Shuttle Builds the International Space Station

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Since its inception, the International Space Station (ISS) was destined to have a close relationship with the Space Shuttle. Conceived for very different missions, the two spacecraft drew on each other's strengths and empowered each other to achieve more than either could alone. The shuttle was the workhorse that could loft massive ISS elements into space. It could then maneuver, manipulate, and support these pieces with power, simple data monitoring, and temperature control until the pieces could be assembled. The ISS gradually became the port of call for the shuttles that served it.

The idea of building a space station dates back to Konstantin Tsiolkovsky's writings in 1883. A space station would be a small colony in space where long-term research could be carried out. Visionaries in many nations offered hundreds of design concepts over the next century and a half, and a few simple outposts were built in the late 20th century. The dreams of an enduring international space laboratory coalesced when the shuttle made it a practical reality.

As a parent and child grow, so too did the relationship between the shuttle and the ISS as the fledgling station grew out of its total dependence on the shuttle to its role as a port of call. The ISS soon became the dominant destination in the heavens, hosting vehicles launched from many spaceports in four continents below, including shuttles from the Florida coast.

Creating the International Space Station Masterpiece—in Well-planned Increments

Building this miniature world in the vacuum of space was to be the largest engineering challenge in history. It was made possible by the incomparable capabilities of the winged fleet of shuttles that brought and assembled the pieces. The space station did not spring into being “out of thin air.” Rather, it made use of progressively sophisticated engineering and operations techniques that were matured by the Space Shuttle Program over the preceding 17 years. This evolution began before the first International Space Station (ISS) assembly flight ever left the ground—or even the drawing board.

Early Tests Form a Blueprint

NASA ran a series of tests beginning with a deployable solar power wing experiment on Discovery’s first flight (Space Transportation System [STS]-41D in 1984) to validate the construction techniques that would be used to build the ISS. On STS-41G (1984), astronauts demonstrated the safe capability for in-space resupply of dangerous rocket propellants in a payload bay apparatus. Astronauts practiced extravehicular activity (EVA) assembly techniques for space-station-sized structures in experiments aboard STS-61B (1985). Several missions tested the performance of large heat pipes in space. NASA explored mobility aids and EVA handling limits during STS-37 (1991).

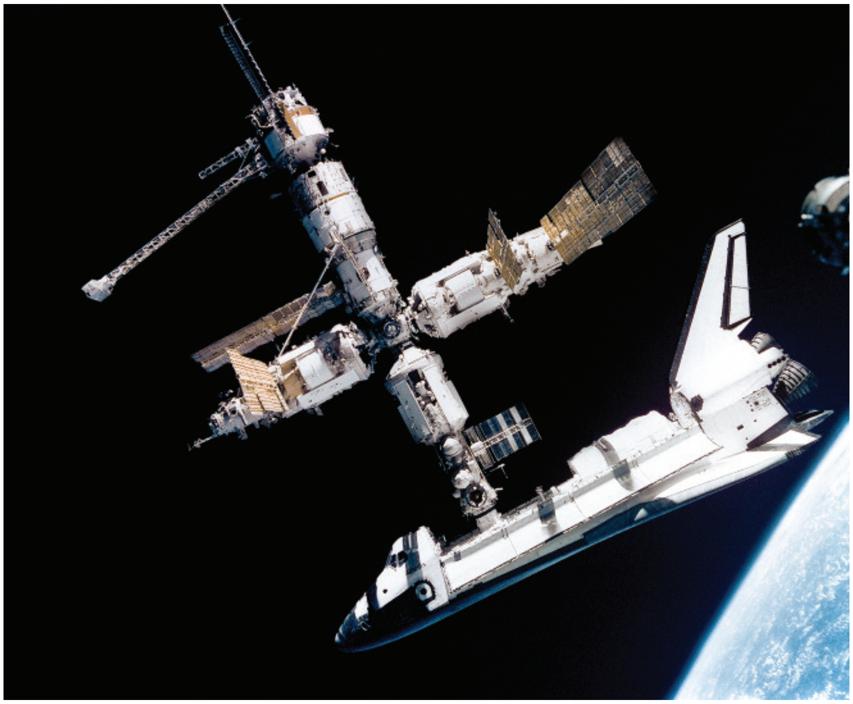
In April 1984, STS-41C deployed one of the most important and comprehensive test programs—the Long Duration Exposure Facility. STS-32 retrieved the facility in January 1990, giving critical evidence of the performance and degradation timeline of materials in the low-Earth environment. It was a treasure trove of data about the micrometeoroid orbital debris threat that the ISS would face. NASA’s ability to launch such huge test fixtures and to examine them back on Earth after flight added immensely to the engineers’ understanding of the technical refinements that would be necessary for the massively complicated ISS construction.

The next stage in the process would involve an international connection and the coming together of great scientific and engineering minds.

Spacelab and Spacehab Flights

Skylab had been an interesting first step in research but, after the Saturn V production ceased, all US space station designs would be limited to something similar to the Orbiter’s 4.6-m (15-ft.) payload bay diameter. The shuttle had given the world ample ways to evolve concepts of space station modules, including a European Space Agency-built Spacelab and an American-built Spacehab. Each module rode in the payload bay of the Orbiter. These labs had the same outer diameter as subsequent ISS modules.

The shuttle could provide the necessary power, communications, cooling, and life support to these laboratories. Due to consumables limits, the shuttle could only keep these labs in orbit for a maximum of 2 weeks at a time. Through the experience, however,



Space Shuttle Atlantis (STS-71) is docked with the Russian space station Mir (1995). At the time, Atlantis and Mir had formed the largest spacecraft ever in orbit. Photo taken from Russian Soyuz vehicle as shuttle begins undocking from Mir. Photo provided to NASA by Russian Federal Space Agency.

astronaut crews and ground engineers discovered many issues of loading and deploying real payloads, establishing optimum work positions and locations, clearances, cleanliness, mobility, environmental issues, etc.

Shuttle-Mir

In 1994, the funding of the Space Station Program passed the US Senate by a single vote. Later that year, Vice President Al Gore and Russian Deputy Premier Viktor Chernomyrdin signed the agreement that redefined both countries' space station programs. That agreement also directed the US Space Shuttle Program and the Russian space program to immediately hone the complex cooperative operations required to build the new, larger-than-dreamed space station. That operations development effort would come through a series of increasingly complex flights of the shuttle to the existing Russian space station Mir. George Abbey, director of Johnson Space Center, provided the leadership to ensure the success of the Shuttle-Mir Program.

The Space Shuttle Program immediately engaged Mir engineers and the Moscow Control Center to begin joint operations planning. Simultaneously, engineers working on the former US-led Space Station Program, called Freedom, went to work with their counterparts who had been designing and building Mir's successor—Mir-II. The new joint program was christened the ISS Program. Although NASA's Space Shuttle and ISS Programs emerged as flagships for new, vigorous international cooperation with the former Soviet states, the immediate technical challenges were formidable. The Space Shuttle Program had to surmount many of these challenges on shorter notice than did the ISS Program.

Astronaut Shannon Lucid floats in the tunnel that connects Atlantis' (STS-79 [1996]) cabin to the Spacehab double module in the cargo bay. Lucid and her crew mates were already separated from the Russian space station Mir and were completing end-of-mission chores before their return to Earth.

Striving for Lofty Heights—And Reaching Them

The biggest effect on the shuttle in this merged program was the need to reach a higher-inclination orbit that could be accessed from Baikonur Cosmodrome in Kazakhstan. At an inclination of 51.6 degrees to the equator, this new orbit for the ISS would not take as much advantage of the speed of the Earth's rotation toward the East as had originally been planned. Instead of launching straight eastward and achieving nearly 1,287 km/hour (800 mph) from Earth's rotation, the shuttle now had to aim northward to meet the vehicles launched from Baikonur, achieving a benefit of only 901 km/hour (560 mph). The speed difference meant that each shuttle could carry substantially less mass to orbit for the same maximum propellant load. The Mir was already in such an orbit, so the constraint was in place from the first flight (STS-63 in 1995).

The next challenge of the 51.6-degree orbit was a very narrow launch window each day. In performing a rendezvous, the shuttle needed to launch close to the moment when the shuttle's launch pad was directly in the same flat plane as the orbit of the target spacecraft. Typically, there were only 5 minutes when the shuttle could angle enough to meet the Russian orbit.

Thus, in a cooperative program with vehicles like Mir (and later the ISS), the shuttle had only a tiny "window" each day when it could launch. The brief chance to beat any intermittent weather meant that the launch teams and Mission Control personnel often had to wait days for acceptable weather during the launch window. As a result of the frequent launch slips, the Mir and ISS control teams had to learn to pack days with spontaneous work schedules for the station crew on a single day's notice. Flexibility grew to become a high art form in both programs.

Once the shuttle had launched into the orbit plane of the Mir, it had to catch up to the station before it could dock and begin its mission at the outpost. Normally, rendezvous and docking would be completed 2 days after launch, giving the shuttle time to make up any differences between its location around the orbit compared to where the Mir or ISS was positioned at the time of launch, as well as time for ground operators to create the precise maneuvering plan that could only be perfected after the main engines cut off 8½ minutes after launch.

Generally, the plan was to launch then execute the lengthy rendezvous preparation the day after launch. The shuttle conducted the last stages of the rendezvous and docking the next morning so that a full day could be devoted to assembly and cargo transfer. This 2-day process maximized the available work time aboard the station before the shuttle consumables gave out and the shuttle had to return to Earth. The Mir and ISS teams worked in the months preceding launch to place their vehicles in the proper phase in their respective orbits, such that this 2-day rendezvous was always possible.

Arriving at the rendezvous destination was only the first step of the journey. The shuttle still faced a formidable hurdle: docking.

Docking to Mir

The American side had not conducted a docking since the Apollo-Soyuz Test Project of 1975. Fortunately, Moscow's Rocket and Space Corporation Energia had further developed the joint US-Russian docking system originally created for the Apollo-Soyuz Test Project in anticipation of their own shuttle—the Buran. Thus, the needed mechanism was already installed on Mir.

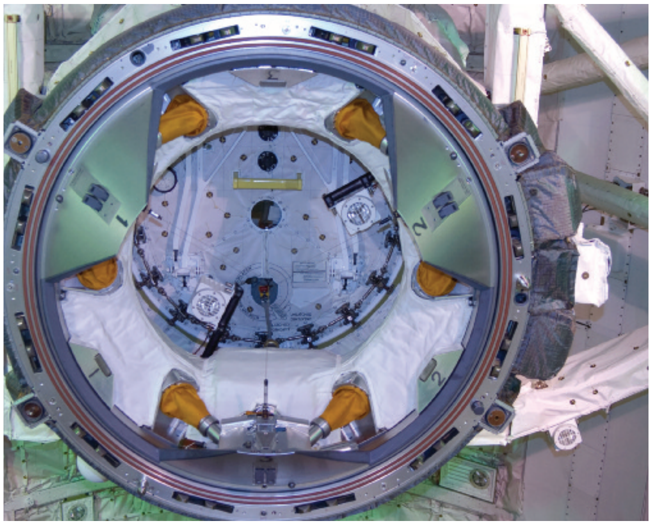
The Russians had a docking mechanism on their space station in a 51.6-degree orbit, awaiting a shuttle. That mechanism had a joint US-Russian design heritage. The Americans had a fleet of shuttles that needed to practice servicing missions to a space station in a 51.6-degree orbit. In a surprisingly rapid turn of events, the US shuttle's basic design began to include a sophisticated Russian mechanism. That mechanism would remain a part of most of the shuttle's ensuing missions.

The mechanism—called an Androgynous Peripheral Docking System—became an integral part of the shuttle's future. It looked a little like a three-petal artichoke when seen from the side. US engineers were challenged to work scores of details and unanticipated challenges to incorporate this exotic Russian apparatus in the shuttle. The bolts that held the Androgynous Peripheral Docking System to the shuttle were manufactured according to *Système International* (SI, or metric) units whereas all other shuttle hardware and tools were English units. For the first time, the US space program began to create hardware and execute operations in SI units—a practice that would become the norm during the ISS era.

All connectors in the cabling were of Russian origin and were unavailable in the West. Electrical and data interfaces had to be made somewhere. The obvious solution would be to put a US connector on the "free" end of each cable that led to the docking system. Each side could engineer from there to its own standards and hardware. Yet, even that simple plan had obstacles. Whose wire would be in the cable?

The Russian wires were designed to be soldered into each pin and socket while the US connector pins and sockets were all crimped under pressure to their wires in an exact fit. US wire had nickel plating, Russian wire did not. US wire could not be easily soldered into Russian connector pins, and Russian wire could not be reliably crimped into American connector pins. Ultimately, unplated Russian wire was chosen and new techniques were certified to assure a reliable crimped bond at each American pin. Even though the Russian system and the shuttle were both designed to operate at 28 volts, direct current (Vdc), differences in the grounding strategy required extensive discussions and work.

The Space Shuttle Atlantis (STS-71) arrived at the Mir on June 29, 1995, with the international boundary drawn at the crimped interface to a Russian wire in every US connector pin and socket. US 28-Vdc power flowed in every Russian Androgynous Peripheral Docking System electronic component, beginning a new era in international cooperation. And this happened just in time, as the US and partners were poised to begin work on a project of international proportions.



View of the Orbiter Docking System that allowed the shuttle to attach to the International Space Station. This close-up image shows the payload bay closeout on STS-130 (2010).

Construction of the International Space Station Begins

The International Space Station (ISS) was a new kind of spacecraft that would have been impossible without the shuttle's unique capabilities; it was the first spacecraft designed to be assembled in space from components that could not sustain themselves independently. The original 1984 International Freedom Space Station—already well along in its manufacture—was reconfigured to be the forward section of the ISS. The Freedom heritage was a crucial part of ISS plans, as its in-space construction was a major goal of the program. All previous spacecraft had either been launched intact from the ground (such as the shuttle itself, Skylab, or the early Salyut space stations) or made of fully functional modules, each launched intact from the ground and hooked together in a cluster of otherwise independent spacecraft.

This timeline represents the Space Shuttle fleet's delivery and attachment of several major components to the International Space Station. The specific components are outlined in red in each photo.

The Mir and the late-era Salyut stations were built from such self-contained spacecraft linked together. Although these Soviet stations were big, they were somewhat like structures built primarily out of the trucks that brought the pieces and were not of a monolithic design. Only about 15% of each module could be dedicated to science. The rest of the mass was composed of the infrastructure needed to get the mass to the station.

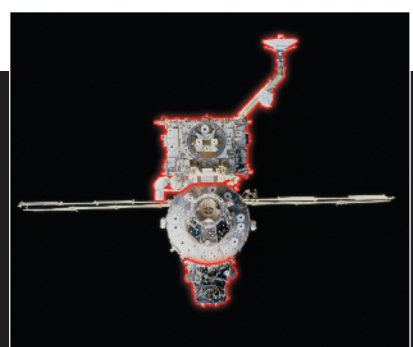
The ISS would take the best features of both the merged Mir-II and the Freedom programs. It would use proven Russian reliability in logistics, propulsion, and basic life support and enormous new capabilities in US power, communications, life support, and thermal control. The integrated Russian modules helped to nurture the first few structural elements of the US design until the major US systems could be carried to the station and activated. These major US systems were made possible by assembly techniques enabled by the shuttle. The United States could curtail expensive and difficult projects in both propulsion and crew rescue vehicles and stop worrying about the problem of bootstrapping their initial infrastructure, while the Russians would be able to suspend sophisticated-but-expensive efforts in in-space construction techniques, power systems, large gyroscopes, and robotics. What emerged out of the union of the Freedom and the Mir-II programs was a space station vastly larger and more robust (and more complicated) than either side had envisioned.

The Pieces Begin to Come Together

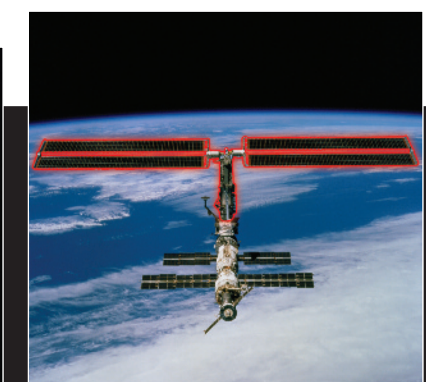
Although the ISS ultimately included several necessary Mir-style modules in the Russian segment, the other partner elements from the United States, Canada, European Space Agency, Italy, and Japan were all designed with the shuttle in mind. Each of these several dozen components was to be supported by the shuttle until each could be supported by the ISS infrastructure. These major elements typically required power, thermal control, and telemetry support from the shuttle. Not one of these chunks could make it to the ISS on its own, nor could any be automatically assembled into the ISS by itself. Thus, the shuttle enabled a new era of unprecedented *in situ* construction capability.

Because it grew with every mission, the ISS presented new challenges to

Endeavour (STS-88) brought US-built Unity node, which attached to Russian-built Zarya.



Discovery (STS-92) delivered Z1 truss and antenna (top) and one of the mating adapters.



Endeavour (STS-97) delivered new solar array panels.

1998 **2000**

spacecraft engineering in general and to the shuttle in particular. With each new module, the spacecraft achieved more mass, a new center of mass, new antenna blockages, and some enhanced or new capability and constraints.

During the assembly missions, the shuttle and the ISS would each need to reconfigure the guidance, navigation, and control software to account for several different configurations. Each configuration needed to be analyzed for free flight, initial docked configuration with the arriving element still in the Orbiter payload bay, and final assembled and mated configuration with the element in its ISS position. There were usually one or two intermediate configurations with the element robotically held at some distance between the cargo bay and its final destination.

Consequently, crews had to update a lot of software many times during the mission. At each step, both the ISS and the shuttle experienced a new and previously unflown shape and size of spacecraft.

Even the most passive cargos involved active participation from the shuttle. For example, in the extremely cold conditions in space, most cargo elements dramatically cooled throughout the flight to the ISS. On previous space station generations like Skylab, Salyut, and Mir, such modules needed heaters, a control system to regulate them, and a power supply to run them both. These functions all passed to the shuttle, allowing an optimized design of each ISS element.

Each mission, therefore, had a kind of special countdown called the "Launch to Activation" timeline. This unique timeline for every cargo considered how long it would take before such temperature limits were reached. Sometimes, the shuttle's ground support systems would heat the cargo in the payload bay for hours before the launch to gain some precious time in orbit. Other times electric heaters were provided to the cargo element at the expense of shuttle power. At certain times the shuttle would spend extra time pointing the payload bay intentionally toward the sun or the Earth during the long rendezvous with the ISS. All these activities led to a detailed planning process for every flight that involved thermal systems, attitude control, robotics, and power.

The growth of the ISS did not come at the push of a button or even solely at the tip of a remote manipulator. The assembly tasks in orbit involved a combination of docking, berthing, automatic capture, automatic deployment, and good old-fashioned elbow grease.

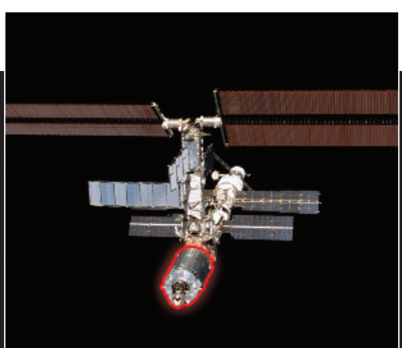
The shuttle had mastered the rendezvous and docking issues in a high-inclination orbit during the Mir Phase 1 Program. However, just getting there and getting docked would not assemble the ISS. Berthing and several other attachment techniques were required.

Docking and Berthing

Docking

Docking and berthing are conceptually similar methods of connecting a pressurized tunnel between two objects in space. The key differences arise from the dynamic nature of the docking process with potentially large residual motions. In addition, under docking there is a need to complete the rigid structural mating quickly. Such constraints are not imposed on the slower, robotically controlled berthing process.

Docking spacecraft need to mate quickly so that attitude control can be restored. Until the latches are secured,



Atlantis (STS-98) brought Destiny laboratory.

Endeavour (STS-100) delivered and attached Space Station Robotic Arm.

Atlantis (STS-104) delivered Quest airlock.

2001

there is very little structural strength at the interface. Therefore, neither vehicle attempts to fire any thrusters or exert any control on "the stack." During this period of free drift, there is no telling which attitude can be expected. The sun may consequently end up pointing someplace difficult, such as straight onto a radiator or edge-on to the arrays. Thus, it pays to get free-flying vehicles latched firmly together as quickly as possible.

Due to the large thermal differences—up to 400° C (752°F) between sun-facing metal and deep-space-facing metal—the thermal expansion of large metal surfaces can quickly make the precise alignment of structural mating hooks or bolts problematic, unless the metal surfaces have substantial time to reach the same temperature. As noted, time is of the essence. Hence, docking mechanisms were forced to be small—about the size of a manhole—due to this need to rapidly align in the presence of large thermal differences.

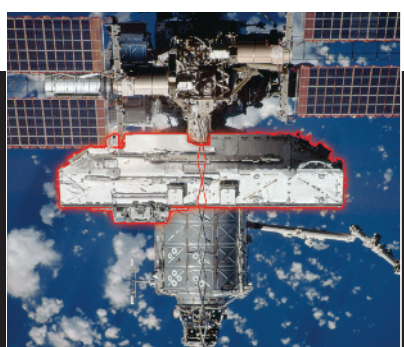
A docking interface is a sophisticated mechanism that must accomplish many difficult functions in rapid succession. It must mechanically guide the approaching spacecraft from its first contact into a position where a "soft capture" can be engaged. Soft capture

Astronaut Peggy Whitson, Expedition 16 commander, works on Node 2 outfitting in the vestibule between the Harmony node and Destiny laboratory of the International Space Station in November 2007.

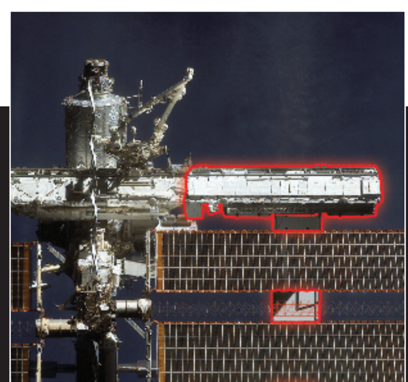
is somewhat akin to the moment when a large ship first tosses its shore lines to dock hands on the pier; it serves only to keep the two vehicles lightly connected while the next series of functions is completed.

The mechanism must next damp out leftover motions in X, Y, and Z axes as well as damp rotational motions in pitch, yaw, and roll while bringing the two spacecraft into exact alignment. This step was a particular challenge for shuttle dockings. For the first time in space history, the docking mechanism was placed well away from the vehicle's center of gravity. Sufficient torque had to be applied at the interface to overcome the large moment of the massive shuttle as it damped its motion.

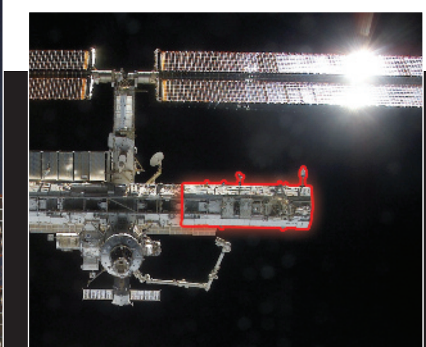
Next, the mechanism had to retract, pulling the two spacecraft close enough together that strong latches could engage. The strong latches clamped the two halves of the mechanism together with enough force to compress the seals. These latches held the halves together against the huge force of pressure that would try to push them apart once the hatches were opened inside. While this final cinching of



Atlantis (STS-110) delivered S0 truss.



Atlantis (STS-112) brought S1 truss.



Endeavour (STS-113) delivered P1 truss.

2002

the latches happened, hundreds of electrical connections and even a few fluid transfer lines had to be automatically and reliably connected. Finally, there had to be a means to let air into the space between the hatches, and all the hardware that had been filling the tunnel area had to be removed before crew and cargo could freely transit between the spacecraft.

Berthing

Once docked, the shuttle and station cooperated in a gentler way called berthing, which led to much larger passageways.

Berthing was done under the control of a robotic arm. It was the preferred method of assembling major modules of the ISS. The mechanism halves could be held close to each other indefinitely to thermally equilibrate. The control afforded by the robotic positioning meant that the final alignment and damping system in berthing could be small, delicate, and lightweight while the overall tunnel could be large.

In the case of the ISS, the berthing action only completed the hard structural mating and sealing, unlike docking, where all utilities were simultaneously mated. All berthing interface utilities were subsequently hooked between the modules in the pressurized tunnel (i.e., in a "shirtsleeve" environment). During extravehicular activities (EVAs), astronauts connected major cable routes only where necessary.

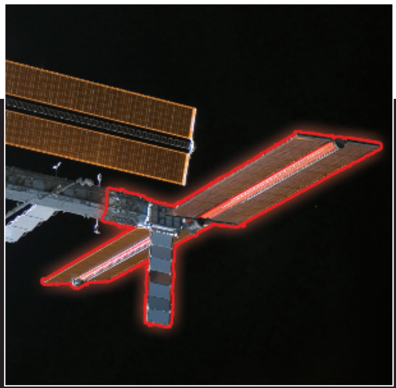
The interior cables and ducts connected in a vestibule area inside the sealing rings and around the hatchways. This arrangement allowed thousands of wires and ducts to course through the shirtsleeve environment where they could be easily accessed and maintained while allowing the emergency closure of any hatch in seconds. This hatch closure could be done without the need to clear or cut cables that connected the modules. This "cut cable to survive" situation occurred, at great peril to the crew, for several major power cables across a docking assembly during the Mir Program.

Robotic Arms Provide Necessary Reach

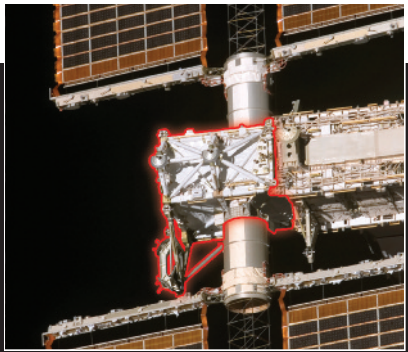
The assembly of the enormous ISS required that large structures were placed with high precision at great distance from the shuttle's payload bay. As the Shuttle Robotic Arm could only reach the length of the payload bay, the ISS needed a second-generation arm to position its assembly segments and modules for subsequent hooking, berthing, and/or EVA bolt-downs.

The Unity connecting module is being put into position to be mated to Endeavour's (STS-88 [1998]) docking system in the cargo bay. This mating was the first link in a long chain of events that led to the eventual deployment of the connected Unity and Zarya modules.

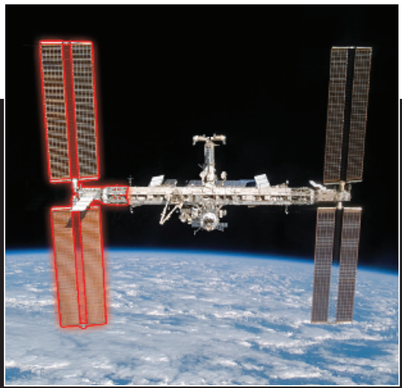
Building upon the lessons learned from the shuttle experience, the same Canadian Space Agency and contractor team created the larger, stiffer, and more nimble Space Station Robotic



Atlantis (STS-115) brought P3/P4 truss.



Discovery (STS-116) delivered P5 truss.



Atlantis (STS-117) delivered S3/S4 truss and another pair of solar arrays.

2006 **2007**

Arm, also known as the "big arm." The agency and team created a 17-m (56-ft) arm with seven joints. The completely symmetric big arm was also equipped with the unique ability to use its end effector as a new base of operations, walking end-over-end around the ISS. Together with a mobile transporter that could carry the new arm with a multiton cargo element at its end, the ISS robotics system worked in synergy with the Shuttle Robotic Arm to maneuver all cargos to their final destinations.

The Space Station Robotic Arm could grip nearly every type of grapple fixture that the shuttle's system could handle, which enabled the astounding combined robotic effort to repair a torn outboard solar array on STS-120 (2007). On that memorable mission, the Space Station Robotic Arm "borrowed" the long Orbiter Boom Sensor System, allowing an unprecedented stretch of 50 m (165 ft) down the truss and 27 m (90 ft) up to reach the damage.

The Space Station Robotic Arm was robust. Analysis showed that it was capable of maneuvering a fully loaded Orbiter to inspect its underside from the ISS windows.

The robotic feats were amazing indeed—and unbelievable at times—yet successful construction of the ISS depended on a collaboration of human efforts, ingenuity, and a host of other "nuts-and-bolts" mechanisms and techniques.

Other Construction Mechanisms

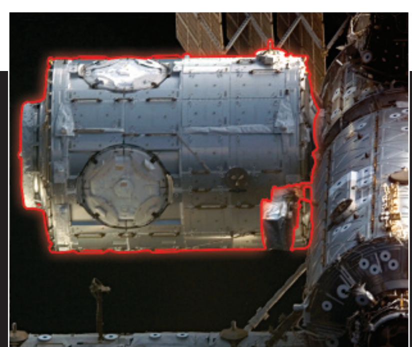
The many EVA tests conducted by shuttle crews in the 1980s inspired ISS designers to create several simplifying construction techniques for the enormous complex. While crews assembled the pressurized modules using the Common Berthing Mechanism, they had to assemble major external structures using a simple large-hook system called the Segment-to-Segment Attachment System designed for high strength and rapid alignment.

The Segment-to-Segment Attachment System had many weight and reliability enhancements resulting from the lack of a need for a pressurized seal. Such over-center hooks were used in many places on the ISS exterior. In major structural attachments (especially between segments of the 100-m [328-ft] truss), the EVA crew additionally drove mechanical bolts between the segments. The crew then attached major appendages and payloads with a smaller mechanism called a Common Attachment System.

Where appropriate, major systems were automatically deployed or retracted from platforms that were pre-integrated to the delivered segment before launch. The solar array wings were deployed by swinging two half-blanket boxes open from a "folded hinge" launch position and then deploying a collapsible mast to extend and finally to stiffen the blankets. Like the Russian segment's smaller solar arrays, the tennis-court-sized US thermal radiators deployed automatically with an extending scissor-like mechanism.

Meanwhile, the ISS design had to accommodate the shuttle. It needed to provide a zigzag tunnel mechanism (the Pressurized Mating Adapter) to optimize the clearance to remove payloads from the bay after the shuttle had docked. ISS needed to withstand the shuttle's thruster plumes for heating, loads, contamination, and erosion. It also had to provide the proper electrical grounding path for shuttle electronics, even though the ISS operated at a significantly higher voltage.

Endeavour (STS-118) delivered the S5 truss segment.



Discovery (STS-120) brought Harmony Node 2 module.

Atlantis (STS-122) delivered European Space Agency's Columbus laboratory.

2007 **2008**

Improvements to the Shuttle Facilitated Assembly of the International Space Station

NASA had to improve Space Shuttle capability before the International Space Station (ISS) could be assembled. The altitude and inclination of the ISS orbit required greater lift capability by the shuttle, and NASA made a concerted effort to reduce the weight of the vehicle. Engineers redesigned items such as crew seats, storage racks, and thermal tiles. The super lightweight External Tank allowed the larger ISS segments to be launched and assembled. Modifications to the ascent flight path and the firing of Orbital Maneuvering System engines alongside the main engines during ascent provided a more efficient use of propellant.

Launch reliability was another concern. For the shuttle to rendezvous with the ISS, the launch window was limited to a period of about 5 minutes, when the launch pad on the rotating Earth was aligned with the ISS orbit. By rearranging the prelaunch checklist to complete final tests earlier and by adding planned hold periods to resolve last-minute technical concerns, the 5-minute launch window could be met with high reliability.

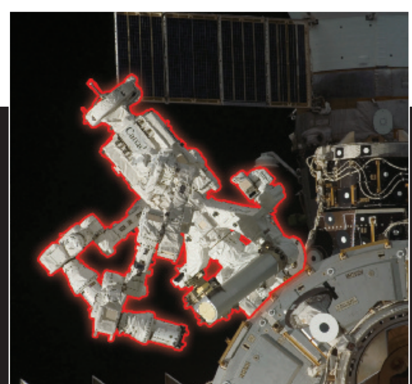
Finally, physical interfaces between the shuttle and the ISS needed to be coordinated. NASA designed docking fixtures and transfer bags to accommodate the ISS. The agency modified the rendezvous sequence to prevent contamination of the ISS by the shuttle thrusters. In addition, NASA could transfer electrical power from the ISS to the shuttle. This allowed the shuttle to remain docked to the ISS for longer periods, thus maximizing the work that could be accomplished.

Astronaut Carl Walz, Expedition 4 flight engineer, stows a small transfer bag into a larger cargo transfer bag while working in the International Space Station Unity Node 1 during joint docked operations with STS-111 (2002).

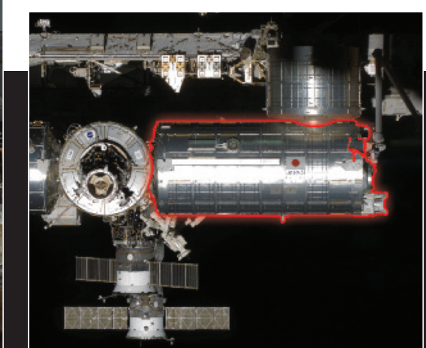
Further Improvements Facilitate Collaboration Between Shuttle and Station

The ISS needed a tiny light source that could be seen at a distance of hundreds of miles by the shuttle's star tracker so that rendezvous could be conducted. The ISS was so huge that in sunlight it would saturate the star trackers of the shuttle, which were accustomed to seeking vastly dimmer points of light. Thus, the shuttle's final rendezvous with the ISS involved taking a relative navigational "fix" on the ISS at night, when the ISS's small light bulb approximated the light from a star.

Endeavour (STS-123) brought Kibo Japanese Experiment Module.



Endeavour (STS-123) also delivered Canadian-built Special Purpose Dextrous Manipulator.



Discovery (STS-124) brought Pressurized Module and robotic arm of Kibo Japanese Experiment Module.

2008 *continued*

Other navigational aids were mounted on the ISS as well. These aids included a visual docking target that looked like a branding iron of the letter "X" erected vertically from a background plate in the center of the hatch. Corner-cube glass reflectors were provided to catch a laser beam from the shuttle and redirect it straight back to the shuttle. This remarkable optical trick is used by several alignment systems, including the European Space Agency's rendezvous system that targeted other places on the ISS. Thus, it was necessary to carefully shield the different space partners' reflectors from the beams of each other's spacecraft during their respective final approaches to the ISS. Otherwise a spacecraft might "lock on" to the wrong place for its final approach.

As the station grew, it presented new challenges to the shuttle's decades-old control methods. The enormous solar arrays, larger than America's Cup yacht sails, caught the supersonic exhaust from the shuttle's attitude control jets and threatened to either tear or accelerate the station in some strange angular motion. Thus, when the shuttle was in the vicinity of or docked to the ISS, a careful ballet of shuttle engine selection and ISS array positions was always necessary to keep the arrays from being damaged.

This choreography grew progressively more worrisome as the ISS added more arrays. It was particularly difficult during the last stages of docking and in the first moments of a shuttle's departure, when it was necessary to fire thrusters in the general direction of the station.

There were also limits as to how soon a shuttle might be allowed to fire an engine after it had just fired one. It was possible that the time between each attitude correction pulse could match the natural structural frequency of that configuration of the ISS. This pulsing could amplify oscillations to the point where the ISS might break if protection systems were not in place. Of course, this frequency changed each time the ISS configuration changed. Thus, the shuttle was always loading new "dead bands" in its control logic to prevent it from accidentally exciting one of these large station modes.

In all, the performances of all the "players" in this unfolding drama were stellar. The complexity of challenges required flexibility and tenacity. The shuttle not only played the lead in the process, it also served in supporting roles throughout the entire construction process.

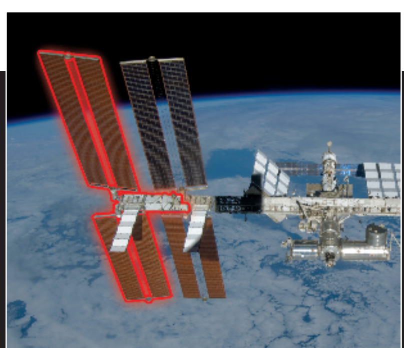
The Roles of the Space Shuttle Program Throughout Construction

Logistics Support—Expendable Supplies

The shuttle was a workhorse that brought vast quantities of hardware and supplies to the International Space Station (ISS). Consumables and spare parts were a key part of that manifest, with whole shuttle missions dedicated to resupply. These missions were called "Utilization and Logistics Flights." All missions—even the assembly flights—contributed to the return of trash, experiment samples, completed experiment apparatus, and other items.

Unique Capacity to Return Hardware and Scientific Samples

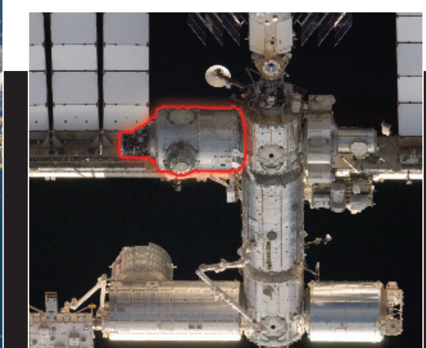
Perhaps the greatest shuttle contribution to ISS logistics was its unsurpassed capability to return key systems and components to Earth. Although most of the ISS worked perfectly from the start, the shuttle's ability to bring components and systems back was essential in rapidly advancing NASA's engineering



Discovery (STS-119) brought S6 truss segment.

Endeavour (STS-127) delivered Kibo Japanese Experiment Module Exposed Facility and Experiment Logistics Module Exposed Section.

2009



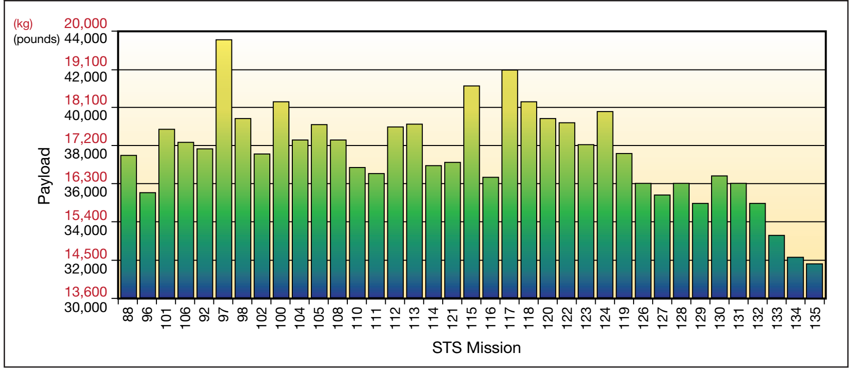
Endeavour (STS-130) delivered Node 3 with Cupola.

2010

knowledge in many key areas. This allowed ground engineers to thoroughly diagnose, repair, and sometimes redesign the very heart of the ISS.

The shuttle upmass was a highly valued financial commodity within the ISS Program, but its recoverable down-mass capability was unique, hotly pursued, and the crown jewel at the negotiation table. As it became clear that more and more partners would have the capability to deliver cargo to the ISS but only NASA retained any significant ability to return cargo intact to Earth, the cachet only increased. Even the Russian partner—with its own robust resupply capabilities and long, proud history in human spaceflight—was seduced by the lure of recoverable down mass and agreed that its value was twice that of 1 kg (2.2 pounds) of upmass. NASA negotiators had a particular fondness for this one capability that the Russians seemed to value higher than their own capabilities.

Mass Transported by Space Shuttle to Station



Symbiotic Relationship Between Shuttle and the International Space Station

Over time the two programs developed several symbiotic logistic relationships. The ISS was eager to take the pure-water by-product of the shuttle's fuel cell power generators because water is the heaviest and most vital consumable of the life support system. The invention of the Station to Shuttle Power Transfer System allowed the shuttle to draw power from the ISS solar arrays, thereby conserving its own oxygen and hydrogen supplies and extending its stay in orbit.

The ISS maintained the shared contingency supply of lithium hydroxide canisters for carbon dioxide scrubbing by both programs, allowing more cargo to ride up with the shuttle on every launch in place of such canisters. The shuttle would even carry precious ice cream and frozen treats for the ISS crews in freezers needed for the return of frozen medical samples.

The shuttle would periodically reboost the ISS, as needed, using any leftover propellant that had not been required for contingencies. The shuttle introduced air into the cabin and transferred compressed oxygen and nitrogen to the ISS tanks as its unused reserves allowed. ISS crews even encouraged shuttle crews to use their toilet so that the precious water could be later recaptured from the wastes for oxygen generation.

The ISS kept stockpiles of food, water, and essential consumables that were collectively sufficient to keep a guest crew of seven aboard for an additional 30 days—long enough for a rescue shuttle to be prepared and launched to the ISS in the event a shuttle already at the station could not safely reenter the Earth's atmosphere.

Extravehicular Activity by Space Shuttle Crews

Even with all of the automated and robotic assembly, a large and complex vehicle such as the ISS requires an enormous amount of manual assembly—much of it "hands on"—in the harsh environment of space. Spacewalking crews assembled the ISS in well over 100 extravehicular activity (EVA) sessions, usually lasting 5 hours or more. EVA is tiring, time consuming, and more dangerous than routine cabin flight. It is also exhilarating to all involved. Despite the dangers of EVA, the main role for shuttle in the last decade of flight was to assemble the ISS. Therefore, EVAs came to dominate the shuttle's activities during most station visits.

These shuttle crew members were trained extensively for their respective missions. NASA scripted the shuttle flights to achieve ambitious assembly objectives, sometimes requiring four EVAs in rapid succession. The level of proficiency required for such long, complicated tasks was not in keeping with the ISS training template. Therefore, the shuttle crews handled most of the burden. They trained until mere days before launch for the marathon sessions that began shortly after docking.

Shuttle Airlock

Between assembly flights STS-97 (2000) and STS-104 (2001)—the first time a crew was already aboard the ISS to host a shuttle and the flight when

Clayton Anderson
Astronaut on STS-117 (2007) and STS-131 (2010).
Spent 152 days on the International Space Station before returning on STS-120 (2007).

"Life was good on board the International Space Station (ISS). Time typically passed quickly, with much to do each day. This was especially true when an ISS crew prepared to welcome 'interplanetary guests'…or more specifically, a Space Shuttle crew! During my 5-month ISS expedition, our 'visitors from another planet' included STS-117 (my ride up), STS-118, and STS-120 (my ride down).

"While awaiting a shuttle's arrival, ISS crews prepared in many ways. We may have said goodbye to 'trash-collecting tugs' or welcomed replacement ships (Russian Progress, European Space Agency Automated Transfer Vehicle, and the Japanese Aerospace Exploration Agency H-II Transfer Vehicle) fully stocked with supplies. Just as depicted in the movies, life on the ISS became a little bit like Grand Central Station!

"Prepping for a shuttle crew was not trivial. It was reminiscent of work you might do when guests are coming to your home! ISS crews 'pre-packed…,' gathering loads of equipment and supplies no longer needed that must be disposed of or may be returned to Earth…like cleaning house! This wasn't just 'trash disposal'—sending a vehicle to its final rendezvous with the fiery friction of Earth's atmosphere. Equipment could be returned on shuttle to enable refurbishment for later use or analyzed by experts to figure out how it performed in the harsh environment of outer space. It was also paramount to help shuttle crews by prepping their spacewalking suits and arranging the special tools and equipment that they would need. This allowed them to 'jump right in' and start their work immediately after crawling through the ISS hatch! Shuttle flights were all about cramming much work into a short timeframe! The station crew did their part to help them get there!

Astronaut Clayton Anderson, Expedition 15 flight engineer, smiles for a photo while floating in the Unity node of the International Space Station.

"The integration of shuttle and ISS crews was like forming an 'All-Star' baseball team. In this combined form, wonderful things happened. At the moment hatches swung open, a complicated, zero-gravity dance began in earnest and a well-oiled machine emerged from the talents of all on board executing mission priorities flawlessly!

"Shuttle departure was a significant event. I missed my STS-117 and STS-118 colleagues as soon as they left! I wanted them to stay there with me, flying through the station, moving cargo to and fro, knocking stuff from the walls! The docked time was grand…we accomplished so much. To build onto the ISS, fly the robotic arm, perform spacewalks, and transfer huge amounts of cargo and supplies, we had to work together, all while having a wonderfully good time. We talked, we laughed, we worked, we played, and we thoroughly enjoyed each other's company. That is what camaraderie and 'crew' was all about. I truly hated to see them go. But then they were home…safe and sound with their feet firmly on the ground. For that, I was always grateful, yet I must admit that when a crew departed I began to think more of the things that I did not have in orbit, some 354 km (220 miles) above the ground.

"Life was good on board the ISS…I cherished every single minute of my time in that fantastic place."

the ISS Quest airlock was activated, respectively—the shuttle crews were hampered by a short-term geometry problem. The shuttle's airlock was part of the docking tunnel that held the two spacecraft together, so in that period the shuttle crew had to be on its side of the hatch during all such EVAs in case of an emergency departure. Further, the preparations for EVA required that the crew spend many hours at reduced pressure, which was accomplished prior to Quest by dropping the entire shuttle cabin pressure. Since the ISS was designed to operate at sea-level atmosphere, it was necessary to keep the shuttle and station separated by closed hatches while EVAs were in preparation or process. This hampered the transfer of internal cargos and other intravehicular activities.

International Space Station Airlock

On assembly flight 7A (STS-104), the addition of the joint airlock Quest allowed shuttle crews to work in continuous intravehicular conditions while their EVA members worked outside. Even in this airlock, shuttle crews continued to conduct the majority of ISS EVAs and shuttles provided the majority of the gases for this work. Docked shuttles could replenish the small volume of unrecoverable air that could not be compressed from the airlock. The prebreathe procedure of pure oxygen to the EVA crew also was supported by shuttle reserves through a system called Recharge Oxygen Orifice Bypass Assembly. This system was delivered on STS-114 (2005) and used for the first time on STS-121 (2006). Finally, the shuttle routinely repressurized the ISS high-pressure oxygen and nitrogen tanks and/or the cabin itself prior to leaving. The ISS rarely saw net losses in its on-board supplies, even in the midst of such intense operations. Fewer ISS consumables were thus used whenever a shuttle could support the EVAs.

The Shuttle as Crew Transport

Although many crews came and went aboard the Russian Soyuz rescue craft, the shuttle assisted the ISS crew rotations at the station during early flights. This shuttle-based rotation of ISS crew had several significant drawbacks, however, and the practice was abandoned in later flights. Launch and re-entry suits needed to be shared or, worse, spared on the Orbiter middeck to fit the arriving and departing crew member. Different Russian suits were used in the Soyuz rescue craft, so those suits had to make the manifest somewhere. Further, a special custom-fit seat liner was necessary to allow each crew member to safely ride the Soyuz to an emergency landing. This seat liner had to be ferried to the ISS with each new crew member who might use the Soyuz as a lifeboat. Thus, a lot of duplication occurred in the hardware required for shuttle-delivered crews.

Shuttle Launch Delays

As a shuttle experienced periodic delays of weeks or even months from its original flight plan, it was necessary to replan the activities of ISS crews who were expecting a different crew makeup. Down-going crews sometimes found their "tours of duty" had been extended. Arriving crews found their tours of duty shortened and their work schedule compressed. As the construction evolved, the shuttle carried a smaller fraction of the ISS crew.

Left photo: *Astronauts John Olivas (top) and Christer Fuglesang pose for a photo in the STS-128 (2009) Space Shuttle airlock.*
Right photo: *Astronauts Garrett Reisman (left) and Michael Good—STS-132 (2010)—pose for a photo between two extravehicular mobility units in the International Space Station (ISS) Quest airlock. By comparison, the Quest airlock is much larger and thus allows enough space for the prebreathe needed to prevent decompression sickness to occur in the airlock, isolated from the ISS.*

Michael Foale, PhD
Astronaut on STS-45 (1992), STS-56 (1993), STS-63 (1995), STS-84 (1997), and STS-103 (1999).
Spent 145 days on Russian space station Mir before returning on STS-86 (1997).
Spent 194 days as commander of Expedition 8 on the International Space Station (2003-2004).

On board the International Space Station, Astronaut Michael Foale fills a water microbiology bag for in-flight analysis.

"When we look back 50 years to this time, we won't remember the experiments that were performed, we won't remember the assembly that was done. What we will know was that countries came together to do the first joint international project, and we will know that that was the seed that started us off to the moon and Mars."

Whenever NASA scrubbed a launch attempt for even 1 day, the scrub disrupted the near-term plan on board the ISS. Imagine the shuttle point of view in such a scrub scenario: "We'll try again tomorrow and still run exactly the script we know."

Now imagine the ISS point of view in the same scenario: "We've been planning to take 12 days off from our routine to host seven visitors at our home. These visitors are coming to rehab our place with a major new home addition. We need to wrap up any routine life we've established and conclude our special projects and then rearrange our storage to let these seven folks move back and forth, start packing things for the visitors to take with them, and reconfigure our wiring and plumbing to be ready for them to do their work. Then we must sleep shift to be ready for them at the strange hour of the day that orbital mechanics says that they can dock. Two days before they are to get here, they tell us that they're not coming on that day. For the next week or so of attempts, they will be able to tell us only at the moment of launch that they will in fact be arriving 2 days later."

At that juncture, did ISS crew members sleep shift? Did they shut down the payloads and rewire for the shuttle's arrival? Did they try to cram in one more day of experiments while they waited? Did they pack anything at all? This was the type of dilemma that crews and planners faced leading up to every launch. Therefore, a few weeks before each launch, ISS planners polled the technical teams for the tasks that could be put on the "slip schedule," such as small tasks or day-long procedures that could be slotted into the plan on very short notice. Some of these tasks were complex, like tearing down a piece of exercise equipment and then refurbishing it; not the sort of thing they could just dive in and do without reviewing the procedures.

Shuttle Helps Build International Partnerships

Partnering With the Russians

It is hard to overstate the homogenizing but draconian effect that the shuttle initially had on all the original international partners who had joined the Freedom Space Station Program or who took part in other cooperative spaceflights and payloads. The shuttle was the only planned way to get their hardware and astronauts to orbit. Thus, "international integration" was decidedly one-sided as NASA engineers and operators worked with existing partners to meet shuttle standards.

Such standards included detailed specifications for launch loads capability, electrical grounding and power quality, radio wave emission and susceptibility limits, materials outgassing limits, flammability limits, toxicity, mold resistance, surface temperature limits, and tens of thousands of other shuttle standards. The Japanese H-II Transfer Vehicle and European Space Agency's (ESA's) Automated Transfer Vehicle were not expected until nearly a decade after shuttle began assembly of the ISS. Neither could carry crews, so all astronauts, cargoes, supplies, and structures had to play by shuttle's rules.

Then the Earth Moved

The Russians and Americans started working together with a series of shuttle visits to the Russian space station Mir. There was more at stake than technical standards. Leadership roles were more equitably distributed and cooperation took on a new diplomatic flavor in a true partnership.

In the era following the fall of the Berlin Wall (1989) along with the end of Soviet communism and the Soviet Union itself, the US government seized the possibility of achieving two key goals—the seeding of a healthy economy in Russia through valuable western contracts, and the prevention of the spread of the large and now-saleable missile and weapon technology to unstable governments from the expansive former Soviet military-industrial complex that was particularly cash-strapped. The creation of a joint ISS was a huge step toward each of those goals, while providing the former Freedom program with an additional logistics and crew transport path. It also provided the Russian government a huge boost in prestige as a senior partner in the new worldwide partnership. That critical role made Russian integration the dominant focus of shuttle integration, and it subsequently changed the entire US perspective on international spaceflight.

Two existing spacecraft were about to meet, and engineers in each country had to satisfy each other that it was safe for each vehicle to do so. Neither side could be compelled to simply accept the other's entire system of standards and practices. The two sides certainly could not retool their programs, even if they had wanted to accept new standards. Tens of thousands of agreements and compromises had to be reached, and quickly. Only where absolutely necessary did either side have to retest its hardware to a new standard. During the Mir Phase 1 Program, the shuttle encountered the new realities of cooperative spaceflight and set about the task of defining new ways of doing business.

It was difficult but necessary to compare every standard for mutual acceptability. In most cases, the intent of the constraint was instantly compatible and the implementation was close enough to sidestep an argument. The standards compatibility team worked tirelessly for 4 years to allow cross certification. This was an entirely new experience for the Americans.

As difficult as the technical requirements were, an even more fundamental issue existed in the documents themselves. The Russians had never published in English and, similarly, the United States had not published in Cyrillic, the alphabet of the Russian language. Chaos might immediately ensue in the computers that tracked each program's data.

Communicating With Multiple Alphabets

The space programs needed something robust to handle multiple alphabets, and they needed it soon. In other words, the programs needed more bytes for every character. Thus, the programs became early adopters of the system that several Asian nations had been forced to adopt as a national standard to capture the 6,000+ characters of kanji—pictograms of Chinese origin used in modern Japanese writing. The Universal Multiple-Octet Coded Character Set—known in one ubiquitous word processing environment as "Unicode" and standardized worldwide as International Standards Organization (ISO) Standard 10646—allowed all character sets of

Financial Benefits of the Space Shuttle for the United States

Just as the International Space Station (ISS) international agreements called for each partner to meet its obligations to share in common operations costs such as propellant delivery and reboost, the agreements also required each partner to bear the cost of delivering its contributions and payloads to orbit and encouraged use of barter. As a result, the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) took on the obligation to build some of the modules within NASA's contribution as payment in kind for the launch of their laboratories. In shifting the cost of development and spares for these modules to the international partners—and without taking on any additional financial obligation for the launch of the partner labs—NASA was able to provide much-needed fiscal relief to its capped "build-to-cost" development budget in the post-redesign years. The Columbus laboratory took a dedicated shuttle flight to launch. In return, ESA built Nodes 2 and 3 and some research equipment. The Japanese Experiment Module that included Kibo would take 2.3 shuttle flights to place in orbit. JAXA paid this bill by building the Centrifuge Accommodation Module (later deleted from the program by NASA after the Vision for Space Exploration refocused research priorities on the ISS) and by providing other payload equipment and a non-ISS launch.

the world to be represented in all desired fonts. Computers in space agencies around the world quickly modified to accept the new character ISO Standard, and instantly the cosmos was accessible to the languages of all nations. This also allowed a common lexicon for acronyms.

National Perceptions

The Russians had a highly "industrial" approach to operating a spacecraft. Their cultural view of a space station appeared to most Americans to be more as a facility for science, not necessarily a scientific wonder unto itself. Although the crews continued to be revered as Russian national heroes, the spacecraft on which they flew never achieved the kind of iconic status that the Space Shuttle or the ISS achieved in the United States. By contrast, the American public was more likely to know the name of the particular one of four Orbiters flying the current mission than the names of the crew members aboard.

Although the Soyuz was reliable, it was a small capsule—so small that it limited the size of crews that could use it as a lifeboat. All crew members required long stays in Russia to train for Soyuz and many Russian life-critical systems. This was in addition to their US training and short training stays with the other partners. Overall, however, the benefits of having this alternate crew and supply launch capability were abundantly clear in the wake of the Columbia (STS-107) accident in 2003. The Russians launched a Progress supply ship to the ISS within 24 hours and then launched an international crew of Ed Lu and Yuri Malenchenko exactly 10 weeks after the accident. Both crew members wore the STS-107 patch on their suits in tribute to their fallen comrades. After the Columbia accident, the Russians launched 14 straight uncrewed and crewed missions to continue the world's uninterrupted human presence in space before the shuttle returned to share in those duties.

Other Faces on the International Stage

All the while, teams of specialists from the Canadian Space Agency, Japanese Space Exploration Agency, Italian Space Agency, and ESA each worked side-by-side with NASA shuttle and station specialists at Kennedy Space Center to prepare their modules for launch aboard the shuttle. Shortly after the delivery of the ESA Columbus laboratory on STS-122 (2008) and the Japanese Kibo laboratory on STS-124 (2008), each agency's newly developed visiting cargo vehicle joined the fleet.

The Europeans had elected to dock their Automated Transfer Vehicle at the Russian end of the station, whereas the Japanese elected to berth their vehicle—the H-II Transfer Vehicle—to the station. The manipulation of the H-II Transfer Vehicle and its berthing to the ISS were similar to the experience of all previous modules that the shuttle had brought to the space station. The big change was that the vehicle had to be grabbed in free flight by the station arm—a trick previously only performed by the much more nimble shuttle arm. NASA ISS engineers and Japanese specialists worked for years with shuttle robotics veterans to develop this exotic procedure for the far-more-sluggish ISS.

The experience paid off. In the grapple of H-II Transfer Vehicle 1 in 2009, and following the techniques first pioneered by shuttle, the free-flight grapple and berth emerged as the attachment technique for the upcoming fleet of commercial space transports expected at the ISS.

> *"For Shuttle ESA was a junior partner, but now with ISS we are equal partners"* —**Volker Damann, ESA**

Canadian Space Agency

European Space Agency

Japan Aerospace Exploration Agency

National Aeronautics and Space Administration

РОСКОСМОС
Russian Federal Space Agency

From Shuttle-Mir to International Space Station—Crews Face Additional Challenges

The Shock of Long-Duration Spaceflights

NASA had very little experience with the realities of long-term flight. Since the shuttle's inception, the shuttle team had been accustomed to planning single-purpose missions with tight scripts and well-identified manifests. The shuttle went through time-critical stages of ascent and re-entry into Earth's atmosphere on every flight, with limited life-support resources aboard. Thus, the overall shuttle culture was that every second was crucial and every step was potentially catastrophic. It took a while for NASA to become comfortable with the concept of "time to criticality," where systems aboard a large station did not necessarily have to have immediate consequences. These systems often didn't even have immediate failure recovery requirements.

For instance, the carbon dioxide scrubber or the oxygen generator could be off for quite some time before the vast station atmosphere had to be adjusted. What mattered most was flexibility in the manifest to get needed parts up to space. The shuttle's self-contained missions with well-defined manifests were not the best experience base for this pipeline of supplies.

New Realities

Russia patiently guided shuttle and then International Space Station (ISS) teams through these new realities. The delivery of parts, while always urgent, was handled in stride and with great flexibility. Their flexible manifesting practices were a shock to veteran shuttle planners. The Soyuz and the uncrewed Progress were particularly reliable at getting off the pad on time, come rain, sleet, wind, or clouds. This reliability came from the Russians' simple capsule-on-a-missile heritage, and allowed mission planners to pinpoint spacecraft arrivals and departures months in advance. The cargos aboard the Progress, however, were tweaked up until the final day as dictated by the needs at the destination, just as overnight packages are identified and manifested until the final minutes aboard a regularly scheduled airline flight. In contrast, the shuttle's heritage was one of well-defined cargos with launch dates that were weather-dependent.

Prior to the Mir experience, the shuttle engineers had maintained stringent manifesting deadlines to keep the weight and balance of the Orbiter within tight constraints and to handle the complex task of verifying the structural loads during ascent for the unique mix of items bolted to structures that would press against their fittings in the payload bay in nonlinear ways. Nonlinearity was a difficult side effect of the way that heavy loads had to be distributed. The load that each part of the structure would see was completely dependent on the history of the loads it

Unheeded Skylab Lesson: Take a Break!

The US planners might be applauded for their optimism and ambition in scheduling large workloads for the crew, but they had missed the lesson of a previous generation of planners resulting from the "Skylab Rebellion." This rebellion occurred when the Skylab-4 crew members suddenly took a day off in response to persistent over-tasking by the ground planners during their 83-day mission. From "Challenges of Space Exploration" by Marsha Freeman:

"At the end of their sixth week aboard Skylab, the third crew went on strike. Commander Carr, science pilot Edward Gibson, and Pogue stopped working, and spent the day doing what they wanted to do. As have almost all astronauts before and after them, they took the most pleasure and relaxation from looking out the windows at the Earth, taking a lot of photographs. Gibson monitored the changing activity of the Sun, which had also been a favourite pastime of the crew."

It is both ironic and instructive to note that during the so-called "rebellion," the crew members actually filled their day off with intellectually stimulating activities that were also of scientific use. Although these activities of choice were not the ones originally scripted, they were a form of mental relaxation for these exhausted but dedicated scientists. The crew members of Skylab-4 just needed some time to call their own.

had seen recently. If a load was moved, removed, or added to any of the cargo, it could invalidate the analysis.

This was an acceptable way of operating a stand-alone mission until one faced a manifesting crisis such as the loss of an oxygen generator or a critical computer on the space station.

Shortly after starting the Mir Phase I Program, the pressures of emergency manifest demands led to a new suite of tools and capabilities for the shuttle team. Engineers developed new computer codes and modeling techniques to rapidly reconfigure the models of where the masses were attached and to show how the shuttle would respond as it shook during launch. Items as heavy as 250 kg (551 pounds) were swapped out in the cargo within months or weeks of launch. In some cases, items as large as suitcases were swapped out within hours of launch.

During the ISS Program, Space Transportation System (STS)-124 carried critical toilet repair parts that had been hand-couriered from Russia during the 3-day countdown. The parts had to go in about the right place and weigh about the same amount as parts removed from the manifest for the safety analysis to be valid. Nevertheless, on fewer than 72 hours' notice, the parts made it from Moscow to space aboard the shuttle.

Training

The continuous nature of space station operations led to significant philosophical changes in NASA's training and operations. A major facet of the training adjustment had to do with the emotional nature of long-duration activities. Short-duration shuttle missions could draw on the astronauts' emotional "surge" capability to conduct operations for extended hours, sleep shift as necessary, and develop proficiency in tightly scripted procedures. It was like asking performers to polish a 15-day performance, with up to 2 years of training to perfect the show. Astronauts spent about 45 days of training for each day on orbit. They would have time to rest before and after the mission, with short breaks, if any, included in their timeline.

That would be a lot of training for a half-year ISS expedition. The crew would have to train for over 22 years under that model. One way to put the training issue into perspective is to realize that most ISS expedition members expect to remain about 185 days in orbit. This experience, per crew member, is equal to the combined Earth orbital, lunar orbital, and trans-lunar experience accumulated by all US astronauts until the moment the United States headed to the moon on Apollo 11. Thus, each such Mir (or ISS) crew member matched the accumulated total crew experience of the first 9 years of the US space effort.

With initially three and eventually six long-duration astronauts permanently aboard the ISS, the US experience in space grew at a rapidly expanding rate. By the middle of ISS Expedition 5

Posing in Node 2 during STS-127 (2009)/Expedition 20 Joint Operations: ***Front row (left to right):*** *Expedition 20 Flight Engineer Robert Thirsk (Canadian Space Agency); STS-127 Commander Mark Polansky; Expedition 19/20 Commander Gennady Padalka (Cosmonaut); and STS-127 Mission Specialist David Wolf.* ***Second row (left to right):*** *Astronaut Koichi Wakata (Japanese Aerospace Exploration Agency); Expedition 19/20 Flight Engineer Michael Barratt; STS-127 Mission Specialist Julie Payette (Canadian Space Agency); STS-127 Pilot Douglas Hurley; and STS-127 Mission Specialist Thomas Marshburn.* ***Back row (left to right):*** *Expedition 20/21 Flight Engineer Roman Romanenko (Cosmonaut); STS-127 Mission Specialist Christopher Cassidy; Expedition 20 Flight Engineer Timothy Kopra; and Expedition 20 Flight Engineer Frank De Winne (European Space Agency).*

(2002), only 2½ years into the ISS occupation, the ISS expedition crews had worked in orbit longer than crews had worked aboard all other US-operated space missions in the previous 42 years, including the shuttle's 100+ flights. Clearly, the training model had to change.

Shuttle operations were like a decathlon of back-to-back sporting events—all intense, all difficult, and all in a short period of time—while space station operations were more like an ongoing trek of many months, requiring a different kind of stamina. ISS used the "surge" of specialized training by the shuttle crews to execute most of the specialized extravehicular activities (EVAs) to assemble the vehicle. The station crew training schedule focused on the necessary critical-but-general skills to deal with general trekking as well as a few planned specific tasks for that expedition. Only rarely did ISS crews take on major assembly tasks in the period between shuttle visits (known in the ISS Program as "the stage").

Another key in the mission scripting and training problem was to consider when and how that "surge capability" could be requested of the ISS crew. That all depended on how long that crew would be expected to work at the increased pace, and how much rest the crew members had had before that period. Nobody can keep competing in decathlons day after day; however, such periodic surges were needed and would need to be compensated by periodic holidays and recovery days.

Humans need a balanced workday with padding in the schedule to freshen up after sleep, read the morning news, eat, exercise, sit back with a good movie, write letters, create, and generally relax before sleep, which should be a minimum of 8 hours per night for long-term health. The Russians had warned eager US mission planners that their expectations of 10 hours of productive work from every crew member every day, 6 days per week was unrealistic. A 5-day workweek with 8-hour days (with breaks), plus periodic holidays, was more like it.

Different Attitude and Planning of Timelines

The ISS plan eventually settled in exactly as the veteran Russian planners had recommended. That is not to say that ISS astronauts took all the time made available to them for purely personal downtime. These are some of the galaxy's most motivated people, so several "unofficial" ways evolved to let them contribute to the program beyond the scripted activities, but only on a voluntary basis.

The ISS planners ultimately learned one productivity technique from the Russians and the crews invented another. At the Russians' suggestion, the ground added a "job jar" of tasks with no particular deadline. These tasks could occupy the crew's idle hours. If a job-jar item had grown too stale and needed doing soon, it found its way onto the short-term plan. Otherwise, the job jar (in reality, a computer file of good "things to do") was a useful means to keep the crew busy during off-duty time. The crew was inventive, even adding new education programs to such times.

Tasks vs. Skills

Generally, training for both the ground and the crew was skills oriented for station operations and task oriented for shuttle operations. The trainers grew to rely on electronic file transfers of intricate procedures, especially videos, to provide specialized training on demand. These were played on on-board notebook computers for the station crew but occasionally for the shuttle crews as well. This training was useful in executing large tasks on the slip schedule, unscheduled maintenance, or on contingency EVAs scheduled well after the crew arrival on station.

Station crews worked on generic EVA skills, component replacement techniques, maintenance tasks, and general robotic manipulation skills. Many systems-maintenance skills needed to be mastered for such a huge "built environment." The station systems needed to closely replicate a natural existence on Earth, including air and water revitalization, waste management, thermal and power control, exercise, communications and computers, and general cleaning and organizing.

The 363-metric-ton (400-ton) ISS had a lot of hardware in need of routine inspection and maintenance that, in shuttle experience, was the job of ground technicians—not astronauts. These systems were the core focus of ISS training. There were multiple languages and cultures to consider (most crew members were multilingual) and usually two types of everything: two oxygen generators; two condensate collectors; two carbon dioxide separators; multiple water systems; different computer architectures; and even different food rations. Each ISS crew member then trained extensively for the specific payloads that would be active during his or her stay on orbit. Scores of payloads needed operators and human subjects. Thus, it took about 3 years to prepare an astronaut for long-duration flight.

Major Missions of Shuttle Support

By May 2010, the shuttle had flown 34 missions to the International Space Station (ISS). Although no human space mission can be called "routine," some missions demonstrated particular strengths of the shuttle and her crews—sometimes in unplanned heroics. A few such missions are highlighted to illustrate the high drama and extraordinary achievement of the shuttle's 12-year construction of the ISS.

STS-88—The First Big Step

The shuttle encountered the full suite of what would soon be routine challenges during its first ISS assembly mission—Space Transportation System (STS)-88 (1998). The narrow launch window required a launch in the middle of the night. This required a huge sleep shift. The cargo element (Node 1 with two of the three pressurized mating adapters already attached) needed to be warmed in the payload bay for hours before launch to survive until the heaters could be activated after the first extravehicular activity (EVA). The rendezvous was conducted with the cargo already erected in a 12-m (39-ft) tower above the Orbiter docking mechanism. This substantially changed the flight characteristics of the shuttle and blocked large sections of the sky as seen from the Orbiter's high-gain television antenna.

The rendezvous required the robotic capture of the Russian-American bridge module: the FGB named Zarya. (Zarya is Russian for "sunrise." "FGB" is a Russian acronym for the generic class of spacecraft—a Functional Cargo Block—on which the Zarya had been slightly customized.) Due to the required separation of the robotic capture of the FGB from the shuttle's cargo element, Space Shuttle Endeavour needed to extend its arm nearly to its limit just to reach the free-flying FGB. Even so, the arm could only touch Zarya's forward end.

In the shuttle's first assembly act of the ISS Program, Astronaut Nancy Currie grappled the heaviest object the Shuttle Robotic Arm had ever manipulated, farther off-center than any object had ever been manipulated. Because of the blocked view of the payload bay (obstructed by Node 1 and the Pressurized Mating Adapter 2), she completed this grapple based on television cues alone—another first.

After the FGB was positioned above the top of the cargo stack, the shuttle used new software to accommodate the large oscillations that resulted from the massive off-center object as it moved. Next, the shuttle crew reconnected the Androgynous Peripheral Docking System control box to a second Androgynous Peripheral Docking System cable set and prepared to drive the interface between the Pressurized Mating Adapter 1 and the FGB. Finally, Currie limped the manipulator arm while Commander Robert Cabana engaged Endeavour's thrusters and flew the Androgynous Peripheral Docking System halves together. The successful mating was followed by a series of three EVAs to link the US and Russian systems together and to deploy two stuck Russian antennas.

This process required continuous operation from two control centers, as had been practiced during the Mir Phase I Program.

Before departing, the shuttle (with yet another altitude-control software configuration) provided a substantial reboost to the fledgling ISS. At a press conference prior to the STS-88 mission, Lead Flight Director Robert Castle called it "…the most difficult mission the shuttle has ever had to fly, and the simplest of all the missions it will have to do in assembling the ISS." He was correct. The shuttle began an ambitious series of firsts, expanding its capabilities with nearly every assembly mission.

STS-97—First US Solar Arrays

STS-97 launched in November 2000 with one of its heaviest cargos: the massive P6 structural truss; three radiators; and two record-setting solar array wings. At nearly 300 m^2 (3,229 ft^2) each, the solar wings could each generate more power than any spacecraft in history had ever used.

After docking in an unusual-but-necessary approach corridor that arrived straight up from below the ISS, Endeavour and her US/Canadian crew gingerly placed the enormous mast high above the Orbiter and seated it with the first use of the Segment-to-Segment Attachment System.

The first solar wing began to automatically deploy as scheduled, just as the new massive P6 structure began to block the communications path to the Tracking and Data Relay Satellites. The software dutifully switched off the video broadcast so as not to beam high-intensity television signals into the structure. When the video resumed, ground controllers saw a disturbing "traveling wave" that violently shook the thin wing as it unfolded. Later, it was determined that lubricants intended to assist in deployment instead added enough surface tension to act as a delicate adhesive. This subtle sticking kept the fanfolds together in irregular clumps rather than letting them gracefully unfold out of the storage box. The clumps would be carried outward in the blanket and then would release rapidly when tension built up near the final tensioning of the array.

Robert Cabana
Colonel, US Marine Corps (retired).
Pilot on STS-41 (1990) and STS-53 (1992).
Commander on STS-65 (1994) and STS-88 (1998).

Reflections on the International Space Station

"Of all the missions that have been accomplished by the Space Shuttle, the assembly of the International Space Station (ISS) certainly has to rank as one of the most challenging and successful. Without the Space Shuttle, the ISS would not be what it is today. It is truly a phenomenal accomplishment, especially considering the engineering challenge of assembling hardware from all parts of the world, on orbit, for the first time and having it work. Additionally, the success is truly amazing when one factors in the complexity of the cultural differences between the European Space Agency and all its partners, Canada, Japan, Russia, and the United States.

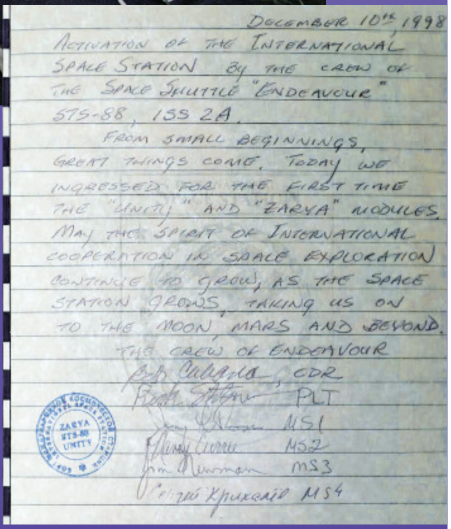
"When the Russian Functional Cargo Block, also known as Zarya, which means sunrise in Russian, launched on November 20, 1998, it paved the way for the launch of Space Shuttle Endeavour carrying the US Node 1, Unity. The first assembly mission had slipped almost a year, but in December 1998, we were ready to go. Our first launch attempt on December 3 was scrubbed after counting down to 18 seconds due to technical issues with the Auxiliary Power Units. It was a textbook count for the second attempt on the night of December 4, and Endeavour performed flawlessly.

"Nancy Currie carefully lifted Unity out of the bay and we berthed it to Endeavour's docking system with a quick pulse of our engines once it was properly positioned. With that task complete, we set off for the rendezvous and capture of Zarya. The handling qualities of the Orbiter during rendezvous and proximity operations are superb and amazingly precise. Once stabilized and over a Russian ground site, we got the 'go' for grapple, and Nancy did a great job on the arm capturing Zarya and berthing it to Unity high above the Orbiter. This was the start of the ISS, and it was the shuttle, with its unique capabilities, that made it all possible.

"On December 10, Sergei Krikalev and I entered the ISS for the first time. What a unique and rewarding experience it was to enter this new outpost side by side. It was a very special 2 days that we spent working inside this fledgling space station.

Robert Cabana (left), mission commander, and Sergei Krikalev, Russian Space Agency mission specialist, helped install equipment aboard the Russian-built Zarya module and the US-built Unity module.

"We worked and talked late into the night about what this small cornerstone would become and what it meant for international cooperation and the future of exploration beyond our home planet. I made the first entry into the log of the ISS that night, and the whole crew signed it the next day. It is an evening I'll never forget.



DECEMBER 10th, 1998
ACTIVATION OF THE INTERNATIONAL SPACE STATION BY THE CREW OF THE SPACE SHUTTLE "ENDEAVOUR" STS-88, ISS 2A.
FROM SMALL BEGINNINGS, GREAT THINGS COME. TODAY WE INGRESSED FOR THE FIRST TIME THE "UNITY" AND "ZARYA" MODULES. MAY THE SPIRIT OF INTERNATIONAL COOPERATION IN SPACE EXPLORATION CONTINUE TO GROW, AS THE SPACE STATION GROWS, TAKING US ON TO THE MOON, MARS AND BEYOND.
THE CREW OF ENDEAVOUR
Bob Cabana, CDR
PLT
MS1
MS2
MS3
MS4

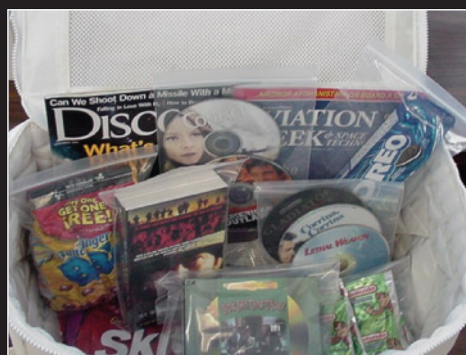
ZARYA STS-88 UNITY

"Since that flight, the ISS has grown to reach its full potential as a world-class microgravity research facility and an engineering proving ground for operations in space. As it passes overhead, it is the brightest star in the early evening and morning skies and is a symbol of the preeminent and unparalleled capabilities of the Space Shuttle."

Psychological Support—

Lessons From Shuttle-Mir to International Space Station

Using crew members' experiences from flying on Mir long-duration flights, NASA's medical team designed a psychological support capability. The Space Shuttle began carrying psychological support items to the International Space Station (ISS) from the very beginning. Prior to the arrival of the Expedition 1 crew, STS-101 (2000) and STS-106 (2000) pre-positioned crew care packages for the three crew members. Subsequently, the shuttle delivered 36 such packages to the ISS. The shuttle transported approximately half of all the packages that were sent to the ISS during that era. The contents were tailored to the individual (and crew). Packages contained music CDs, DVDs, personal items, cards, pictures, snacks, specialty foods, sauces, holiday decorations, books, religious supplies, and other items.



The shuttle delivered a guitar (STS-105 [2001]), an electronic keyboard (STS-108 [2001]), a holiday tree (STS-112 [2002]), external music speakers (STS-116 [2006]), numerous crew personal support drives, and similar nonwork items. As communications technology evolved, the shuttle delivered key items such as the Internet Protocol telephones.

The shuttle also brought visitors and fellow space explorers to the dinner table of the ISS crews. In comparison to other vehicles that visited the space station, the shuttle was self-contained. It was said that when the shuttle visited, it was like having your family pull up in front of your home in their RV—they arrived with their own independent sleeping quarters, galley, food, toilet, and electrical power. This made a shuttle arrival a very welcome thing.

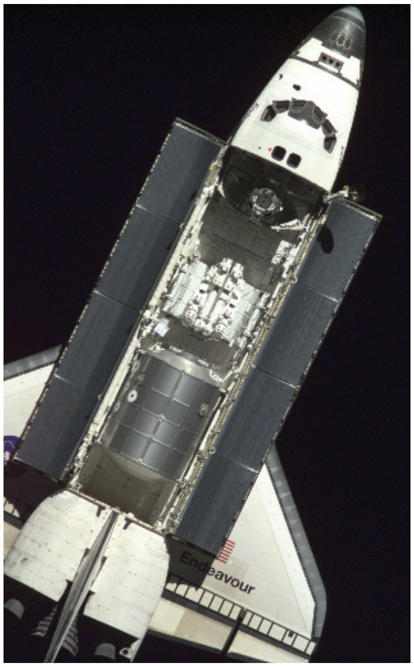
The deployment was stopped and a bigger problem became apparent. The wave motion had dislodged the key tensioning cable from its pulley system and the array could not be fully tensioned. The scenario was somewhat like a huge circus tent partially erected on its poles, with none of the ropes pulled tight enough to stretch the tent into a strong structure. The whole thing was in danger of collapsing, particularly if the shuttle fired jets to leave. Rocket plumes would certainly collapse the massive wings. If Endeavour left without tensioning the array, another shuttle might never be able to arrive unless the array was jettisoned.

Within hours, several astronauts and engineers flew to Boeing Rocketdyne in Canoga Park, California, to develop special new EVA techniques with the spare solar wing. A set of tools and at least three alternate plans were conceived in Houston, Texas, and in California. By the time the crew woke up the next morning, a special EVA had been scripted to save the array. Far beyond the reach of the Shuttle Robotic Arm, astronauts Joseph Tanner and Carlos Noriega crept slowly along the ISS to the array base and gently rethreaded the tension cable back onto the pulleys. They used techniques developed overnight in California that were relayed in the form of video training to the on-board notebook computers.

Meanwhile, engineers rescripted the deployment of the second wing to minimize the size of the traveling waves. The new procedures worked. As STS-97 departed, the ISS had acquired more electric power than any prior spacecraft and was in a robust configuration, ready to grow.

STS-100—An Ambitious Agenda, and an Unforeseen Challenge

STS-100 launched with a four-nation crew in April 2001 to deliver the Space Station Robotic Arm and the Raffaello Italian logistics module with major experiments and supplies for the new US Destiny laboratory, which had been delivered in February. The Space Station Robotic Arm deployed worked well, guided by Canada's first spacewalker, Chris Hadfield. Hadfield reconnected a balky power cable at the base of the Space Station Robotic Arm to give the arm the required full redundancy.



Raffaello, the Italian logistics module, flies in the payload bay on STS-100 in 2001.

Raffaello was successfully berthed and the mission went smoothly until a software glitch in the evolving ISS computer architecture brought all ISS communications to a halt, along with the capability of the ground to command and control the station. Coordinating through the shuttle's communications systems, the station, shuttle, and ground personnel organized a dramatic restart of the ISS.

A major control computer was rebuilt using a payload computer's hard drive, while the heartbeat of the station was maintained by a tiny piece of rescue software—appropriately called "Mighty Mouse"—in the lowest-level computer on the massive spacecraft. Astronaut Susan Helms directly commanded the ISS core computers through a notebook computer. That job was normally assigned to Mission Control. Having rescued the ISS computer architecture, the ISS crew inaugurated the new Space Station Robotic Arm by using it to return its own delivery pallet to Endeavour's cargo bay. Through a mix of intravehicular activity, EVA, and robotic techniques shared across four space agencies, the ISS and Endeavour each ended the ambitious mission more capable than ever.

STS-120—Dramatic Accomplishments

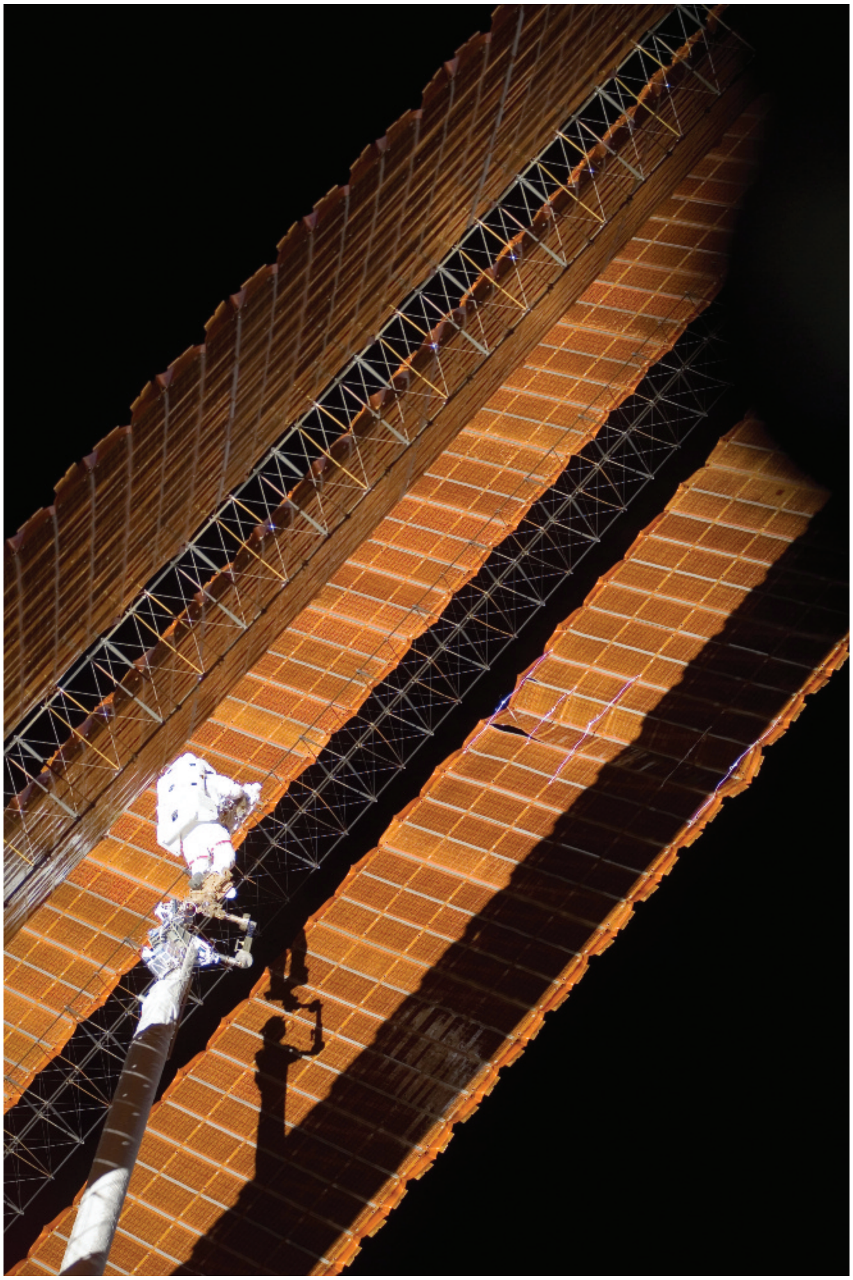
By 2007, with the launch of STS-120, ISS construction was in its final stages. Crew members encountered huge EVA tasks in several previous flights, usually dealing with further problems in balky ISS solar arrays. A severe Russian computer issue had occurred during flight STS-117 in June of that year, forcing an international problem resolution team to spring into action while the shuttle took over attitude control of the station.

STS-120, however, was to be one for the history books. It was already historic in that by pure coincidence both the shuttle and the station were commanded by women. Pamela Melroy commanded Space Shuttle Discovery and Peggy Whitson commanded the ISS. Further, the Harmony connecting node would need to be relocated during the stage in a "must succeed" EVA. During that EVA, the ISS would briefly be in an interim configuration where the shuttle could not dock to the ISS. On this flight, the ISS would finally achieve the full complement of solar arrays and reach its full width.

Shortly after the shuttle docked, the ISS main array joint on the starboard side exhibited a problem that was traced to crushed metal grit from improperly treated bearing surfaces that fouled the whole mechanism. While teams worked to replan the mission to clean and lubricate this critical joint, a worse problem came up. The outermost solar array ripped while it was being deployed. The wing could not be retracted or further deployed without sustaining greater damage. It would be destroyed if the shuttle tried to leave. The huge Space Station Robotic Arm could not reach the distant tear, and crews could not safely climb on the 160-volt array to reach the tear.

In an overnight miracle of cooperation, skill, and ingenuity, ISS and shuttle engineers developed a plan to extend the Space Station Robotic Arm's reach using the Orbiter Boom Sensor System with an EVA astronaut on the end. The use of the boom on the shuttle's arm for contingency EVA had been

Astronaut Pamela Melroy (left), STS-120 (2007) commander, and Peggy Whitson, Expedition 16 commander, pose for a photo in the Pressurized Mating Adapter of the International Space Station as the shuttle crew members exit the station to board Discovery for their return trip home.



While anchored to a foot restraint on the end of the Orbiter Boom Sensor System, Astronaut Scott Parazynski, STS-120 (2007), assesses his repair work as the solar array is fully deployed during the mission's fourth session of extravehicular activity while Discovery is docked with the International Space Station. During the 7-hour, 19-minute spacewalk, Parazynski cut a snagged wire and installed homemade stabilizers designed to strengthen the damaged solar array's structure and stability in the vicinity of the damage. Astronaut Douglas Wheelock (not pictured) assisted from the truss by keeping an eye on the distance between Parazynski and the array.

validated on the previous flight. The new technique using the Space Station Robotic Arm and boom would barely reach the damaged area with the tallest astronaut in the corps—Scott Parazynski—at its tip in a portable foot restraint. This technique came with the risk of potential freezing damage to some instruments at the end of the Orbiter Boom Sensor System. Overnight, Commander Whitson and STS-120 Pilot George Zamka manufactured special wire links that had been specified to the millimeter in length by ground crews working with a spare array.

In one of the most dramatic repairs (and memorable images) in the history of spaceflight, Parazynski, surrounded by potentially lethal circuits, rode the boom and arm combination on a record-tying fifth single-mission EVA to the farthest edge of the ISS. Once there, he carefully "stitched" the vast array back into perfect shape and strength with the five space-built links.

These few selected vignettes cannot possibly capture the scope of the ISS assembly in the vacuum of space. Each shuttle mission brought its own drama and its own major contributions to the ISS Program, culminating in a new colony in space, appearing brighter to everyone on Earth than any planet. This bright vision would never have been possible without the close relationship—and often unprecedented cooperative problem solving—that ISS enjoyed with its major partner from Earth.

The International Space Station and Space Shuttle Endeavour, STS-135 (2011)—as photographed by European Space Agency astronaut Paolo Nespoli from aboard the Russian Soyuz spacecraft—following completion of space station assembly.

Summary

When humans learn how to manipulate any force of nature, it is called “technology,” and technology is the fabric of the modern world and its economy. One such force—gravity—is now known to affect physics, chemistry, and biology more profoundly than the forces that have previously changed humanity, such as fire, wind, electricity, and biochemistry. Humankind’s achievement of an international, permanent platform in space will accelerate the creation of new technologies for the cooperating nations that may be as influential as the steam engine, the printing press, and fire. The shuttle carried the modules of this engine of invention, assembled them in orbit, provided supplies and crews to maintain it, and even built the original experience base that allowed it to be designed.

Over the 12 years of coexistence, and even further back in the days when the old Freedom design was first on the drawing board, the International Space Station (ISS) and Space Shuttle teams learned a lot from each other, and both teams and both vehicles grew stronger as a result. Like a parent and child, the shuttle and station grew to where the new generation took up the journey while the accomplished veteran eased toward retirement.

The shuttle’s true legacy does not live in museums. As visitors to these astounding birds marvel up close at these engineering masterpieces, they need only glance skyward to see the ongoing testament to just a portion of the shuttles’ achievements. In many twilight moments, the shuttle’s greatest single payload and partner—the stadium-sized ISS—flies by for all to see in a dazzling display that is brighter than any planet.