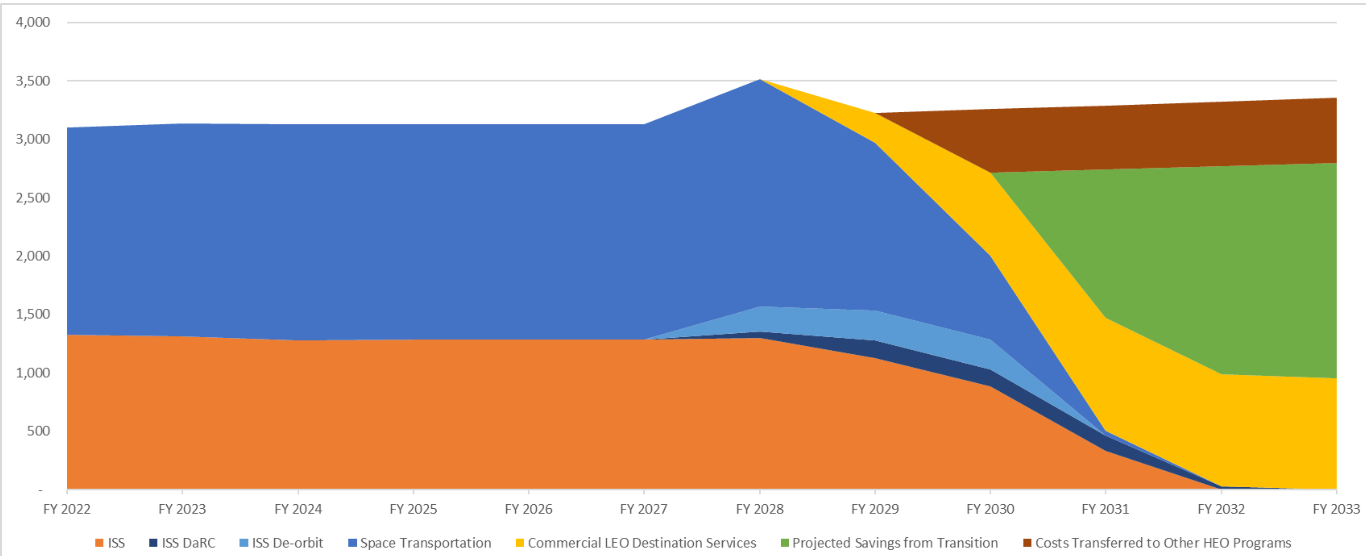

Figure 3. LEO Budget Cost Assessment through 2030.

The ISS Program analyzes its program and budget requirements on an annual basis. The latest budget estimate for ISS life extension through 2030 (Figure 3) assumes deorbit in January 2031 and includes space transportation costs. These assumptions and associated costs will continue to be refined each budget cycle.

The categories in Figure 3 are defined as follows:

- "ISS" includes Systems Operations and Maintenance (O&M) and ISS Research. ISS O&M supports vehicle operations in the extreme conditions of space with constant, around-the-clock-support. These costs are expected to be fairly stable, as maintenance costs have trended steady with upgrades to more reliable systems over time. NASA continues to seek cost efficiencies to offset inflationary impacts and plans to strategically reduce requirements where possible as ISS approaches end of life. ISS Research conducts research on ISS across a diverse array of disciplines, from space biology, fundamental physics and biophysics to human physiology and biotechnology. Direct support for research in these disciplines is funded through NASA's Science Mission Directorate and is not displayed above, though the Agency expects to continue this support regardless of which platform(s) the researchers supported through this budget are using. ISS Research also provides $15 million annually to fund the ISS National Laboratory;

- "ISS DaRC" (Decommissioning and Retirement) includes costs for contractor retention and severance, contract closeout activities, real and personal property disposition and environmental impacts, program data archiving, and international closeout of assets in partner facilities;

- "ISS De-orbit" includes estimated costs to de-orbit the ISS, including the cost associated with three Progress vehicles needed to support that effort;

- "Space Transportation" includes crew and cargo transportation to and from the ISS, including the Commercial Crew Program and Crew Cargo Program. This funding line is displayed as declining because NASA's current assumption is that its CLD services contracts will include transportation. If one or more of the providers that NASA contracts with to provide CLD services does not include transportation as part of its service to the Agency (e.g., if NASA purchases access to a CLD but is responsible for delivering its own crew and research capabilities to that platform), then NASA would continue purchasing crew and cargo transportation services directly;

- "Commercial LEO Destination Services" includes the purchase of services from CLD providers for NASA needs, such as crew accommodations and training, human research, science research, and technology demonstrations;

- "Projected Savings from Transition" represents the estimated savings from transitioning from the ISS to CLDs. This amount can be applied to NASA's deep space exploration initiatives, allowing the Agency to explore further and faster into deep space. This amount can also be applied to other NASA programs. This savings is estimated to be approximately $1.3 billion in 2031, ramping up to $1.8 billion by 2033; and

- "Costs Transferred to Other HEO Programs" includes facilities and contracts where ISS is currently covering the majority of the costs, and some or all of those costs will need to be transferred to remaining programs. The largest drivers of these costs are flight and ground operations (e.g., mission control) and civil servant labor.

The Projected Savings from Transition wedge is an estimate based on NASA's current understanding of the capabilities and potential prices for CLD services. The amount of these projected savings will be refined over time as the CLD providers mature their concepts and as NASA gains a more precise understanding of the Agency's requirements in LEO. The rationale for NASA's expectation that savings will be realized is severalfold: the Agency will only be paying for the specific services it needs rather than paying for the cost of maintenance and operations of the ISS; there will likely be other non-NASA customers for CLD services, so the Agency would not be paying for all the CLD costs; the CLDs will be newer, requiring less maintenance and fewer spare parts than the ISS; the development and operations of the CLDs should be efficient and cost-effective since NASA will be leveraging a private-sector-led business model; and, with lower maintenance requirements (fewer replacement parts and spares), there will be a reduction in transportation costs.

2.2 ISS Technical Health and De-Orbit Plan

NASA and the ISS International Partners remain vigilant regarding the safe operation of the ISS. Based on the ISS structural health analysis performed to date, there is high confidence that ISS life can be further extended through 2030. To provide continuous, safe operations of the ISS, the Program regularly evaluates the risk and safety of standard on-orbit maintenance and pending visiting vehicle missions to the ISS. Additionally, teams regularly assess opportunities for efficiency and infrastructure improvements for station operations which often support future human exploration missions, as well.

The technical lifetime of the ISS is limited by the primary structure, which includes the modules, radiators, and truss structures. Other systems such as power, environmental control and life support, and communications, are all repairable or replaceable on orbit. The lifetime of the primary structure is affected by dynamic loading (such as vehicle dockings/undockings) and orbital thermal cycling. Each ISS International Partner is responsible for performing life extension analyses for its own modules and structures. NASA, the Canadian Space Agency (CSA), European Space Agency (ESA), and the Japan Aerospace Exploration Agency (JAXA) have completed life extension analyses through 2028. Roscosmos has completed its extension analysis through 2024 and is working on analyzing extension through 2030. The ISS Partnership is examining the recent technical issues aboard the Russian Segment, primarily the atmospheric leak in the Service Module, and working together to ensure there is no threat to the long-term viability of the ISS.

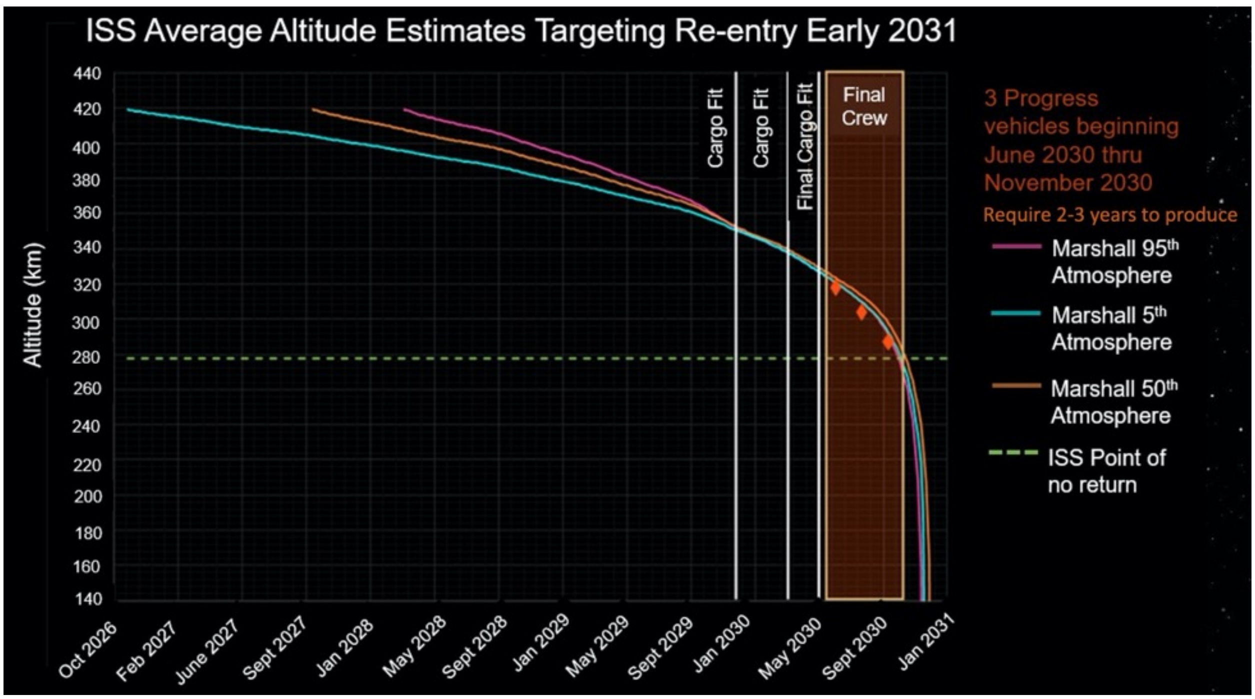

Figure 4. ISS End-of-life De-orbit Planning Assumptions.

Figure 4 shows the ISS end-of-life de-orbit altitude, cargo resupply, and de-orbit plan assumptions. This timeline assumption is reflected in the budget discussion above for de-orbit vehicle procurement.

In the nominal scenario, ISS mission control will begin scheduling retrograde (rather than posigrade) ISS maneuvers in the lead-up to ISS deorbit to begin slowly lowering the operational altitude of the ISS. Figure 4 shows that these retrograde maneuvers may start at different times depending on solar cycle activity and its effect on Earth's atmosphere (higher solar activity tends to expand the Earth's atmosphere and increase resistance to the ISS' velocity, resulting in more drag and natural altitude loss). This lower altitude results in higher velocity overall. Eventually, after performing maneuvers to line up the final target ground track and debris footprint over the South Pacific Oceanic Uninhabited Area (SPOUA), the area around Point Nemo, ISS operators will perform the ISS re-entry burn, providing the final push to lower ISS as much as possible and ensure safe atmospheric entry.

The ISS will accomplish the de-orbit maneuvers by using the propulsion capabilities of the ISS and its visiting vehicles. The overall de-orbit would require extra visiting vehicles beyond the regular cadence of traffic to the ISS. Not all visiting vehicles can be used to assist in the de-orbit. NASA and its partners have evaluated varying quantities of Russian Progress spacecraft and determined that three can accomplish the de-orbit. Additionally, Northrop Grumman has been expanding the propulsion capabilities of its Cygnus spacecraft, and NASA has been evaluating whether Cygnus could also be part of the vehicle capability needed to the de-orbit the ISS.

3.0 GOALS FOR THE NEXT DECADE

This section addresses NASA's goals for the next decade of ISS operations in LEO, prior to and including transition to CLDs. NASA has identified much of the specific work and capabilities that are most effectively conducted on the ISS prior to a 2030 transition. The Agency has also identified work that will need to continue beyond the lifetime of the ISS to support future exploration beyond LEO, and that should be able to be conducted on board future CLDs. Also included in this section are plans for continuing to cooperate with ISS International Partners and others beyond the life of the ISS, including deep space destinations, as well as plans to continue to grow and enhance NASA's LEO international collaboration beyond the ISS partners. The ISS will play a key role in this leadership for the duration of its operational lifetime.

3.1 Enable Deep Space Exploration

Goals through 2030:

- Successfully test and validate critical exploration technologies such as Environmental Control and Life Support Systems (ECLSS) that are most effectively conducted on ISS;
- Advance human research to ensure humans can survive and thrive outside of LEO; and
- Enable the ISS to be as much of an analog for a Mars transit mission as is feasible, within the constraints of safe ISS operations.

Implementation Strategies through 2030:

- Execute integrated ISS/LEO fly-off plan and timeline of all exploration capability gaps (Figure 5).
- Gain information and experience about operational reliability and maintenance for exploration hardware;
- Continue to execute Human Research Program (HRP) risk reduction plan (Figure 6);
- Use ISS as an analog to address the operational challenges and hazards of human spaceflight for long-duration missions, including extensive communication delays, distance from Earth, and gravity changes; and
- Continue to conduct biological and physical science experiments and technology demonstrations with an emphasis on autonomy.

The Post-ISS Plan:

- Purchase exploration technology testbed and analog services, such as the testing of life support, medical, food production, and exercise equipment, on a CLD;
- Purchase private astronaut time on or rent space on CLD facilities to continue HRP risk reduction activities best suited for a LEO platform, using NASA astronauts and/or purchasing private astronaut data as available;
- Purchase time on CLD facilities to build NASA astronaut flight experience; and
- Employ CLDs as a proving ground to test and validate biological and physical science experiments and technology prior to lunar and Mars missions.

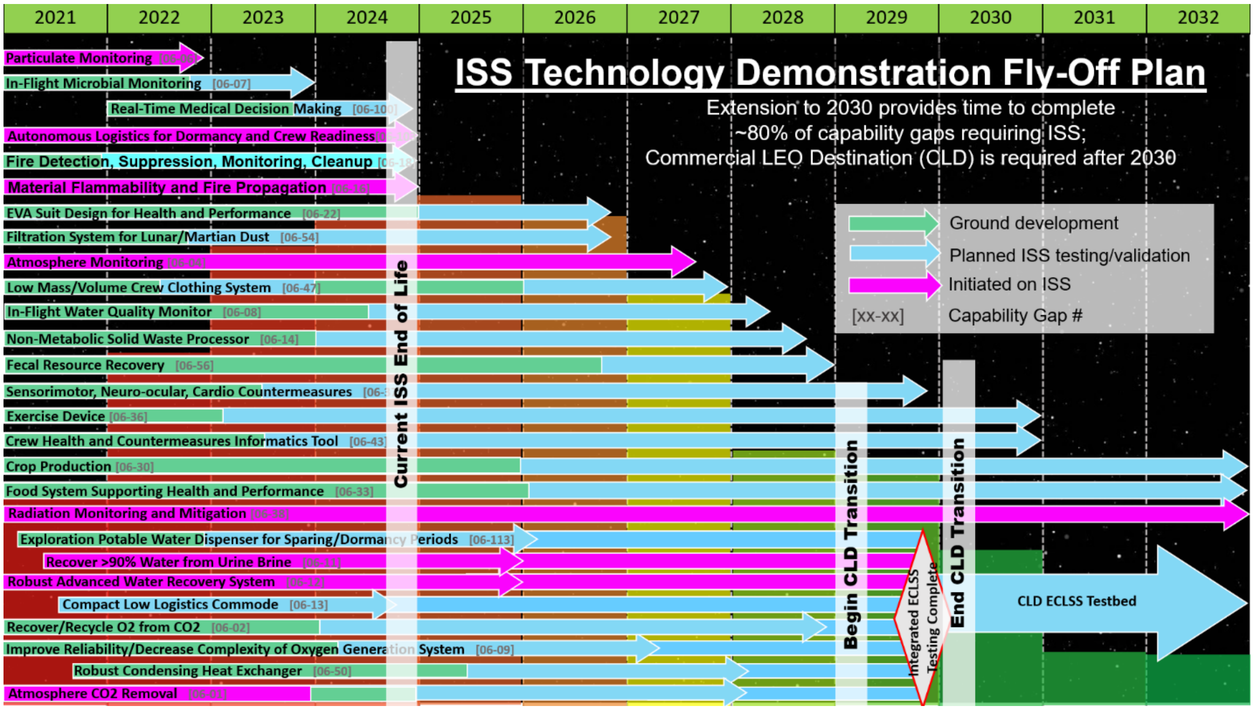

Figure 5. The ISS Technology Demonstration Fly-Off Plan.

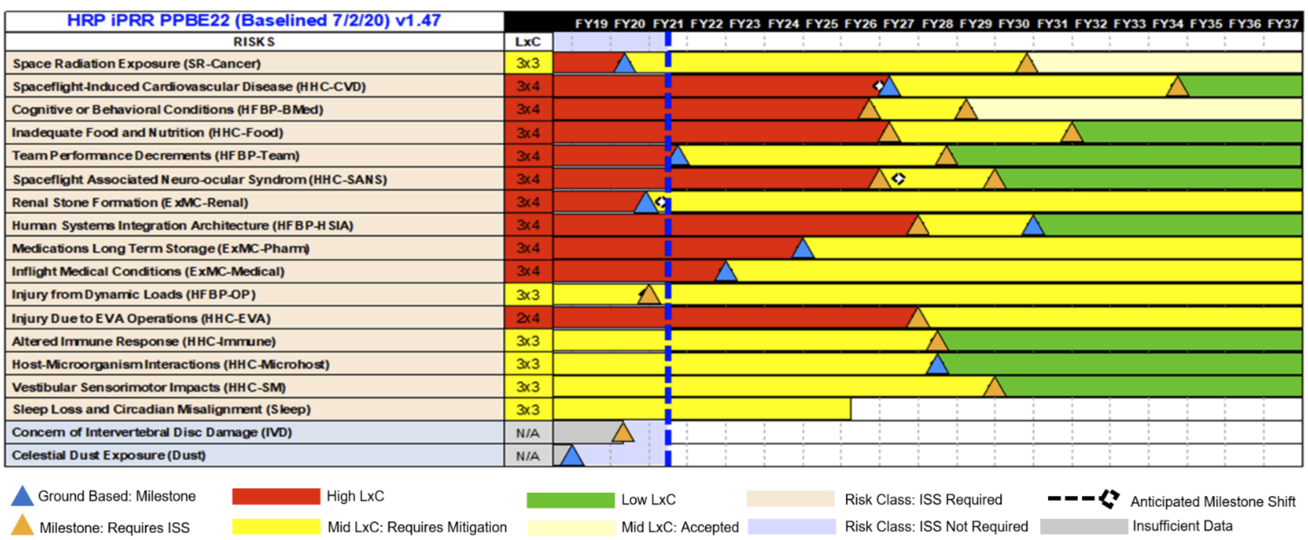

Figure 6. The Human Research Program Plan for Risk Reduction.

NASA is preparing for human exploration missions beyond LEO by using the ISS as a stepping stone to expand human presence farther into the solar system. The ISS provides a platform to gain knowledge in human research and experience in long-duration spaceflight operations, as well as serving as a testbed for technology demonstrations for new capabilities and upgraded spacecraft systems needed for exploration missions. Long-duration, distant human exploration missions require capabilities beyond currently available technologies and mitigations for managing the effects of extended stays in space on human health and performance. Testing new capabilities and mitigating human health risks aboard the ISS in the unique environmentally closed-loop and microgravity environment helps to reduce exploration risks and associated costs.

The unique environment and operations of the ISS as a long-duration spacecraft enable it to be a good analog for exploration missions. Demonstrating the performance of technologies first on the ISS, where they are not required for safety of the crew or vehicle operations, allows engineers to assess and demonstrate their performance while improving their reliability without risking the crew or mission prior to their use in an operational spacecraft or in a remote deep space environment. Through years of experience and lessons learned from ISS operations, the vehicle's systems and operational processes have become less reliant on resupply and communications from Earth through logistics reduction and increased system capabilities and reliability, but there is still a considerable gap between the current state of the art and what is needed to support missions well beyond LEO. One important example of technology demonstration using the ISS as a testbed is the ECLSS. Prior to the ISS, the life support systems on spacecraft were primarily designed to be used once and discarded. The ISS has advanced the state-of-the-art ECLSS technology from an open-loop, consumables-based system to a closed-loop, integrated regenerative system that recovers both water and oxygen. Continued evolution of these closed-loop systems to higher levels of reusability is a critical capability for deep space missions because using an open-loop system that needs regular resupply while in deep space would either create severe mass challenges on board the spacecraft or exacerbate already-challenging logistics issues.

The Human Research Program is conducting ISS investigations and using research findings to reduce or mitigate the potentially negative effects of the space environment on the health and performance of humans working in that setting. Research conducted on ISS by the Biological and Physical Sciences program helps inform HRP on the risks to crew while expanding scientific understanding of the spaceflight environment on biology, materials, combustion, and fluidics. Use of ISS has enabled (and will continue to enable) NASA to identify the risks to the human system and gaps in knowledge about characterizing and mitigating these risks, while also allowing the Agency to execute plans to ameliorate those risks.

Accomplishments achieved on ISS to date demonstrate the progress being made to mitigate human risks from long-duration spaceflight and are stepping stones for an ongoing roadmap to mitigate these spaceflight risks. The continued development and testing of technologies and crew health countermeasures that allow for enhanced on-orbit diagnostics, medical treatment, and crew health maintenance will directly affect the systems and methods used for future exploration missions. Many additional efforts are in process and will provide results in the coming years to inform NASA's next great leap in space exploration, including future human missions to the Moon and, eventually, to Mars.

3.2 Conduct Research to Benefit Humanity

Goals through 2030:

- Test and demonstrate advanced space technologies;
- Accelerate the understanding of climate models using different instruments on and off the ISS;
- Advance the current understanding of fundamental physics in the field of quantum and atom optics as well as the development of quantum sensors by using the microgravity environment;
- Manufacture life-saving and revolutionary products that can only be developed in microgravity;

- Expand ISS as a virtual tech hub across its 13 major science disciplines and >275 subdisciplines, and continue to populate the open science data systems; and
- Continue to use ISS as a platform for creation of science, technology, engineering, and mathematics (STEM) content, student opportunities, and inspiration; and
- Lead development of miniaturized, autonomous, self-reliant medical care techniques, devices, and drugs for spaceflight that spin off for use in at-home personal care, remote locations, and developing countries.

Implementation Strategies through 2030:

- Continue to forecast decadal-driven microgravity research through NASA and other U.S. Government engagement;
- Partner with research institutions and industry to spin off spaceflight technologies to benefit humanity;
- Use ISSNL as a technology incubator for in-space production applications;
- Expand capabilities to enable a more Earth-like lab in space including up-to-date research capabilities, on-orbit experiment iteration, and research partnerships within and across disciplines;
- Broaden fundamental physics capabilities to study ultra-cold quantum gases in partnership with international collaborators; and
- Promote student research opportunities from elementary school through college.

The Post-ISS Plan:

- A commercial LEO facility or National Lab supported by NASA and potentially other U.S. Government agencies that will facilitate development of basic and applied microgravity research, educational activities, and incubation of promising commercial applications, and obtain flight opportunities and services on CLDs and other commercial assets (e.g., suborbital flights); and
- A commercial LEO facility or National Lab that will provide a location for continued Earth and space observational instruments and for research that requires exposure to the unique LEO space environment.

Implementation strategies for post-2030 activities will be developed in the coming years.

Earth observation instruments on the ISS expand our Nation's understanding of the climate and carbon cycle by being used in concert with free-flying instruments in other orbits. The ISS instruments allow for cross-calibration of free-flying instruments measuring the same phenomenon with different technologies as the two sets of instruments cross orbits, providing unique data about day/night cycles not obtained with the free-flying instruments alone. The instruments help us measure the stresses of drought and the health of forests to enable improved understanding of the interaction of carbon and climate at different time scales (Figure 7). These spacecraft and instruments include the Orbiting Carbon Observatory (OCO-3), which measures carbon dioxide and methane fluxes and sinks; the Stratospheric Aerosol and Gas Experiment III (SAGE III), which measures ozone and related gases in the stratosphere; the Total Solar Irradiance Sensor (TSIS-1) which measures the Sun's energy input to Earth; the Global Ecosystem Dynamics Investigation (GEDI), which measures forest heights; and the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), which measures the temperature of plants.

The research conducted aboard ISS over the past two decades has spanned every major scientific discipline (see Figure 8) and is returning benefits to humanity in the areas of understanding human health, the Earth's climate, and the origins of the cosmos, and inspiring the next generation of STEM explorers, to name a few.

The ISS life support system technologies include innovations in carbon dioxide removal and repurposing to useful products, recycling of water and waste, and food production in harsh environments and small spaces.

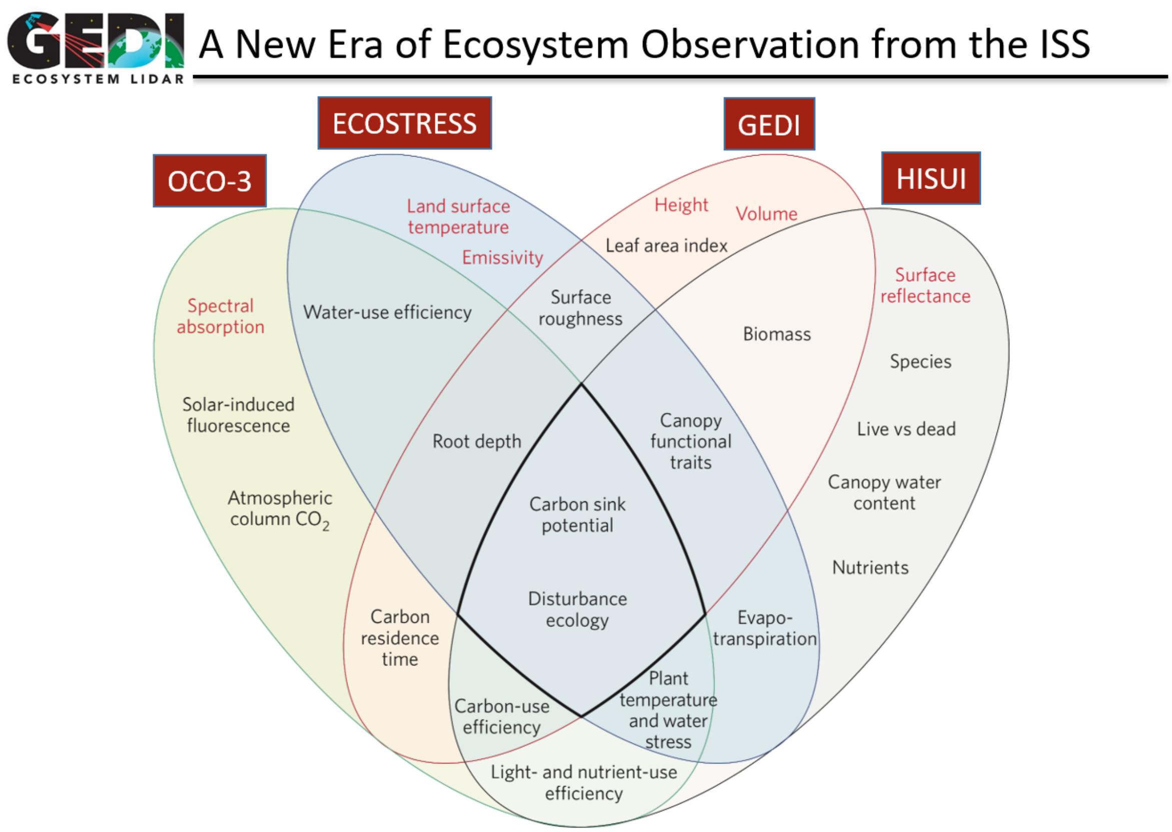

Figure 7. Earth Observation Instruments on the ISS. HISUI is the Hyperspectral Imager Suite. (Image Credit: Natasha Stavros)

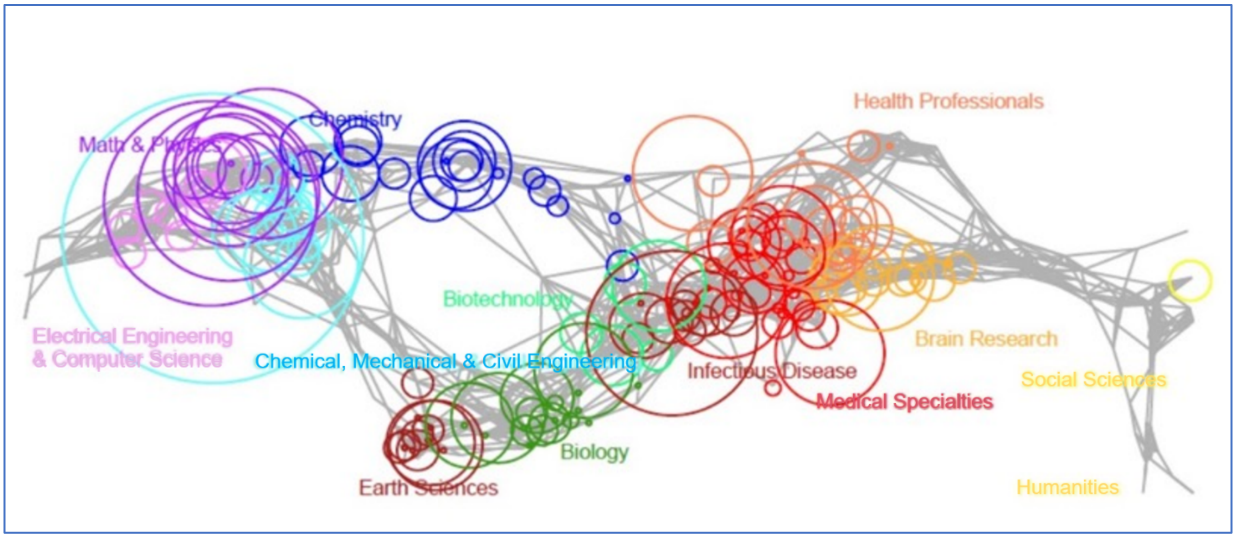

Figure 8. Research on ISS spans many disciplines.

ISS medical research, such as protein crystal growth, enables more effective pharmaceuticals such as Merck's cancer drug Keytruda, while the National Institutes of Health's Organs-on-Chips research models human organs and tissues and can offer solutions for modeling human physiology and disease. Research on the ISS is also being applied to find solutions to challenges relating to macular degeneration, bone health, immune response, cardiovascular health, and mental resilience during isolation. Innovative medical technologies developed for exploration, such as robotics, non-invasive diagnostic tools, wound treatment, and remote medicine, have been applied to save lives on Earth. Patients whose brain tumors were considered inoperable are alive today because of robotic technology from ISS that has been used to improve surgical assistance robots.

The ISS serves as an innovation laboratory for experiments that cannot be conducted on Earth and is used by small and large universities, biotech startups, and large pharmaceutical companies. Research in promising new commercial markets, such as optical fibers, more efficient combustion, and high-strength turbine blades, may lead to new innovative products. Colloidal flow studies on ISS led to two patents granted to Procter & Gamble (P&G) in 2018 for advancements relevant to commercial product function and shelf life.

Experiments on the ISS are also unlocking the mysteries of the cosmos. NASA's Astrophysics Division supports the Neutron star Interior Composition Explorer (NICER) payload, which provides high-precision measurements of neutron stars and black holes and can test the use of distant pulsars as navigation beacons. The Alpha Magnetic Spectrometer (AMS), a Department-of-Energy-sponsored collaboration, has been operational on the ISS since 2011 and has revolutionized the field of cosmic ray particle physics. The AMS experimental data will now require new theories to be developed regarding how cosmic ray particles are produced and propagated across our Milky Way Galaxy. In addition, continued AMS operations on the ISS may prove crucial in the search for dark matter and antimatter and to our understanding the formation of the universe. NASA's Biological and Physical Sciences Division supports the Cold Atom Laboratory (CAL), a facility for studying ultra-cold quantum gases on the space station such as Bose-Einstein condensates. CAL's breakthrough temperatures unlock the potential to observe new quantum phenomena and test some of the most fundamental laws of physics.

As a research and development facility, ISS supports a variety of science laboratories, external testbeds, and observatory sites – both governmental as well as commercially-owned and -operated sites. Research facilities aboard the ISS have evolved in recent years from primarily Government-funded and -operated to commercially-owned and -operated. Since 2012, commercial research facilities have greatly increased the breadth and volume of ISS-supported research. The result of these new facilities is a threefold increase in the number of active investigations compared to the early years of ISS operations. These commercial endeavors help optimize research capabilities and operations aboard ISS which could translate to future CLDs.

Since 2011, the non-profit Center for the Advancement of Science In Space has managed the activities of the Congressionally-designated ISS National Laboratory to increase the utilization of the ISS by other U.S. Government agencies, such as the National Science Foundation and National Institutes of Health, and by the private sector. The ISS National Laboratory works to ensure the station's unique capabilities are available to the broadest possible cross-section of U.S. scientific, technological, and industrial communities. The ISS National Laboratory is helping to establish and demonstrate the market for research, technology demonstration, and other activities in LEO beyond the requirements of NASA. To date, in total over 530 payloads have flown through the ISS National Lab, with $240 million of external funding adding to the total $150 million in funding provided by NASA through the cooperative agreements with the ISSNL operator. The commercial sector accounts for 50 percent of the projects, with $453 million of capital raised by startups following their ISS National Lab flight awards.

3.3 Foster a U.S. Commercial Space Industry

Goals through 2030:

- Create a robust commercial LEO marketplace by enabling the development of commercially-owned and -operated LEO destinations and associated research capabilities that are safe, reliable, and cost-effective and allow NASA to be one of many customers;
- Ensure NASA can meet its needs in LEO, as it transitions from ISS operations to new CLDs that are commercially-owned and -operated;
- Drive down costs so NASA can free resources to be used for future human space exploration on its Artemis missions to the Moon and on to Mars as well as on other missions; and
- Utilize innovative, nontraditional arrangements for acquiring commercial space goods and services to meet NASA requirements.

Implementation Strategies through 2030:

- Support the development of CLDs through the Commercial LEO Development Program supply strategy;
- Create research/applications roadmaps for promising areas and develop strategies and partnerships to advance activities on roadmaps; continue demand stimulation activities for in-space production activities, partnering with other Government agencies to co-fund areas of intersecting interests;
- Continue using ISS to grow commercial interest and markets by facilitating commercial activities, including Private Astronaut Missions; and
- Use or create expanded procurement approaches to drive the transition of Government purchasing towards procurement of commercial services, including research facilities on CLDs.

The Post-ISS Plan:

- One or more CLDs are available to meet forecasted needs;
- Cost of LEO services to NASA is significantly reduced;

- Commercial demand for tourism, in-space manufacturing, and other activities supplements business for CLDs beyond U.S. Government needs; and
- Multiple commercial crew and cargo transportation and research capability providers exist.

Guided by NASA's Strategic Goals and Objective 2.1 to "Lay the foundation for America to maintain a constant human presence in low-Earth orbit enabled by a commercial market," the Agency created the Commercial LEO Development Program as a focused effort to develop a robust commercial space economy in LEO and lower the Agency's costs in the long-term. To achieve these goals, NASA is committed to enabling the development of a LEO economy through supporting the development of increased supply (i.e., future LEO destinations providing services) and demand (i.e., commercial market and demand for on-orbit services or products of commercial value). The Commercial LEO Development Program will enable the development of commercially-owned and -operated LEO destinations that are safe, reliable, and cost-effective, and allow NASA to be one of many customers. The ISS is also enabling the development of a commercially-owned and -operated LEO destination by hosting a new commercial segment by Axiom Space that will attach to the ISS Node 2 forward port and expand the habitable volume for commercial research and other activities. Axiom Space, Blue Origin, Nanoracks, and Northrop Grumman will ultimately be able to compete for a phase two services contract.

Creating a robust LEO economy relies on bringing many new businesses and people into space and will require the development of supply of services and demand for those capabilities. NASA will support the first Private Astronaut Mission on the ISS early in 2022. Private Astronaut Missions will be dedicated missions that are privately-funded, fully-commercial spaceflights that enable tourism, outreach, commercial research, and NASA-approved commercial and marketing activities on ISS. The Agency has also opened the ISS for business by expanding opportunities for in-space manufacturing, marketing, and promoting commercial products and services aboard the station. As NASA increases the opportunities for business on ISS, the goal is for the number and types of companies taking advantage of those opportunities to also increase, and that in turn could help create more demand.

NASA's Commercial Resupply Services and Commercial Crew Programs are also enabling multiple companies to develop and operate the next generation of spacecraft and launch systems. Commercial transportation to and from the space station has fueled the growing market share of U.S. launch providers in the world marketplace and driven down launch costs, making space accessible to a broader market, and is providing expanded utility, additional research time, and broader opportunities for discovery and space exploration. An important goal of this commercialization strategy is to encourage the development of new industrial capabilities, enabling these companies to sell future services to all customers, not just to NASA.

A robust LEO economy ensures national interests for research and development in space are fulfilled while allowing NASA to focus Government resources on deep space exploration through the Artemis program and land the first woman and first person of color on the surface of the Moon.

3.4 Lead and Enable International Collaboration

Goals through 2030:

- Maintain strong U.S. leadership in LEO (the U.S. continues to set norms and standards for space operations, including debris mitigation, space situational awareness, interoperability standards, etc.);
- Maintain existing partnerships, and ensure existing and new partnerships are working in LEO and with Artemis; and

- Enable expanded global engagement in joint LEO science and education efforts, including and beyond ISS International Partners.

Implementation Strategies through 2030:

- Continue U.S. leadership of ISS partnership in LEO, including developing a transition plan to one or more U.S. CLDs; and
- Study how to increase the availability of sovereign astronaut missions.

The Post-ISS Plan:

- Continued international interest and investment aboard U.S. CLDs; and
- Partnership with NASA and/or participation directly in LEO activities aboard U.S. CLDs.

The ISS is the premier destination for research, development, education, and other activities in LEO. Nearly 110 countries and areas have participated in activities aboard the ISS, and people from 19 countries have visited the orbiting complex. The Intergovernmental Agreement (IGA), ratified by the 15 participating countries, provides the structural framework for the ISS International Partnership. Central to this agreement is NASA's role as the leader of the Partnership:

> *The United States, acting through NASA…shall also be responsible for…overall system engineering and integration; establishment of overall safety requirements and plans; and overall planning for and coordination of the execution of the overall integration operation of the Space Station.*[4]

As part of this leadership role, NASA has the ability to establish U.S. operational requirements through contractual requirements with global leaders in U.S. industry, and thereby influence global norms relating to orbital debris mitigation, interoperability standards, and other key parts of operating as a responsible global actor in LEO. Continued ISS operations through 2030 will reinforce U.S. leadership in these domains.

It is NASA's goal to continue to partner with ISS International Partners beyond the life of the ISS. Each Partner is currently working to identify its needs in LEO through and beyond the ISS, and all have expressed interest in the expansion of commercial uses of LEO. It is NASA's intention to ensure continued collaboration with Partners on a U.S. CLD through government-to-government, government-to-industry, or industry-to-industry arrangements. U.S. leadership in commercial space will be an important balance to other aspiring spacefaring nations with regard to continuity of operational standards, intellectual property protection, and Earth and space applications and technologies.

To this end, NASA is evaluating the capabilities and desires of the existing ISS Partnership, as well as new entrants to the space field, to partner in continuing LEO operations post-ISS. It is the Agency's goal to make partnering in LEO an accessible and transparent capability for new partners by implementing these partnerships in such a way that is beneficial to all parties. Through the lifetime of ISS, NASA will use the station to conduct pathfinding activities for these future partnerships, including expanding the use of ISS by non-IGA signatory countries, and opening access to sovereign astronauts to gauge the global marketplace for such activities. NASA is also gauging International Partner interest in capabilities on U.S. CLDs to include their potential requirements in the Agency's forward planning.

---

[4] https://www.state.gov/wp-content/uploads/2019/02/12927-Multilateral-Space-Space-Station-1.29.1998.pdf

It is also NASA's goal to ensure the ISS International Partnership remains unified through the life of the program. International Partner interest in continuing ISS operations is evidenced by recent investments including:

- Roscosmos' Multipurpose Laboratory Module (MLM), added in July 2021, is a considerable enhancement that increases utilization on the Russian Segment for the next decade;
- ESA's European Robotic Arm was deployed on the MLM;
- ESA's Bartolomeo external payload facility was deployed on the Columbus Module in 2020;
- JAXA is continuing development work on the H-II Transfer Vehicle-X (HTV-X) cargo transfer vehicle, which will provide next-generation cargo delivery to the ISS and lunar destinations; and
- CSA has recently outlined several potential contributions that are currently under evaluation.

Roscosmos, ESA, JAXA, and CSA have indicated their desire to continue ISS operations through 2030, pending coordination within their respective governments and in accordance with their applicable decision-making procedures.

3.5 Inspire Humankind

Goals through 2030:

- Broaden the audience reached by the ISS to create more awareness of the benefits of microgravity research and development (R&D) and orbital activities to humanity;
- Promote participation in LEO R&D among next-generation STEM students to create a diverse future STEM workforce; and
- Continue to engage the public through different platforms to communicate the values that ISS brings to the Nation and the world.

Implementation Strategies through 2030:

- Continue ISSNL STEM activities;
- Increase social media/public engagement presence; and
- Explore ways to engage a diverse group of students, educators, and the general public through inspirational opportunities such as ISS immersive experiences.

The Post-ISS Plan:

- Continue partnering with minority serving institutions, universities, K-12 schools, and other informal and formal STEM organizations to encourage continued research on CLDs;
- Incentivize commercial companies that build commercial destinations to partner with students in conducting microgravity research in these destinations;
- Attract diverse groups of students to LEO activities through internships, fellowships, and research partnerships, with commercial partners;
- Continue engaging youth through social media platforms, showing the diversity of careers associated with space, including STEM, communications, business, and others; and
- Provide space-related resources, curriculum, and materials to educators to continue to stimulate diverse groups of students' interest in, and curiosity about, space.

The ISS provides many avenues for students and educators to participate, innovate, and be inspired by NASA's space exploration efforts. More than 1,500,000 students per year participate in STEM activities on ISS. Through STEM programs on the ISS, students have been able to directly develop hardware used on station, conduct research with astronauts, and even directly engage with astronauts through downlinks. Many STEM programs are run through the ISSNL from Pre-K through post-doctoral research, such as EarthKAM, Story Time From Space, Zero-Robotics, Space Station Research Explorers, and High School Students United With NASA to Create Hardware (HUNCH). Additionally, STEM on Station, a Next Gen STEM activity, facilitated and funded by NASA's Office of STEM Engagement, uses the space station, its crew, and the onboard research to inspire, engage, and educate students and educators. Continuing STEM on Station initiatives include a comprehensive website full of educational resources, in-flight education downlinks, STEMonstrations (on-orbit videos demonstrating STEM concepts with corresponding lesson plans), and continued partnerships with organizations such as Microsoft Hacking STEM, U.S. Forest Services, and Texas Instruments to leverage expertise, develop resources and opportunities, and broaden educational reach (Figure 9).

Over the past 20 years, 2.8 million U.S. students in primary and secondary schools have designed, launched, operated, or used data from the more than 800 student experiments launched to ISS. Students are able to indirectly connect with station through applications like Spot the Station, which informs the public when they can see the ISS over their location, and which has approximately a million monthly users and 300,000 subscribers worldwide (Figure 10).

The future of NASA's missions, to the Moon, Mars, and beyond, rely on the younger generation. Today's youth are tomorrow's Moon and Mars explorers. Today's youth are tomorrow's scientists, engineers, and researchers. It is thus crucial to our Nation and NASA's efforts to maintain the interest and curiosity of today's students so they continue to be inspired by and participate in the wide scope of space exploration roles.

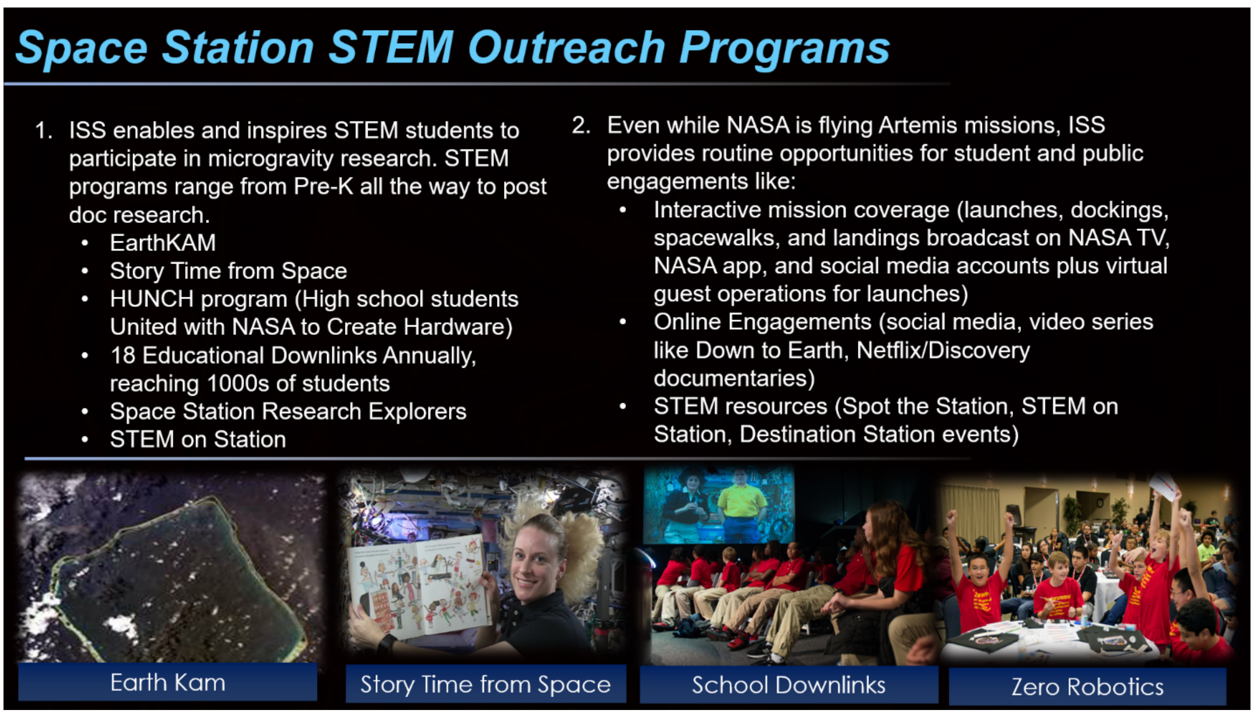

Figure 9. STEM Programs on Station engage all students from Pre-K to Post-Doc researchers.

Figure 10. Space Station reaches a wide audience through various social media platforms.