National Aeronautics and
Space Administration

white paper

International Space Station Deorbit Analysis Summary

The International Space Station Today

The International Space Station is one of humanity's great cooperative and engineering achievements. Built and operated by 15 countries over nearly 30 years, the space station has been home to more than 265 people from 20 countries and has been occupied continuously since November 2000. The space station's mission is to conduct research and development in low Earth orbit (LEO) to learn how humanity can better live and work in space and to return the benefits of this research to people on the ground. At the end of the space station's useful life in 2030, NASA and its international partners will deorbit the station, safely disposing the vehicle into a remote part of the ocean.

NASA and its four space agency partners – CSA (Canadian Space Agency), ESA (European Space Agency), JAXA (Japan Aerospace Exploration Agency), and the Russian State Space Corporation "Roscosmos" – have conducted thousands of experiments in space and engaged tens of millions of students during more than two decades of crewed space station operations. Technology demonstrations and development aboard have advanced state-of-the-art applications with benefits both on Earth and in space. Climate sensors deployed on the space station have validated climate models and contributed a host of new information about Earth's changing climate environment, while space science instruments on the space station have advanced our knowledge of phenomena, including neutron stars and dark matter. The space station crews have been a critical part of the experiments as well, volunteering as test subjects for research into human adaptation to living and working in microgravity. Without continuing these long-duration demonstrations and experiments into the joint human-and-vehicle system, human exploration of the solar system will not be possible.

NASA intends to continue safely operating the space station through 2030 with its international and commercial partners to realize the returns and advancement that microgravity and LEO research and development can offer.

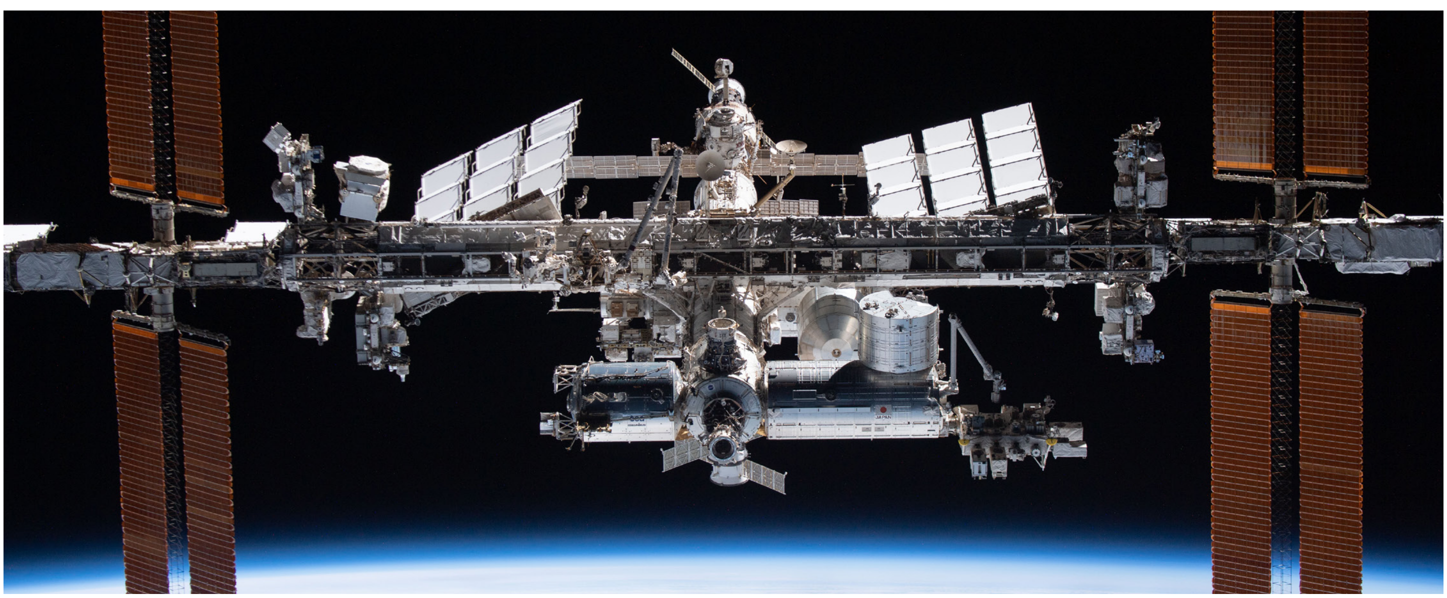

Figure 1. *The International Space Station is pictured from the SpaceX Crew Dragon Endeavour during a fly-around of the orbiting lab that took place following its undocking from the Harmony module's space-facing port on Nov. 8, 2021.*

Why Deorbit is the Necessary Choice

The first pieces of the space station, the Functional Cargo Block "Zarya" (or FGB) and Node 1 "Unity," were launched in 1998. Other pieces followed over the next 13 years until the end of the Space Shuttle program in 2011, which signaled the end of the construction of the original design of the space station. While the space station has been added to and enhanced over the last decade-plus, with new partner-provided structures and capabilities, the originally designed parts still lie at the space station's core. These parts, which include the modules where the crew lives and the truss structures, which provide electrical power, cooling, and communications, among other capabilities, were originally designed for a 30-year structural life in LEO. In 2030, the FGB and Node 1 will have been operating for 32 years, though other space station components that launched later, such as the U.S. Lab "Destiny" (2001), the European Lab "Columbus" (2008), and the Japanese Lab "Kibo" (2008), will have been in space for less time.

NASA and its international partners regularly conduct structural analyses of the station to ensure it continues to be safely and productively crewed and operated. These analyses show ample margin to fly through at least 2030. Much of the space station can be repaired or replaced in orbit, while other parts can be returned to the ground for repair and relaunched. These parts include the solar arrays, communications equipment, life support equipment, and science hardware. However, the primary structure of the station, such as the crewed modules and the truss structures, cannot be repaired or replaced practically. These structures are subject to dynamic loading events, such as visiting spacecraft dockings and undockings and thermal cycling as the space station orbits in and out of Earth's shadow. These forces were accounted for in the original 30-year structural life estimate, and while NASA's flown experience indicates the actual forces imparted to the station have been less than originally forecast, there is still a finite lifetime available in the primary structure.

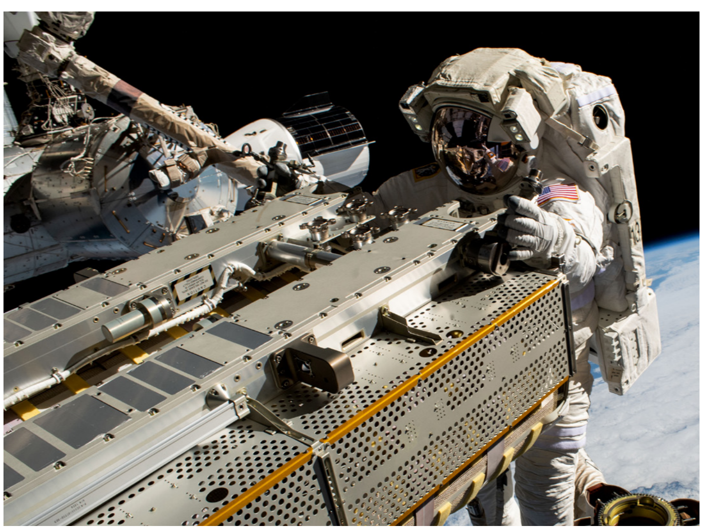

Figure 2. *NASA astronaut and Expedition 68 Flight Engineer Woody Hoburg rides the Canadarm2 robotic arm while maneuvering a roll-out solar array toward the International Space Station's truss structure for installation during a six-hour and three-minute spacewalk.*

NASA will ensure maximum productivity on the space station through its end of life. However, it is also critical that NASA and its International Partners plan to safely end the space station program by disposing of the station itself, the single largest structure ever built in space, in a way that minimizes risk to people on the ground as well as to other orbiting spacecraft. **NASA has concluded that deorbiting the International Space Station using a U.S.-developed deorbit vehicle, with a final target in a remote part of the ocean, is the best option for station's end of life.**

In reaching this conclusion, NASA evaluated several alternative options to deorbit, including:

- Uncontrolled re-entry
- Disassembly and return to Earth
- Disassembly and repurposing in LEO
- Disassembly and deorbit in smaller pieces
- Boosting to a higher orbit
- Decomposition or fragmenting of the space station while in space
- Transitioning the space station to a commercial operator
- Continuing International Space Station operations beyond 2030

Uncontrolled Re-entry

The U.S. Government specifies that re-entering spacecraft must meet or exceed a 1-in-10,000 likelihood of public risk due to debris. An inability to meet this specification requires the spacecraft to conduct a controlled deorbit, which is a standard industry practice for spacecraft that exceed the U.S. Government's safe re-entry requirements unless the spacecraft operates near a disposal orbit, such as a geosynchronous orbit. An uncontrolled deorbit occurs when a spacecraft enters the atmosphere without navigational or propulsive control and is only acceptable when the debris impact risk to the public is small (i.e., a small spacecraft or the structure breaks into small pieces and has a small debris footprint). The International Space Station requires a controlled re-entry because it is very large, and uncontrolled re-entry would result in very large pieces of debris with a large debris footprint, posing a significant risk to the public worldwide. Ensuring the space station is well maintained continues to be the safest operational approach while also planning for deorbit at the space station's end of life.

The use of existing space station propulsion systems, such as the Russian Progress vehicles, would provide an alternative to an uncontrolled re-entry prior to the arrival of the U.S. Deorbit Vehicle (USDV). However, these systems do not provide sufficient margin to lower the public risk to an acceptable level. The USDV will provide this margin to lower the public risk to U.S. Government standards.

Disassembly and Return to Earth

The space station is a unique artifact whose historical value cannot be overstated. NASA considered this when determining if any part of the station could be salvaged for historical preservation or technical analysis. The station's modules and truss structure were not designed to be easily disassembled in space. The space station covers an area about the size of a football field, with the initial assembly of the complex requiring 27 space shuttle flights, using the since-retired shuttle's large cargo bay, and multiple international partner missions, spanning 13 years and 161 extravehicular activities (EVAs), commonly known as spacewalks. Any disassembly effort to safely disconnect and return individual components (such as modules) would face significant logistical and financial challenges, requiring at least an equivalent number of EVAs by space station crew, extensive planning by ground support personnel, and a spacecraft with a capability similar to the space shuttle's large cargo bay, which does not currently exist. Though large modules are not feasible for return, NASA has engaged with the Smithsonian National Air and Space Museum and other organizations to develop a preservation plan for some smaller items from the space station.

Disassembly and Repurposing in LEO

NASA evaluated reusing or repurposing parts or systems of the space station for reuse since many of these will still have some operational life remaining at deorbit and are already flight proven. Repurposing parts for reuse in LEO poses many of the same logistical challenges as returning it to Earth, including a significant number of EVAs and the requirement for an in orbit vehicle capable of moving large modules. NASA did not receive any feasible proposals for repurposing parts of the station for commercial use in discussions with U.S. industry.

As mentioned above, most of the habitable modules have been in space for 15 or more years. These modules were designed as a multi-module integrated system and are not self-sufficient independent spacecraft. Additionally, the technology and architectures are of 1990s-era design and are incompatible with those being explored for future commercial destinations. Reusing these habitable modules will require developing a vehicle that can provide these commodities using space station interfaces, which were designed nearly 30 years ago. Additionally, these modules are currently orbiting at a 51.6° inclination, meaning that the most cost- and delta-v efficient use would be in this same inclination. Developing and launching a new module using modern design techniques would likely be cheaper than repurposing a space station module. Finally, NASA does not own all of the space station; international and commercial partners have provided and own modules, elements, and instruments throughout the lifetime of the space station, meaning that any reuse of an International Partner module or non-NASA-owned capability would need to be negotiated with the relevant owner (see "transitioning to a commercial operator" below).

Disassembly and Deorbit in Smaller Pieces

NASA evaluated the concept of disassembling the space station to deorbit individual pieces over an extended period to avoid a one-time massive re-entry of the entire spacecraft. However, the space station requires a full-time crew to maintain safe operation of the vehicle. This requirement will be in place until shortly before the USDV begins the final deorbit of the station. As such, power, communications, thermal control, and other commodities also will be necessary through station's end of life. Removing smaller, module-level pieces would require a significant number of EVAs, as well as a newly developed propulsive vehicle capable of taking these modules away from station and performing a safe, controlled deorbit with each of them, as each module still consists of a significant and dense amount of mass that will survive re-entry. Most of the station, including the entire truss structure, must remain functional through deorbit, so a considerable portion of station would remain as an integrated vehicle for the final re-entry. Development for the new deorbit vehicle(s) for both the smaller module-level re-entry and the larger integrated vehicle, combined with additional launches, separate re-entries, the complexity of disassembling select modules, and the lack of docking ports for these modules, makes this a less feasible, riskier, more costly disposal method.

Boosting to a Higher Orbit

NASA evaluated moving the station from its present orbit to a higher orbital regime where its lifetime could be theoretically extended, thereby preserving the spacecraft for future generations. The space station flies at an altitude where Earth's atmosphere still creates drag and requires regular reboosts to stay in orbit. The station operates in LEO around 257 miles (415 km) in altitude and as a mass of more than 945,000lbs (430,000kg). Depending on solar activity, the station's orbital lifetime (the time before the station would naturally re-enter from atmospheric drag alone) at this altitude is roughly one-to-two years without reboosts. For this reason, the station cannot remain in orbit indefinitely, as it will naturally fall back to Earth, where an uncontrolled deorbit could pose a threat to people on the ground (see uncontrolled re-entry option).

Space station operations require a full-time crew to operate, and as such, an inability to keep crews onboard would rule out operating at higher altitudes. The cargo and crew vehicles that service the space station are designed and optimized for its current 257 mile (415km) altitude and, while the ability of these vehicles varies, NASA's ability to maintain crew on the space station at significantly higher altitudes would be severely impacted or even impossible with the current fleet. This includes the International crew and cargo fleet, as Russian assets providing propulsion and attitude control need to remain operational through the boost phase.

Ignoring the requirement of keeping crew onboard, NASA evaluated orbits above the present orbital regime that could extend just the orbital lifetime of the space station. If viewed from a perspective of years-in-orbit, the estimated altitudes (depending on solar cycles) could look like this:

Target Orbit Lifetime	Estimated Target Altitude Range	dV Required	Propellant Required
100 years	640-680 km	120-140 m/s	18,900-22,300 kg
200 years	690-730 km	150-170 m/s	23,200-26,700 kg
500 years	770-810 km	190-210 m/s	30,200-33,700 kg
700 years	800-840 km	210-230 m/s	32,800-36,400 kg
1000 years	835-875 km	225-250 m/s	36,000-39,600 kg
5000 years	1025-1075 km	320-346 m/s	52,000-56,200 kg
>>10,000 years	2000 km	760 m/s	132,570 kg
Controlled Deorbit		57 m/s	9,000 kg

However, ascending to these orbits would require the development of new propulsive and tanker vehicles that do not currently exist. While still currently in development, vehicles such as the SpaceX Starship are being designed to deliver significant amounts of cargo to these orbits; however, there are prohibitive engineering challenges with docking such a large vehicle to the space station and being able to use its thrusters while remaining within space station structural margins. Other vehicles would require both new certifications to fly at higher altitudes and multiple flights to deliver propellant.

The other major consideration when going to a higher altitude is the orbital debris regime at each specified locale. The risk of a penetrating or catastrophic impact to space station (i.e., that could fragment the vehicle) increases drastically above 257miles (415km). While higher altitudes provide a longer theoretical orbital life, the mean time between an impact event decreases from ~51 years at the current operational altitude to less than four years at a 497 mile (800km), ~700-year orbit. This means that the likelihood of an impact leaving station unable to maneuver or react to future threats, or even a significant impact resulting in complete fragmentation, is unacceptably high. NASA has estimated that such an impact could permanently degrade or even eliminate access to LEO for centuries (see "Decomposing or Fragmentation" below).

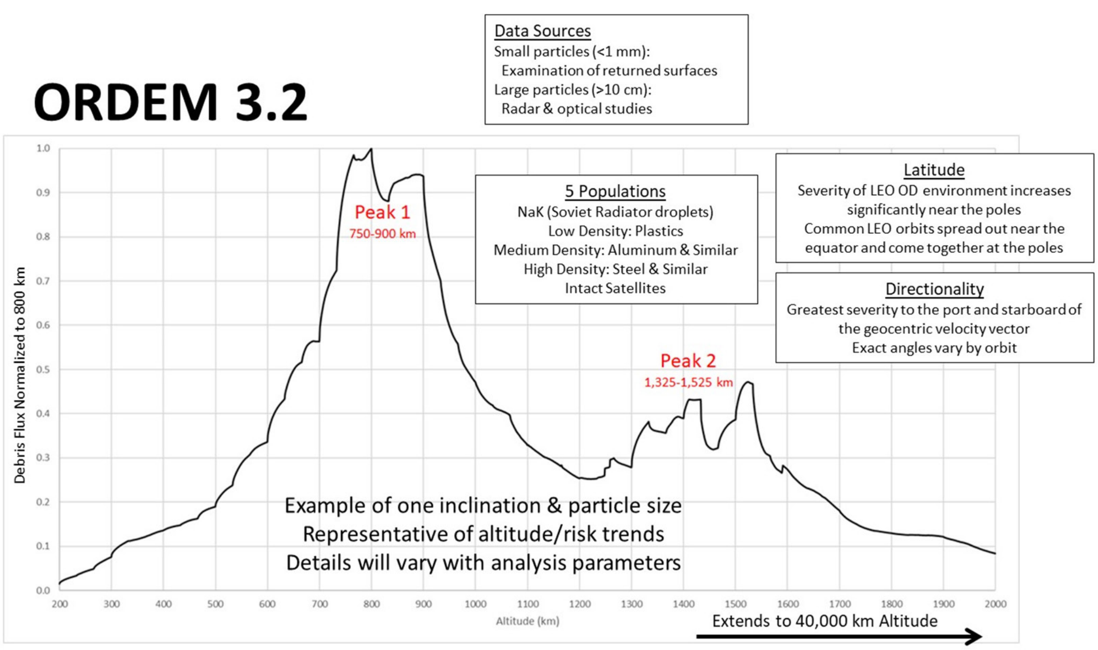

Figure 3. *Debris Flux vs. Altitude, courtesy of NASA/XI*

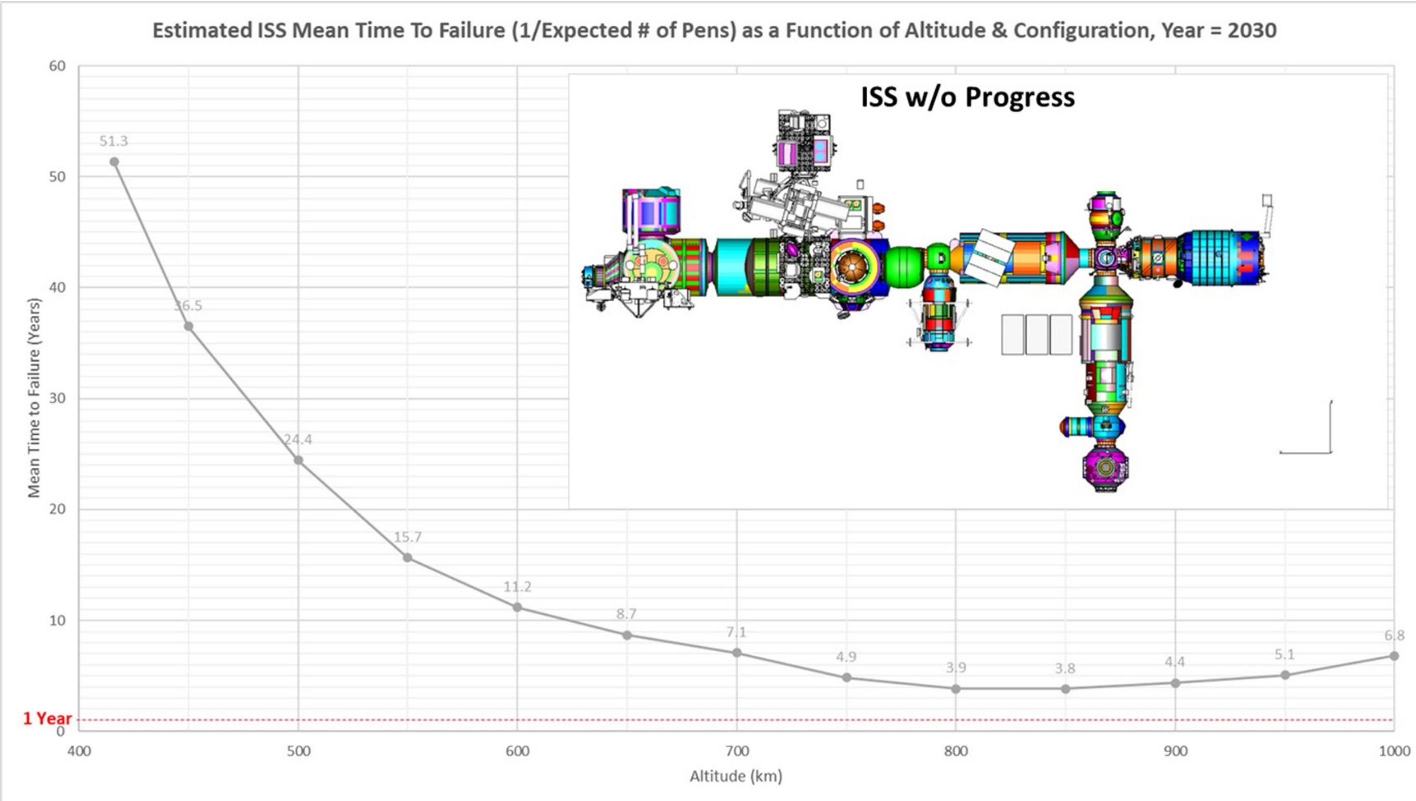

Figure 4. *Mean Time to Failure from Penetration (in years) vs. International Space Station Altitude, courtesy of NASA/XI*

Solar Electric Propulsion
Solar Electric Propulsion (SEP), while more efficient in terms of propellant, is challenging for station use because of the long duration it would take to move the space station to a lifetime-safe orbit. The amount of time required to use SEP to raise its altitude would expose it to considerable risk of encountering a debris strike that could render the space station inoperable and lead to in orbit debris shedding or an eventual uncontrolled re-entry. Assuming a system derived from Gateway's Power and Propulsion Element, ascending to a 1,000-year safe orbit as described above would take approximately three years of constant thrust utilizing 15,000 kg of propellant, during which time Russian propulsion assets would still be required for attitude control. Solar electric propulsion cannot presently provide the short-term delta-v required for debris avoidance maneuvers. Additionally, without crew maintenance, station cannot provide the amount of power through its docking ports that an SEP vehicle would require, and the space station's large solar arrays and appendages would frequently shadow any arrays installed on a visiting vehicle. During a transit to a 1,000-year safe orbit, station would spend a considerable period of time moving through the Van Allen radiation belts, which its systems were not designed to withstand and which would likely result in system failures.
The same orbital debris hazards as described above would also likely result in system failures or total space station breakup. Additionally, the cost of developing an SEP system capable of moving station would require significantly more funding and time than developing a deorbit capability.

Finally, there are ethical considerations to temporarily extending station's lifetime while not providing for its eventual safe disposal. While orbital debris considerations mean that a 1,000-year orbit would likely result in its near-term destruction, the fact remains that even without such a consideration, the space station would still eventually re-enter the Earth's atmosphere in an uncontrolled manner, with the attendant risks to human life on the ground as described above.

Decomposing or Fragmenting the Space Station While in Space
Previous destructive events in LEO demonstrate that fragmenting the space station while in orbit is not a viable disposal option. NASA's Orbital Debris Program Office calculates that the complete destruction and/or fragmentation of the 420-ton space station while in orbit would generate approximately 220 million pieces of debris greater than 1mm in size. The current estimate of the total amount of debris in Earth orbit 1mm and greater is about 100 million pieces. Adding this amount of debris would likely limit or eliminate access to LEO for decades. Fragmentation of the space station at a low altitude (i.e., shortly before atmospheric capture) still

poses a significant orbital debris risk. While many pieces would re-enter the atmosphere faster, a significant amount would be propelled upwards to high apogees, increasing the total number of potentially hazardous objects would present a greater risk to the ground and to other on-orbit assets than a one-time space station re-entry.

Transitioning to a Commercial Operator

NASA worked with industry to evaluate various options for commercializing parts of the space station. In discussions with U.S. industry regarding interest in repurposing any parts of the station for commercial use in LEO or taking over space station operations, NASA received no feasible proposals to utilize the hardware beyond the life of the space station. The reasons for this are due to the age, complexity, and distributed ownership across industry and international partners when compared to deploying newer and modern hardware.

As NASA does not own the entire space station, the international and commercial partners retain ownership of the pieces they provided. NASA also does not have the intellectual property for all of the space station's engineering data, which is required to sustain and operate the vehicle. U.S. industry, which designed and now sustains large parts of the space station, retains the information necessary for continued space station operations. Transitioning some or all of the space station to a commercial provider, were one to signal interest (where to date none have), would be significantly challenging domestically and internationally, especially when compared to deploying new hardware.

Continuing International Space Station Operations Beyond 2030

NASA has evaluated continuing space station operations beyond 2030 in lieu of deorbit. From a policy perspective, NASA has direction from Congress to operate the space station through at least September 30, 2030, at which point NASA plans to have completed the transition to U.S. commercial industry for LEO operations.

The technical lifetime of the space station is limited by the primary structure, which includes the modules, radiators, and truss structures. Other systems, such as power, ECLSS, and communications, are all repairable or replaceable in orbit. The lifetime of the primary structure is affected by dynamic loading (such as vehicle dockings/undockings) and orbital thermal cycling. Each agency is responsible for performing life extension analyses for its modules and structures, and all five have completed life extension analyses through at least 2028. NASA's preliminary analysis has shown high confidence that the primary USOS structure would support operations beyond 2030 if necessary, and the agency has begun detailed analysis to confirm.

If there are no commercial LEO destinations ready to support NASA's ongoing needs in LEO by 2030, extension of space station operations is a possibility. Additionally, the space station's international partner agencies would also need to support ongoing operations. Should operations be extended beyond 2030 for any reason, the USDV can dwell on the ground while awaiting a final deorbit decision.

International Space Station Deorbit Operation

The primary objective during space station deorbit operations is the safe re-entry of vehicle's structure into a remote area in the ocean. The chosen approach for decommissioning is a combination of natural orbital decay and the execution of a re-entry maneuver to control the size of the debris footprint and to place this footprint in an uninhabited region of the ocean.

Due to high propellant cost of this final space station maneuver, the Earth's natural atmospheric drag will be used as much as possible to lower station's altitude while setting up deorbit. Eventually, once all crew have safely returned to Earth and after performing maneuvers to line up the final target ground track and debris footprint over an uninhabited area of the ocean, space station operators will command a large re-entry burn, providing the final push to propel station through the atmosphere into the re-entry target footprint. Once the debris enters the ocean, it is expected to settle to the ocean floor. Based on the findings of the International Space Station Environmental Impact Statement[1], no substantial long-term impacts would be expected.

Conclusion

The International Space Station is the longest-serving, permanently crewed vehicle in space in human history. Research and operations onboard continue to return benefits to humanity on Earth and future human exploration of the solar system that will be felt for decades. NASA recognizes a desire to ensure that every valuable contribution the investment in the space station can make is realized to its full potential. Operating through 2030 will achieve this goal, along with the transition to commercial destinations, to ensure there is no gap in U.S. human spaceflight in LEO. However, for the reasons outlined above, deorbiting the space station at the end of its life is the safest and only viable method to decommission this historic symbol of science, technology, and collaboration.

[1]https://ntrs.nasa.gov/citations/19960053133