2

The Shuttle-ISS Assembly Missions

Once rocket craft capable of ferrying loads to and from the terminal orbit have been successfully demonstrated, the building [of a space station] is estimated to last ten years

Kenneth W. Gatland and Anthony M. Kunesch,
from *Space Travel*, 1953

A review of human space activities of 2011 reveals that it was a milestone year in many ways. April 12 celebrated the 50th anniversary of the launch of the world's first manned space flight. Since then, more than 500 individuals from around the world had ventured into space on over 300 missions lasting from a few brief hours, to several weeks and up to fourteen months. Five decades after Yuri Gagarin's 108 min, single orbit of Earth, a permanent human presence was being maintained by multi-national crews on board the International Space Station. In September, China, the new player in the field of human space exploration, had launched its first unmanned space laboratory, named Tiangong, and they would later demonstrate their automated rendezvous and docking capabilities during the unmanned Shenzhou 8 mission prior to sending their first crew to the station in 2012. It could be said, therefore, that 2011 was a year that celebrated past successes while looking towards future prospects.

It was also the year in which the majority of the assembly and outfitting of the ISS was finished and the American Space Shuttle made its final flights. After thirty years and 135 missions, Shuttle orbital operations came to a close. Since 1995 a significant number of these missions (over one third of the total) had been associated with space station operations. The Shuttle-Mir program involved one rendezvous mission to the Russian space station, nine docking missions, and a solo flight. Later, a further thirty-seven dockings were executed at the ISS. Across both programs, all of the attempted dockings were successful. It was a remarkable achievement over sixteen years, thanks to the efforts of dedicated teams of workers on the ground and in space.

D.J. Shayler, *Assembling and Supplying the ISS*, Springer Praxis Books,
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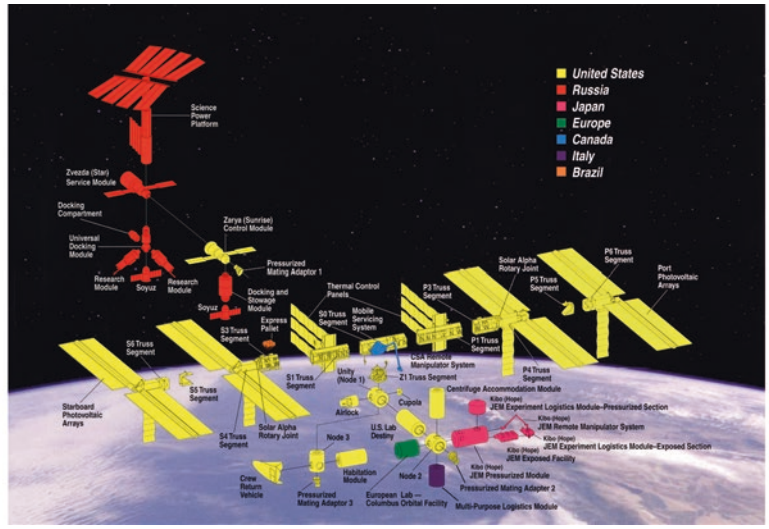


A 1999 image showing the original components intended for the International Space Station prior to budget cuts.

PAGES FROM HISTORY

The ISS has existed for almost two decades. Remarkably, it took almost as long from President Reagan's authorization in January 1984 for NASA to build a space station to the launch of the first hardware in November 1998. Beginning in the 1960s, even as it was developing Apollo to take astronauts to the Moon, and through the 1970s when it was developing the Space Shuttle, the space agency had devoted considerable effort to debating, designing, proposing, costing, and repeatedly redesigning a large variety of stations it imagined might host potentially multi-national crews. At the time of writing this book, the ISS is hosting its 50th long-duration crew, and with agreement to operate it until at least 2024 there is the potential for the 100th crew to take up residence there; a remarkable achievement.

As daring as the pioneering Vostok, Voskhod, Mercury, and Gemini programs were, and as inspiring as Apollo became, it is the experiences of the crews of Salyut, Skylab, Mir and now the ISS that will provide the foundation for even greater achievements in space. There is tremendous potential for sustained human presence in space, for a return to the Moon, and for ventures deeper into the solar system. One vital key for unlocking this potential was the ability of the Shuttle to expand operations involving Mir and then to assemble and maintain the ISS.

Although NASA did not possess extensive space station experience, for several years Shuttle missions had been developing the techniques and procedures required to support station assembly. A three-phase program was devised to address this shortfall. Phase-I was to include Shuttle missions docking at the Russian Mir space station. Phase-II was to see sufficient flights of the Shuttle and other spacecraft to develop the core of the ISS to the

point at which a resident crew could remain aboard without requiring a Shuttle to be present with consumables. Finally, Phase-III would see a number of Shuttle missions expand the station, particularly by the addition of power systems, science and habitation modules, crew facilities, and the supplies to make the ISS an operational laboratory for research into the microgravity environment.

SHUTTLE MISSIONS TO CREATE THE ISS (PHASE- II)

In December 1998, Shuttle flight operations under the International Space Station program finally began. This was some four years after the plan agreed following the initial authorization by President Ronald Reagan had scheduled the construction of Space Station Freedom to be *finished*. During the first eighteen months, progress was slow due in part to waiting for Russia to launch Zvezda as the second of the two core modules but also due to ongoing problems with the electrical wiring and main engines of the Shuttle fleet.

The objective of the early missions was to create the core of the station as a facility capable of hosting a three-person resident crew without a Shuttle attached. This core station would include research facilities on board, independent access for EVA at the station, and sufficient power resources and consumables for such activities. The next step would be to expand the 'backbone' truss to support both additional solar arrays to increase the power supply and radiator panels to regulate heat. The third phase would add further habitation and laboratory modules, as well as enhanced robotics, to enable the station to support six-person resident crews. The early crews would be comprised only of Russian cosmonauts and American astronauts. Command of the station would alternate between these two nations. Once the station was expanded with laboratories from Europe and Japan and could support six there would finally be opportunities for representatives from the European, Canadian and Japanese space agencies to serve on the station, making it a truly international resource.

The Shuttle was essential to this plan, primarily owing to its capacity to deliver the required hardware to the station. It could also serve as a major logistics and resupply craft, a resident crew taxi, and a garbage truck for returning unwanted items to Earth. These roles would be supported later in the program by other vessels. From 2000 the Russian Soyuz supplemented crew transport duties and served as an always-available Crew Rescue Vehicle, while the unmanned Progress version of that ship assisted with logistics supply and waste disposal. The latter tasks were further supplemented by the ESA Automated Transfer Vehicle (ATV) beginning in 2008 and by the Japanese H-II Transfer Vehicle (HTV) in 2009. But in the early stages the sheer volume of material that was required to stock up the station, install the scientific hardware, and replenish the supplies could only be transported by the Shuttle.

The other essential aspect of the Shuttle was its reusability. In addition to its cargo capacity of several tons (vastly superior to that of the Soyuz of about 110 lb or 50 kg), the large volume of the payload bay and pressurized modules could transport surplus material and, most importantly, experiment samples and data back to Earth. While the automated Progress, ATV, and HTV resupply ships were extremely useful, they were designed to burn up in the atmosphere during re-entry, destroying anything they were carrying.

Following the retirement of the Shuttle fleet, the US cargo delivery capacity was taken up by commercial enterprises, initially with the Dragon spacecraft in 2012 and the Cygnus in 2013. The Cygnus carrier burns up in the atmosphere. The Dragon can return cargo to Earth, although not as much as the Shuttle could accommodate.

The Shuttle launch manifest and assembly sequence changed several times over the course of the program. There were a variety of reasons, with the foremost being delays in production of hardware for the station, difficulties preparing and launching Shuttles, the loss of Columbia and the long recovery from that tragedy, and budgetary changes across several of the partner nations (as well as the US). There was also a lack of clear direction in America concerning long-term planning for programs beyond the Shuttle.

What follows is a brief summary of Shuttle-ISS missions that made it through this background and actually flew.

1998: Towards the end of the year, the physical assembly of the ISS began with the launch of the first core module by Russia and the first docking node by the USA. From November 1998 through to October 2000, between the launch of the Control Module and the first resident crew (Expedition One, or EO-1), the pre-residency missions were flown under the 'Expedition Zero' banner. For NASA, this included the flights of STS-88, -96, -101, -106 and -92.[*]

STS-88, Endeavour: 1st ISS Assembly Flight 2A (December 4–15, 1998): This first flight in the Shuttle assembly series was actually the second launch of the ISS program because the Russian Zarya ('Dawn') Control Module had been launched unmanned a fortnight earlier from the Baikonur Cosmodrome in Kazakhstan using a Proton rocket. The primary mission of STS-88 was to rendezvous with Zarya in order to mate it with the 'Unity' docking node. On December 5, Unity, which featured six ports to facilitate expansion of the American segment by subsequent flights, was lifted from its stowage using the RMS and then securely attached to the Shuttle docking system located in the front of the payload bay. The following day the crew guided Endeavour to rendezvous with Zarya, to permanently mount Unity on the forward docking port of that module. Three spacewalks completed the attachment and activation of the combined structure. Inside, the crew removed launch bolts and restraints and inspected the interiors of both modules to confirm their readiness to support further activities. It was a good start to a long and complicated program.

1999: Delays finishing Russian hardware and various problems with the Shuttle fleet meant that only one Shuttle mission visited the ISS during this year, frustrating attempts to complete the core configuration and begin an early residency. The good start seen at the close of 1998 was not followed up throughout 1999 and most of 2000.

STS-96, Discovery: 2nd ISS Assembly Flight 2A (May 27– June 6, 1999): Six months after the initial Shuttle-ISS mission, this second launch was the first dedicated logistics mission to start the delivery of additional hardware and supplies. It was a direct follow-on to STS-88, which could not have carried both the Unity Node and all the necessary early logistics. STS-96 became the first vehicle to physically dock with the station. It was also the only Shuttle-ISS mission in 1999, primarily due to delays in launching the Russian

[*] Note that Shuttle missions were not flown in the strict order of their numerical designations.

1998: STS-88, the first ISS assembly mission berths the US Unity Node to the Russian Zarya Control Module to start the assembly of ISS.

Zvezda ('Star') Service Module that would host resident crews. The result was a frustrating wait between this mission and the next of almost a year. The STS-96 crew had a busy program of transferring hardware and supplies around both the interior and exterior of the station. A single EVA supported the transfer of the US Orbital Transfer Device and the first parts of the Russian Strela crane that would be assembled by later crews. There were some concerns reported over air quality when astronauts worked in Zarya. This was attributed to open panel doors interrupting the flow of air around the module, enabling carbon dioxide to accumulate. This type of 'contamination' was not uncommon in commissioning Russian modules, and in later interviews the astronauts played down the 'bad air' reports.

2000: The primary goal of this year was to get the station to the point where the first resident crew could be launched in a Soyuz spacecraft. For this to occur, Zvezda had to be launched and docked automatically to Zarya. The expanded core station would also require the delivery of a large amount of supplies and logistics, as well as internal and external outfitting before the first resident crew arrived. This would enable Expedition One to focus on creating the foundations for prolonged habitability aboard the station and the start of scientific operations.

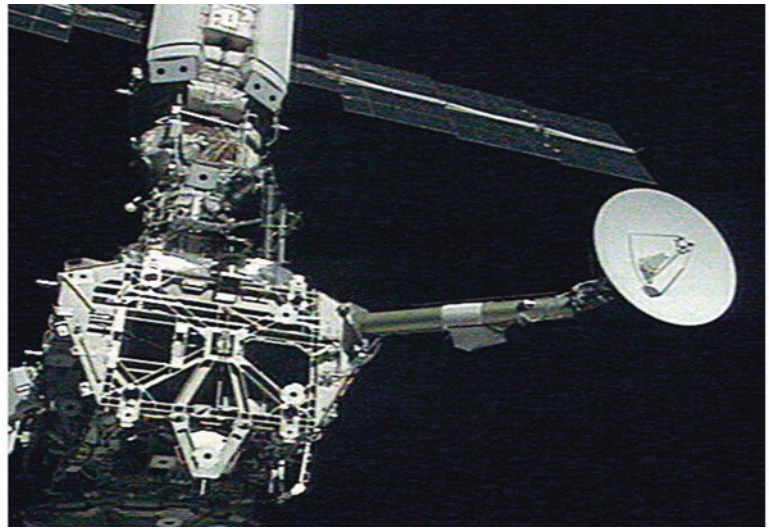
STS-101, Atlantis: 3rd ISS Assembly Flight 2A.2a (May 19–29, 2000): With the ISS assembly placed on hold, NASA cleared some of the backlog of Shuttle missions in its manifest by flying three non-ISS missions: STS-93 which deployed the Chandra X-Ray Observatory, the STS-103 Hubble servicing (designated SM-3A), and STS-99 with the Shuttle Radar Topographic Mission. Meanwhile, further slippage in preparing Zvezda for launch caused maintenance concerns for the Unity-Zarya combination already on-orbit. The batteries on Zarya had not been designed to function for so long without the more

capable power systems offered by the Service Module. The setback also affected planning for the next Shuttle flight. The crew for STS-101 had trained to work with the Service Module after its docking at the ISS. With that module still slipping, a decision was made to split the original STS-101 (2A.2) mission over two flights and divide up the crew between the two missions. The revised -101 mission (now designated 2A.2a) would fly first, taking fresh logistics to the station and making a single EVA to finish work on the external cranes that was started by STS-96. The rest of the preparations to make the station ready to receive the first resident crew would be completed by a new mission, STS-106 (2A.2b), that would launch after Zvezda had docked at the rear port of Zarya. The new Shuttle crew was supplemented by the three ISS-2 crewmembers to give them experience aboard the station a year *before* their official residency.

STS-106, Atlantis: 4th ISS Assembly Flight 2A.2b (September 8–20, 2000): The successful launch of Zvezda and subsequent docking with Zarya on July 26, 2000, and then the docking of the first unmanned Progress mission (Progress M1-3) with Zvezda, came as a huge relief to the ISS planners. At last, the station had its own flight control and orbital maintenance functions. Before a crew could live on board the ISS without a Shuttle being present it needed to be outfitted both internally and externally. The STS-106 mission became the second logistics flight of the year, finishing the work that had originally been assigned to STS-101. The single EVA of the new mission ran cabling between the two Russian modules. The way was now clear for a fast expansion of the ISS to host a resident crew of three that could undertake significant scientific research, robotics, and station-based EVAs without requiring a Shuttle in attendance.

STS-92, Discovery: 5th ISS Assembly Flight 3A (October 11–24, 2000): This flight included the largest piece of hardware delivered to the station by the Shuttle since the Unity Node nearly two years earlier. The Zenith (Z1) truss became the focal point for the expansion of the truss structure which would support a number of solar arrays and radiators to power and regulate the temperature of the station. The full structure was so large that it needed to be split up and assigned to several flights and, as it turned out, a number of years. Installing the Z1 truss segment at the uppermost (zenith) port of Unity was accomplished using the RMS and the support of four EVAs. The crew also finished work within the station, continuing the delivery of supplies and logistics to support the first residents who were scheduled to arrive at the end of the month, barely a week after the departure of the STS-92 crew. The third Pressurized Mating Adapter (PMA-3) was installed to provide an alternative location at the nadir (lower) port of Unity to receive a Shuttle. Although STS-92 was docked for a week, the majority of the time was devoted to installing the Z1 truss and the crew only entered the station for about 24 hr at the end of their stay.

STS-97, Endeavour: 6th ISS Assembly Flight 4A (November 30–December 11, 2000): This was the first Shuttle mission to dock at the ISS with a resident crew already on board, namely the EO-1 trio of William M. ('Bill') Shepherd, Yuri P. Gidzenko and Sergei K. Krikalev. They had arrived on November 2 on Soyuz TM-31 after their two day rendezvous. STS-97 docked at the newly installed PMA-3 and carried the initial set of solar arrays (Port 6 or P6). The installation of this unit on the Z1 truss was supported by three spacewalks. This was the first of eleven Shuttle missions over the next two years that would enable the ISS to reach a point where it could be sustained (albeit only just) when the Shuttle fleet was grounded between 2003 and 2005 in the wake of the loss of Columbia.



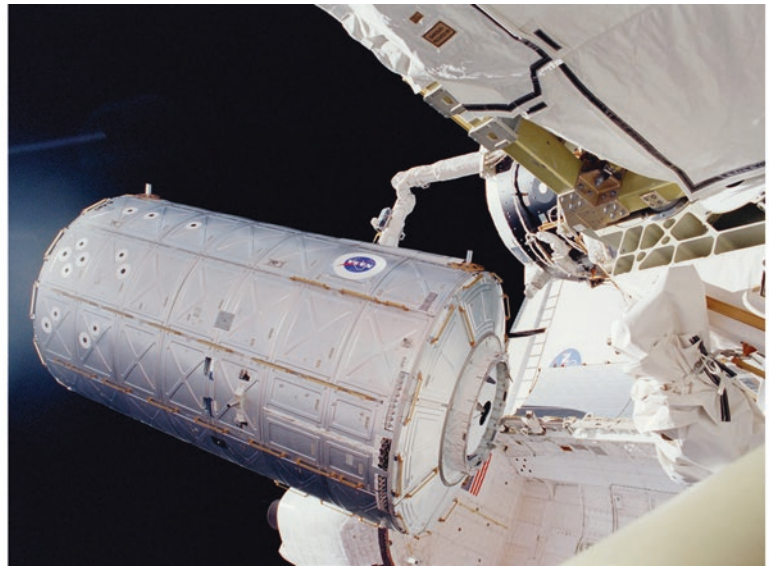
2000: STS-92 delivers Z1, the initial segment of the Integrated Truss Structure.

2001: In the year in which Stanley Kubrick's 1968 movie 'A Space Odyssey' was set, partly inspired by the story 'The Sentinel' published by Arthur C. Clarke in 1951, there was a real space odyssey underway in Earth orbit. It was a great year for the ISS. The station grew in size and capability and the rotation of resident crews began to take on a routine pattern. During a very busy twelve months, six Shuttle missions delivered more hardware and supplies. After the essentially quiet period of Expedition Zero (November 1998–October 2000) in advance of the arrival of the first resident crew, the pace began to step up.

STS-98, Atlantis: 7th ISS Assembly Flight 5A (February 7–20, 2001): The objective of this first mission of the year was to add NASA's science laboratory, named Destiny. Once it was in place on the Unity Node the Shuttle crew, assisted by the resident crew, began the process of configuring and outfitting of the large pressurized module to open the station's first real scientific facility for business. The installation was supported by the Orbiter crew undertaking three spacewalks. Although it was still a very early stage in the assembly process, there was a sense of growing maturity in orbital operations at the station.

In March 2001, Mir was finally de-orbited amid much regret from most of those in the Russian program. That same month the first resident crew of the ISS landed after a highly successful 141 day mission. The baton had now clearly been handed over to the new facility.

STS-102, Discovery: 8th ISS Assembly Flight 5A.1 (March 8–21, 2001): As the first mission fully to draw upon the experience gained from Shuttle-Mir, Discovery arrived with the ISS-2 crew and a significant amount of supplies in the payload bay aboard the first Multi-Purpose Logistics Module (MPLM) known as Leonardo. The visit included two EVAs, one of which was carried out by two members of the new ISS crew and its purpose was to continue the reconfiguration of the fittings, power and utility cables on the exterior



2001: The US Destiny laboratory is delivered by STS-98.

of the station. The MPLM was temporarily berthed on the side of Unity to transfer 5 tons of materials into the ISS and then over a ton of unwanted hardware and miscellaneous trash, much of it packaging, into the module for return to Earth. After a single expedition these operations confirmed the logistical challenge that the program would face in maintaining the station in the state needed to support a crew comfortably and also support their research work. Mindful of ensuring a smooth transition from one expedition crew to the next, this first handover saw the individual members of the two crews exchange roles in stages over an interval of several days. In particular, each pair had to transfer their Sokol pressure suits and Soyuz seat liners. This was the first of a series of exchanges of complete expeditions on the station via Shuttle missions, a feat achieved only once on Mir during STS-71.

STS-100, Endeavour: 9th ISS Assembly Flight 6A (April 19–May 21, 2001): With astronauts from the US, Canada and Italy working with the US-Russian residents this mission gave the ISS a truly international feel. The second logistics mission delivered 3.4 tons of cargo within the MPLM Raffaello and, outside, the Space Station Remote Manipulator Systems (SSRMS or 'Canadarm2'). This improved version of the Shuttle RMS was also the first part of what would become the Mobile Base System (MBS) of the station. The increased pace of activity at the ISS was highlighted a few hours after Endeavour undocked, when the first short-term visiting crew arrived in a replacement Soyuz. This capacity to utilize the Soyuz as a resident crew ferry and stand-by rescue ship would prove vital in the three years that followed the grounding of the Shuttle in 2003 and then again following the retirement of the fleet in 2011.

2001: STS-100 transfers a pallet containing the station's robotic arm, known as Canadarm2.

STS-104, Atlantis: 10th ISS Assembly Flight 7A (July 12–24, 2001): The task of this mission was to add the Joint Airlock named Quest to the Unity Node of the ISS. There was now a permanent three-person crew aboard the station, the Destiny laboratory for research, the Canadarm2 robotic arm for external manipulation, and an adequate stock of stores. Quest would increase the station's independence of visiting Shuttles because ISS crews would be able to perform spacewalks at any time, instead of waiting for the next Shuttle to arrive in order to employ its airlock. With the Quest airlock on the US segment, and a second airlock which was added to the Russian segment a few months later, station crews would be able to undertake EVA tasks that were deferred from the flight plans of visiting Shuttles. The installation of Quest required a coordinated effort using the Shuttle and ISS robotic manipulators plus support from three EVAs, with the last of these excursions being the first to be performed from the new Quest airlock. As events transpired, Quest would not be used operationally again until 2002.

This mission marked the end of the second phase of ISS assembly. During a period of just twelve months – from the docking of Zvezda to the attachment of Quest – over 31,292.5 lb. (69,000 kg) of hardware augmented the core station of Zarya-Unity. Since the docking of Zvezda, all the large components installed on the station (the Z1, PMA-3, the P6 with its solar arrays and radiator, Destiny, Canadarm2 and now Quest) were delivered by the Shuttle. This rapid expansion established a routine of crew exchange and logistics supply, and allowed the station to make a start on scientific research.

The next phase of assembly would focus on delivering the remaining truss elements to provide the planned power generating capacity, prior to completing the assembly by delivering the final modules and other facilities.

2001: The Joint Airlock Quest arrives on STS-104.

SHUTTLE MISSIONS TO EXPAND THE ISS (PHASE-III)

With the delivery of the Destiny laboratory, the SSRMS and the Quest airlock, the ISS was now at the cusp of supporting more extensive resident crew activities independent of visiting Shuttles. The remaining Shuttle flights of 2001, which kicked off Phase-III, would stock up the station in preparation for the expansion of the truss and solar array assemblies planned for the following year.

STS-105, Discovery: 11th ISS Assembly Flight 7A.1 (August 10–22, 2001): This logistics mission delivered over 6,615 lb (3,000 kg) of supplies. These included more internal experiment and equipment racks and additional external experiment platforms that were installed during two EVAs. The newly arrived ISS-3 crew took over from the retiring ISS-2 trio, who returned home aboard Discovery. The ISS-3 crew were aboard the station when the Russian Pirs ('Pier') Docking Compartment arrived in September. The airlock incorporated into this module provided alternative access for EVAs on the Russian segment that used Russian rather than American equipment.

STS-108, Endeavour: 12th ISS Assembly Flight UF1 (December 5–17, 2001): The final Shuttle visit of the year saw the exchange of the ISS-3 crew with the ISS-4 crew and the delivery of over 5,953.5 lb (2,700 kg) of supplies. The single EVA undertook routine maintenance tasks on the exterior of the station and several get-ahead tasks in preparation for more extensive spacewalking operations planned for the coming year.

2002: With the fourth resident crew on the ISS, the new year of Shuttle operations began in March with the 4th HST service mission (designated SM-3B). It was the only solo Shuttle flight on the manifest prior to the planned international scientific research mission of STS-107 with the Spacehab double module configuration for experiments to support future research aboard the ISS. The other four planned Shuttle missions for the year all focused on delivering truss and solar array elements, and stocking the station with more

supplies. The year also saw the Shuttle complete the exchange of two new resident crews (ISS-5 and ISS-6) and it was also the year in which a new model of the Soyuz (TMA) was introduced, providing extra room for larger crewmembers (notably the Europeans and Americans) and allowing space tourists, space flight participants, and international cosmonaut researchers to make brief visits to the station.

STS-110, Atlantis: 13th ISS Assembly Flight 8A (April 8–20, 2002): The year's first Shuttle flight to the ISS featured a major expansion of the truss and solar array system. STS-110 installed the Starboard Zero (S0) truss element on a bracket atop the Destiny laboratory to serve as a platform to support other truss segments and their solar arrays. Four EVAs were made by four Shuttle astronauts working in pairs and alternating the assignments to give each pair a day off between excursions. One of their tasks was to release the launch clamps on the Mobile Transporter (MT) which was meant to enable future astronauts to travel along the truss on carts running on rails, thereby saving the spacewalkers time and energy. This 'railcar' system would be expanded across future missions to carry out inspection and maintenance tasks far away from the pressurized modules.

STS-111, Endeavour: 14th ISS Assembly Flight UF2 (June 5–19, 2002): The next Shuttle mission was another logistics flight. It delivered the ISS-5 crew and retrieved their predecessors. The fifth flight of an MPLM was the third for Leonardo, which on this trip carried over 7,938 lb (3,600 kg) of supplies. Another 992.25 lb (450 kg) was transferred from Endeavour's mid-deck lockers. Making the trip home would be over 4,630.5 lb (2,100 kg) of unwanted items, trash, equipment, and samples from science experiments.

STS-112, Atlantis: 15th ISS Assembly Flight 9A (October 7–18, 2002): The goal of this mission was to resume the expansion of the station's truss. It involved three EVAs. The Starboard 1 (S1) truss was connected to the starboard end of the S0 unit and Crew Equipment Translation Aid (CETA) Cart A was placed on S0 as the first of the pair of human-powered carts for the 'railcar' system.

STS-113, Endeavour: 16th ISS Assembly Flight 11A (November 21–December 7, 2002): The final visit of the year saw the installation of the Port 1 (P1) truss and CETA Cart B. In addition to delivering over 4,189.5 lb (1,900 kg) of logistics the mission saw the ISS-5 crew replaced by their ISS-6 counterparts. The new truss unit was attached to the port end of S0 by the crew across three EVAs. CETA B cart was attached to CETA A to form a double translation unit. Unknown at the time was that this would be the last Shuttle to dock with the station and the last successful landing for over two and a half years.

2003: In December 2002, the NASA Station Program Manager, William ('Bill') Gerstenmaier, said, "The year ahead will be the most complex so far in the history of ISS and its construction in orbit. The station literally becomes a new spacecraft with each assembly mission and that will be true next year, with dramatic changes in the configuration of its cooling and power systems as well as in its operations."[1] *At the start of the year things looked good for ISS operations, with a new crew aboard and plans for major expansion of the truss system over five docking missions. Before that, however, there would be the solo flight of STS-107. It launched on January 16, 2003, and was an international science research flight designed to train scientists to develop their experiments and procedures for more extensive research on the ISS. The mission was originally created in order to bridge the gap between the final Spacelab mission (the Neurolab flown by STS-90 in*

Table 2.1 Space Shuttle Missions To The International Space Station 1998–2002

International Designation	STS Flight	Station Mission	Orbiter Vehicle (OV)	Shuttle Crew Number	Launch Date	KSC	Docking Date	Date Undocked	Docked Duration DD:HH:MM	Landing Date	Land on Orbit	Shuttle Mission Duration DD:HH:MM:SS	Miles (m)	Km (m)
A. SHUTTLE ISS ASSEMBLY AND RESUPPLY MISSIONS 1998–2002														
1998-069A	88	2A	105	6	1998 Dec 4	39A	1998 Dec 6	1998 Dec 13	6:20:38	1998 Dec 15	185	11:19:18:47	4.7	7.6
1999-030A	96	2A.1	103	7	1999 May 27	39B	1999 May 29	1999 Jun 3	5:18:17	1999 Jun 6	154	9:19:13:57	3.7	6.0
2000-027A	101	2A.2a	104	7	2000 May 19	39A	2000 May 20	2000 May 26	5:18:32	2000 May 29	155	9:21:10:10	4.1	6.6
2000-053A	106	2A.2b	104	7	2000 Sep 8	39B	2000 Sep 10	2000 Sep 17	7:21:54	2000 Sep 19	185	11:19:12:15	4.9	7.9
2000-062A	92	3A	103	7	2000 Oct 11	39A	2000 Oct 13	2000 Oct 20	6:21:23	2000 Oct 24	203	12:21:43:47	5.3	8.5
2000-078A	97	4A	105	5	2000 Nov 30	39B	2000 Dec 2	2000 Dec 9	6:23:13	2000 Dec 11	170	10:19:58:20	4.5	7.2
2001-006A	98	5A	104	5	2001 Feb 7	39A	2001 Feb 9	2001 Feb 16	6:21:15	2001 Feb 20	202	12:21:21:00	5.3	8.5
2001-010A	102	5A.1	103	7 U/7D*	2001 Mar 8	39B	2001 Mar 10	2001 Mar 18	8:21:54	2001 Mar 21	201	12:19:51:57	5.3	8.5
2001-016A	100	6A	105	7	2001 Apr 19	39A	2001 Apr 21	2001 Apr 29	8:03:35	2001 May 1	186	11:21:31:14	4.9	7.9
2001-028A	104	7A	104	5	2001 Jul 12	39B	2001 Jul 13	2001 Jul 22	8:04:46	2001 Jul 24	200	12:18:36:39	5.3	8.5
2001-035A	105	7A.1	103	7 U/7D*	2001 Aug 10	39A	2001 Aug 12	2001 Aug 20	7:20:10	2001 Aug 22	186	11:21:13:52	4.3	7.0
2001-054A	108	UF1	105	7 U/7D*	2001 Dec 5	39B	2001 Dec 7	2001 Dec 15	7:21:25	2001 Dec 17	185	11:19:36:45	4.8	7.7
2002-018A	110	8A	104	7	2002 Apr 8	39B	2002 Apr 10	2002 Apr 17	7:02:26	2002 Apr 20	171	10:19:42:44	4.5	7.2
2002-028A	111	UF2	105	7 U/7D*	2002 Jun 5	39A	2002 Jun 7	2002 Jun 15	7:21:05	2002 Jun 19	217	13:20:35:56	5.8	9.3
2002-047A	112	9A	104	6	2002 Oct 7	39B	2002 Oct 9	2002 Oct 16	6:22:56	2002 Oct 18	170	10:19:58:44	4.5	7.2
2002-052A	113	11A	105	7 U/7D*	2002 Nov 23	39A	2002 Nov 25	2002 Dec 2	7:22:11	2002 Dec 7	216	13:18:48:38	5.6	9.0
2003-2005 Shuttle flights to ISS suspended pending investigation following loss of Columbia and crew on February 1, 2003														

Key:
(*) Resident station crew member exchanged (See Table 5)
U/D Total crew members Up / total crew members Down
A = American mission
E = European mission
J = Japanese mission
UF = Utilization Flight
LF = Logistics Flight
ULF = Utilization & Logistics Flight

April 1998) and the start of full scale research on the Destiny laboratory of ISS in 2001. Initially scheduled for launch in 2000, STS-107 was delayed no less than thirteen times before it finally lifted off. Once on-orbit, Columbia and its crew of seven performed admirably and there was talk of scheduling a second flight even before they wrapped up their studies, based upon their efforts and success. Tragically, however, while they worked in the Spacehab double module the fate of the crew had already been sealed by damage caused as debris struck the leading edge of one wing of the Orbiter during launch. A fortnight later, and just 16 min prior to the scheduled landing in Florida, the effects of that damage led Columbia to break up at hypersonic speed around 200,000 ft (60,960 m) above Texas.

For the second time, a Shuttle and seven astronauts had been lost. It was just a few days after the 17th anniversary of the loss of Challenger. This time the tragedy would have terminal implications for the Shuttle program. There would be an inquiry with a series of recommendations for changes and a Return-To-Flight program to qualify the Shuttle for further use, but this time it would be for the sole purpose of completing its obligations to the assembly of the ISS. Once this had been achieved, the fleet would be retired. At that time this was expected to be in 2010. As the recovery from Columbia's loss progressed the future of the entire US human space program, any replacement for the Shuttle, and indeed the continuation of the ISS were very much in doubt.

2004: This was only the second calendar year since 1981 that a Shuttle had not left the pad, and both times the cause was the loss of an Orbiter. During the post-Columbia inquiry the surviving ships – Discovery, Atlantis and Endeavour – remained in storage. Once the sequence of events that claimed Columbia and its crew were understood, a number of measures were devised to prevent a recurrence. As new Shuttle procedures, contingency actions and safeguards were being implemented, operations involving the ISS continued with a reduced two-person caretaker crew. The three-person ISS-6 crew who had arrived on STS-113 and were expected to leave on STS-114 had instead made the trip home in Soyuz TMA-1, having been relieved by the two-person ISS-7 crew who launched aboard TMA-2. The Russian Soyuz crew taxis and Progress resupply vessels became the savior of the ISS program at this stage. These veteran vehicles enabled the station to continue to be inhabited and supplied. The science programs were reduced until such time as the Shuttle could resume flying to deliver hardware and supplies to complete the ISS assembly.

2005: It took almost thirty months to prepare the Shuttle to fly again, with STS-114 as the Return-To-Flight mission. However, things did not go as well on that flight as hoped, and further work was required to understand the problems and come up with solutions. This led to the postponement of the second Return-To-Flight mission (STS-121), thus imposing a further, costly, twelve month delay. In the manifest of October 2000 there had been twenty-eight Shuttle flights assigned to assemble and supply the station through 2002. In February 2001 the FY2002 budget was announced. It had a serious reduction in Shuttle missions, reflecting questions which were already being raised about its longevity. After the loss of Columbia and the delays in implementing the Return-To-Flight, the manifest of June 2005, shortly prior to STS-114, listed only twenty-two Shuttle missions to the ISS, with the cancellation of some of the intended payloads and hardware. The grounded items included the US Habitation Module, the US Propulsion Module, and the X-38 Crew Rescue Vehicle. These deletions, coupled with the delays and uncertainty over the Shuttle program, had implications for the ISS partners in trying to plan their own long-term goals,

fund programs, and develop new hardware. In 2005, the completion of the ISS and indeed its ultimate fate still hung in the balance. The key to the station's future, once again would depend on when, if ever, the Shuttle could resume operations.

RETURN TO FLIGHT, AGAIN

By the summer of 2005, the Shuttle was once again deemed ready to resume flying. It was now imperative to complete the expansion of the ISS truss so that the solar arrays could provide the power to support the remaining science laboratories and increase the resident crew to six persons.

However, prior to launching the truss elements, the next two Shuttle flights were to test the improvements to the Shuttle that had been developed in response to the loss of Columbia. The payloads for these missions were logistics and supplies to build up the stocks that had been depleted over the nearly two and a half years that the Shuttle fleet had been grounded. During that time it had been a challenge to sustain just a core crew of two on board the station. There was an urgency to resume the nominal three-person resident crew before implementing a rotational six-person presence and expanding the science program as the assembly phase drew to a close.

STS-114, Discovery: 17th ISS Assembly Flight LF1 (July 26–August 9, 2005): A mission originally designated ULF1 and planned for March 2003, it was intended to deliver both an extensive logistics payload and the three-person ISS-7 crew to replace the retiring ISS-6 crew. However, following the loss of Columbia this mission and all others planned at the time were grounded. As the program geared up to resume flying, the ISS launch manifest was revised and STS-114 was given the vital Return-To-Flight mission. Redesignated LF1 it carried the MPLM Raffaello loaded with over 3,748.5 lb (1,700kg) of urgent supplies to the station and returned with over 3.5 tons of unwanted material and trash that had accumulated in the intervening two and a half years.

In the post-Columbia plan, the ISS was to serve as a 'safe haven' in the event that a Shuttle was unable to return to Earth. Prior to docking, the crew used the RMS and the newly installed Orbiter Boom Sensor System (OBSS) to scan the surface of Discovery and downlink the results for ground analysis, as well as visually seeking any evidence of damage caused during launch. Then, as Discovery approached the ISS, Commander Eileen M. Collins executed the first Rendezvous Pitch Manoeuver when approximately 600 ft (183 m) away, back-flipping the spacecraft at a rate of 0.75° per second to allow the ISS crew to photo-document and visually inspect the underside and protective tiles. No significant damage was found on the Thermal Protection System (TPS), but further analysis of the images revealed protruding tile gap fillers that could potentially produce hot spots when re-entering the atmosphere. With the inevitable caution associated with this flight, the Shuttle crew performed an unplanned EVA to remove the fillers. There were three EVAs. The first involved working on deliberately damaged TPS tiles in the payload bay in order to evaluate various repair procedures and methods. In addition to miscellaneous long-awaited ISS maintenance work, the second EVA replaced a failed Control Moment Gyroscope (CMG) in the Z1 truss segment. The third EVA was added to tackle the issue

discovered during the inspection of the thermal tiles. Extracting the protruding fillers by hand was simpler than predicted. Discovery returned home safely. Analysis of ground imagery taken at launch and imagery taken in flight indicated that foam insulation was still detaching from the ET and striking the Orbiter. The ensuing corrective work and tests of the improvements progressed so slowly that almost a year passed before the next Shuttle was ready to leave the pad.

2006: Back on the road again. After more than three difficult years, the Shuttle returned to operational status with the success of STS-121. Two other missions had flown by the end of the year, and the assembly of the ISS was once again underway.

STS-121, Discovery: 18th ISS Assembly Flight ULF1.1 (July 4–17, 2006): This was officially the second Return-To-Flight mission, the one that finally qualified the Shuttle for service and permitted assembly of the ISS to resume. The delivery of logistics to the station had fallen so far behind that this mission was added to the manifest in order both to certify the new safety procedures and to function as a utilization flight. It carried the Leonardo MPLM loaded with over 7,276.5 lb (3,300 kg) of logistics. Three EVAs were made when docked to undertake station maintenance, test improved EVA apparatus and procedures, and perform several delayed get-ahead tasks to prepare for extensive EVAs during later flights. One highlight was the transfer of Thomas Reiter, an ESA astronaut from Germany, to work with the ISS-13 and ISS-14 resident crews as Flight Engineer 2. He would return to Earth on a later Shuttle, which would deliver his replacement. This started a series of single-person transfers during assembly missions over the next three years. Three-person resident crews were no longer to be transported by Shuttle but this single exchange option brought an end to the two-person caretaker crews on the station after three years. It also meant that the third seat on each Soyuz carrying a new pair of residents to the ISS would be available for fee-paying participants who would return to Earth with the departing residents after about a week aboard the station.

STS-115, Atlantis: 19th ISS Assembly Flight 12A (September 9–21, 2006): Atlantis paid its first visit to the ISS in almost four years. It was carrying the P3 and P4 trusses, which were installed during the first few days, supported by three EVAs. The day after Atlantis undocked, Soyuz TMA-9 was launched. It was the first time since April 2001 that three crews were simultaneously in space on different craft. This activity reflected the complexity of ISS space operations during the initial years of the new millennium. At the homecoming celebration in Houston shortly after Atlantis landed on September 21, Mission Specialist Heidemarie Stefanyshyn-Piper collapsed twice and was taken to hospital for a checkup. The problem was diagnosed as being related to her personal re-adaptation to gravity after her first mission and twelve days in space, and there were no lasting effects.

STS-116, Discovery: 20th ISS Assembly Flight 12A.1 (December 9–22, 2006): As a reflection of the increased pace now that the Shuttle was again operational this mission flew less than three months after STS-115. Whilst mission safety remained paramount, the defined end to the Shuttle program left little time to spare in planning the remaining assembly and logistic missions to the ISS. With uncertainly remaining about what (if anything) would follow the Shuttle, pressure to complete the station was evident. Due to restrictions imposed by the loss of Columbia, STS-116 was the first night launch in four years. Its primary objective was to install the P5 truss section, a task supported by three

2006: High above New Zealand, the expansion of the station's truss and solar array system continues with STS-116 installing the P5 truss.

spacewalks. Some difficulties were encountered in fully retracting the P6 solar arrays to make room for the new arrays (the P6 unit was to be relocated from its initial position atop the Z1 truss to the end of the port truss by a mission in 2007) so a fourth EVA was added to finish this retraction process. The smaller mass and dimensions of the P5 truss (which would function as a spacer between P4 and P6 when the latter was relocated) meant that there was room in the payload bay for a Spacehab single module to carry supplies to stock up the station. While the EVAs were in progress, over 2 tons of logistics were simultaneously transferred internally. STS-116 also featured the first exchange of an ISS crewmember since STS-113 in 2003, with Thomas Reiter of ESA being replaced as FE2 by NASA's Sunita L. Williams, who would work in succession with the ISS-14 and ISS-15 resident crews.

2007: Despite the backlog, only three Shuttle missions were flown this year, due in part to the delay in launching STS-117 after a hail storm which caused damage to the thermal protection on both Atlantis and its External Tank. On the positive side though, the ISS continued to expand, with more of the truss structure being installed as well as the second pressurized node, named Harmony.

STS-117, Atlantis: 21st ISS Assembly Flight 13A (June 8–22, 2007): As the first mission to leave Pad 39A since STS-107 in January 2003, STS-117 delivered the S3 and S4 segments of the truss and several tons of logistics and supplies. At 42,671 lb (19,355.5 kg)

this was the heaviest payload the Shuttle had lifted so far. Two pairs of astronauts working in the now familiar alternating system, made a total of four EVAs. After the recent spate of problems, this mission further demonstrated the flexibility of the Shuttle and its value to the ISS program. Following difficulties experienced by the computers on the Russian segment during the docked phase, the Orbiter's propulsion system was employed to assist in controlling the station's attitude in space while the Russian system was attended to. This mission also featured the next ISS crewmember exchange, with Clayton C. ('Clay') Anderson superseding Sunita Williams as FE2 to work sequentially with the ISS-15 and ISS-16 crews.

STS-118, Endeavour: 22nd ISS Assembly Flight 13A.12 (August 8–21, 2007): After a five-year program of major modifications, this was the first flight of Endeavour since it flew STS-113 in 2002. Four EVAs were carried out in support of the installation of the S5 truss section and an External Stowage Platform (ESP). The astronauts also replaced another failed CMG on the ISS. This mission also introduced the occasional change of EVA crewing where a serving American ISS resident participated in one or more of the planned spacewalks. In this case, ISS-16 FE Clay Anderson joined STS-118's Richard A. ('Rick') Mastracchio and Canadian Dafydd (David or 'Dave') R. Williams on the third and fourth EVAs respectively. STS-118 was the first mission to make use of the Station-to-Shuttle Power Transfer System (SSPTS) that permitted a docked Orbiter to draw additional power from the station so that flights could be extended, if needed. It was also the final flight of the Spacehab resupply module. One other highlight of this mission was the inclusion of Mission Specialist Barbara R. Morgan. The professional teacher from Idaho had served as back-up to fellow teacher Christa McAuliffe for the ill-fated STS-51 L Challenger mission. In 1998, Morgan had been selected for NASA astronaut training and during this mission she broadcast three educational events and answered many questions from school children, in addition to completing her normal Mission Specialist workload.

STS-120, Discovery: 23rd ISS Assembly Flight 10A (October 23–November 7, 2007): This very busy mission delivered the Node 2 (Harmony) module, relocated the P6 truss segment from atop Z1 to its permanent position on the port end of the main truss, and exchanged ISS crewmember Clay Anderson with Daniel M. Tani, who joined the ISS-16 crew as FE2. With the spacewalkers focusing upon the priority repair of the Solar Alpha Rotary Joint (SARJ) during four EVAs, a fifth planned EVA was reassigned to the ISS residents to undertake at a later date. Discovery also replenish the station with another logistics payload, and returned 2,020 lb (916.3 kg) of materials and scientific samples to Earth. The media tended to focus on the fact that, for the first time, female astronauts commanded both the Shuttle (Pamela A. Melroy) and the station (Peggy A. Whitson) and had therefore shaken hands in space.

2008. This was a very busy and significant year for ISS operations, with the delivery of several large elements for two of the remaining scientific laboratories, one European and the other Japanese. Their installation and outfitting paved the way to increase the permanent resident crew to six persons from 2009, and justified the assignment of both Japanese and European astronauts to resident crews, alongside those of Canada, who had supplied the station's main robotics systems.

2008: ESA's long-awaited Columbus laboratory arrives at the ISS via STS-122.

STS-122, Atlantis: 24th ISS Assembly Flight 1E (February 7–20, 2008): The ESA Columbus science laboratory, named after the historic 15th century Italian explorer Christopher Columbus, was a development of the earlier European Spacelab module that flew aboard several Shuttle missions between 1983 and 1998. It featured much-improved and expanded experiment racks and research facilities. This flight had been scheduled for launch in December 2007 but was delayed twice owing to problems in fueling the Shuttle's ET. The installation of Columbus was supported by three EVAs. Work on activating the internal systems and facilities was carried out by French ESA astronaut Leopold Eyharts, following his joining the ISS-16 crew as replacement for Dan Tani. For the first time since 2002, the Shuttle Orbiter was employed to re-boost the altitude of the ISS when the Orbital Maneuvering System (OMS) on Atlantis was fired to raise the orbit by 1.4 miles (2.25 km).

STS-123, Endeavour: 25th ISS Assembly Flight 1J/A (March 11–26, 2008): With Columbus added to the ISS, the focus turned to the Japanese laboratory called Kibo ('Hope'). The Japanese laboratory (like Columbus) had originally been intended for Space Station Freedom, and was formally named the Japanese Experiment Module (JEM). With a total mass exceeding 62,044 lb (28,138 kg), it was by far the biggest module delivered by the Shuttle and was too massive to be launched in one piece. Its installation was spread across three Shuttle missions, of which this was the first. STS-123 carried the Experiment Logistics Module Pressurized Section (ELM-PS) together with a new Canadian robotic arm that had the impressive name of the Special Purpose Dexterous Manipulator and was more affectionately known as 'Dextre.' The ELM-PS was temporarily attached to the Harmony Node while awaiting the delivery of the next segment of the Japanese laboratory on the next Shuttle. Five EVAs were conducted (a record for a Shuttle assembly flight) totaling 33 hr 28 min. Much of this duration was spent on various tasks associated with the

attachment of Kibo and Dextre, as well as get-ahead tasks in preparation for later spacewalks. In addition, this mission also saw the exchange of Leopold Eyharts after just one month on the ISS-16 crew by NASA astronaut Garrett E. Reisman who would also work sequentially with the ISS-16 and ISS-17 crews.

2008: STS-123 delivers the Special Purpose Dexterous Manipulator known as 'Dextre.'

STS-124, Discovery: 26th ISS Assembly Flight 1J (May 31–June 14, 2008): The second mission associated with the delivery of Kibo carried the Pressurized Module (JEM-PM) as its primary payload. Since this was so large, there was no capacity to carry the OBSS inspection device as well. That had been temporarily stowed on the station during STS-123 and would be brought home at the end of STS-124 once the Japanese laboratory had been offloaded. The ELM-PS was relocated to its intended position on top of the JEM-PM. The installation operations were supported by three spacewalks. Garrett Reisman was replaced by Gregory E. ('Greg') Chamitoff, who served as FE2 with first the ISS-17 crew and then the ISS-18 crew.

STS-126, Endeavour: 27th ISS Assembly Flight ULF2 (November 14–30, 2008): The final Shuttle flight of the year saw 6.5 tons of logistics delivered using MPLM Leonardo. Sandra H. Magnus replaced Greg Chamitoff as FE2 on the ISS-18 crew. This mission was primarily "home improvements and maintenance," with the cargo featuring two large water recycling racks, a new 'kitchen' unit, a second toilet, two additional sleep stations, more exercise apparatus, and a multitude of other essential supplies. In addition to performing three EVAs, the Shuttle crew assisted the station crew with the installation of a new Water Recovery System designed to make waste water drinkable and maximize the supply of potable water aboard the ISS. This was another vital step toward the kind of closed-cycle life support system that would be essential for establishing an outpost on the Moon or making exploratory missions to asteroids or to Mars.

2009. The final element of the huge truss structure was delivered this year, more than eight years after the installation of the first piece. The four Shuttle flights to the ISS were overshadowed by STS-125's daring and highly successful final HST service mission (SM-4). Originally deleted from the manifest following the loss of Columbia, but reinstated to fly in May between STS-119 and STS-127, this became the final solo Shuttle mission and supported the last EVAs directly from the Shuttle airlock, a series which began with STS-6 in April 1983. The year also saw the size of the resident crew aboard the ISS increased to six for the first time, including representatives from ESA, Canada, and Japan. As a result, the availability of third seats on the Soyuz flights for fee-paying participants was greatly reduced. The year also saw the final resident crew transfers via the Shuttle.

STS-119, Discovery: 28th ISS Assembly Flight 15A (March 15–28, 2009): The task of this mission was to deliver and install the S6 truss segment with the fourth and final set of solar arrays in order to increase the overall power generation capacity of the ISS to the specified 120 kW. In addition to doubling the power available for the research laboratories from 15 kW to 30 kW, there would still be sufficient power to support a permanent crew of six and, for short periods, up to nine. The first of the three EVAs conducted on this flight was in support of installing the S6 truss. The other two were associated with maintenance and get-ahead tasks. Sandra Magnus was superseded by JAXA astronaut Koichi Wakata on the ISS-18 crew, making him the first Japanese to serve on a resident crew.[*] He would work with both the ISS-19 and ISS-20 crews.

STS-127, Endeavour: 29th ISS Assembly Flight 2J/A (July 15–31, 2009): Just two months after the highly successful final HST service mission, attention returned to the ISS with STS-127 completing the Kibo laboratory by adding its Exposed Facility (EF). Five EVAs supported this work, as well as conducting various other tasks including the addition of the Integrated Cargo Carrier – Vertical Light Deployable (ICC-VLD) to the port side of the Mobile Base System. By this point, all of the major science facilities of the US Segment were in place, but the planned, and much-delayed, remaining Russian science modules were still in the factory. Astronaut Timothy L. Kopra replaced Koichi Wakata on the ISS-20 crew.

STS-128, Discovery: 30th ISS Assembly Flight 17A (August 28–September 12, 2009): This was the first of two missions in this year primarily devoted to stocking up the ISS with supplies and logistics. STS-128 also featured the final exchange of an ISS resident crewmember by Shuttle, with Nicole M. P. Stott superseding Tim Kopra on the ISS-20 crew and later working with the ISS-21 crew. The three EVAs of the mission involved relocating apparatus and the installation of new experiment platforms, EVA aids and a range of hardware for future replacement. NASA later stated that this mission marked the transition of the ISS from an assembly site to a long-term research facility. MPLM Leonardo carried 7.5 tons of supplies that included new experiment racks and sample freezers for Destiny. The MPLM was packed with 5,223 lb (2,400 kg) of experiment results, trash, and unwanted hardware for return to Earth. A further 861 lb (390.5 kg) was stored in Discovery's mid-deck lockers.

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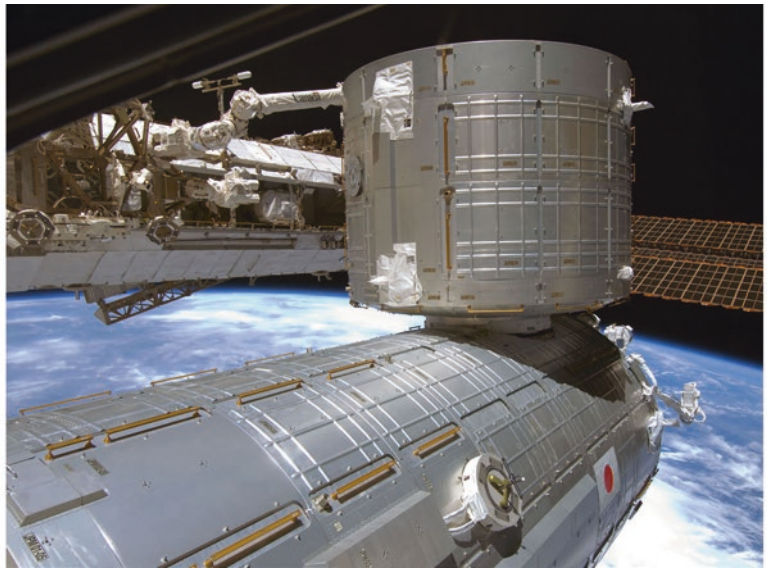
[*] The Japanese Aerospace eXploration Agency was formed on October 1, 2003, by merging the former Institute of Space and Astronautical Sciences (ISAS), the National Aerospace Laboratory of Japan (NAL) and the National Space Development Agency of Japan (NASDA).



2008–2009 saw a series of three Shuttle missions deliver elements of the Japanese Experiment Module Kibo ('Hope').

STS-129, Atlantis: 31st ISS Assembly Flight ULF3 (November 16–27, 2009): The final Shuttle mission of the year ferried over a ton of supplies to the ISS and returned with a similar mass of unwanted materials and trash. The robotic arms on the Shuttle and station installed a pair of Express Logistics Carriers (ELC-1 and ELC-2) on the Earth-facing (nadir) side of the port truss. The three EVAs on this flight once again supported a wide variety of activities, tasks, and chores across the exterior. Another closure occurred when Nicole Stott, having served with the ISS-20 and ISS-21 crews, transferred across to the Orbiter without being superseded. She was the last of eleven resident crewmembers exchanged by Shuttles between July 2006 and November 2009: eight Americans, two Europeans (one from Germany and the other from France), and one Japanese. For the foreseeable future, *all* station crewmembers would arrive and depart via Soyuz spacecraft.

2010. The penultimate year of Shuttle operations saw a series of flights designed to fill the station with sufficient supplies to last the six-person resident crews at least one year after the Shuttle was retired. These flights would also remove much of the clutter and unwanted material from inside the station, and stock up as many spare parts and Orbital Replacement Units (ORU) as possible inside and outside of the facility.

STS-130, Endeavour: 32nd ISS Assembly Flight 20A (February 8–21, 2010): This mission delivered two major components. After the cancellation of the US Habitation Module, the newly delivered Node 3, named Tranquility, carried facilities to improve living conditions for the six-person crew. The second major item was the Cupola, the seven-paned panoramic viewing module which would ultimately serve as the station's central robotic

control facility. These were the last major habitable modules of the US segment of the ISS. Their installation was supported by three EVAs. In addition to the much-needed living quarters Tranquility provided air revitalization, oxygen regulation and waste handling systems. Eventually almost all of the US segment's waste and crew hygiene equipment would be relocated to Tranquility. The recently installed Combined Operational Load Bearing External Resistance Treadmill with the contrived acronym of COLBERT[2] was later moved to Tranquility, along with other exercise apparatus, to free up working volume elsewhere. The Cupola, which had been awaiting flight assignment for several years, provided a 360° view of the world, the station structure, and the starry background. It would also come to serve as a quiet place for crewmembers to reflect on their unique experiences and the job they were doing.

2010: STS-130 delivers the station's Cupola.

STS-131, Discovery: 33rd ISS Assembly Flight 19A (April 5–20, 2010): When the Shuttle was retired the opportunity to deliver substantial cargoes to the ISS and return bulky hardware to Earth would be lost, probably for many years. Other vehicles were operating, or would soon become available, but their payloads were smaller and they had limited (or zero) ability to return items to Earth. With STS-130 the ISS assembly was 98% complete, therefore STS-131 was to deliver as many supplies, consumables and spares as possible and retrieve unwanted items. With less clutter to deal with, the residents would be able to focus upon routine maintenance and scientific experiments. The Leonardo MPLM delivered 17,999 lb (7,711.2 kg) of cargo, and once it had been emptied it was refilled with bags of unwanted material, broken equipment and various discarded items for the trip home. The tasks undertaken during the three EVAs of this mission included replacing an empty 1,800lb (816.5 kg) ammonia coolant tank with a new unit.

STS-132, Atlantis: 34th ISS Assembly Flight ULF4 (May 14–26, 2010): An all-veteran crew flew Atlantis on this mission, completing the Shuttle launch manifest for the year. An Integrated Cargo Carrier (ICC) was transferred to the exterior of the ISS. However, most of the interest focused upon the installation of the Russian-built Mini Research Module 1 called Rassvet ('Dawn'). This was the first major item of Russian hardware to be carried by Shuttle since the Docking Module augmented Mir in 1995. Rassvet was permanently attached to the lower (nadir) port of Zarya. The ICC carried spares and supplies to support the ISS through to at least 2020. Its payload included a spare K_u-band antenna and truss support, six nickel-hydrogen batteries, and a range of spares for the Dextre manipulator. The flight once again included three EVAs, totaling 21 hr 20 min. These supported the installation of Rassvet and the ICC and performed a number of get-ahead tasks. In total, over 2,800lb (1,300 kg) of cargo was moved from Atlantis to the station, and over 822 lb (3,730 kg) was moved the other way. STS-132 was initially to have been the final flight of Atlantis, but its retirement was delayed to allow the Orbiter to be prepared as a Launch-On-Need (LON) rescue ship (designated STS-335) for the final manifested Shuttle flight (STS-134). But then it was decided to prepare Atlantis for one more flight (designated STS-135) to the ISS.

2010: Installation of the Russian Rassvet ('Dawn') Mini Research Module 1 on the nadir port of Zarya by STS-132.

2011. The year that saw the 50th anniversary of Yuri Gagarin's historic first manned orbital flight also witnessed the completion of the first flight a new Soyuz variant, Soyuz TMA-M, after 160 days in space. In addition there was the launch of the first unmanned Chinese space laboratory (Tiangong-1), the automated docking with that laboratory by the unmanned Shenzhou 8, and a second redocking 11 days later. Alongside these new programs, 2011 also witnessed the ending of two eras. The main assembly phase of the ISS was finally completed, as were the final three flights of the Shuttle before the fleet was retired.

STS-133, Discovery: 35th ISS Assembly Flight ULF5 (February 24–March 9, 2011): With ISS assembly essentially complete, this was the first of three missions to deliver supplies. In the payload bay was a newly modified Leonardo Multi-Purpose Logistics Module, redesignated the Permanent Multipurpose Module (PMM). The MPLM had been designed for temporary berthing on the ISS during a Shuttle visit to allow direct transfer of materials without having to pass through the narrow hatches and tunnels of the Orbiter Docking System. It had been long recognized that *space* (volume) aboard the station was at a premium, so one of the three MPLMs had been modified so that it could be permanently affixed to the ISS to provide additional storage. Discovery also carried miscellaneous apparatus and spares on Express Logistics Carrier 4 for external transfer, and a humanoid robotic device (Robonaut R2) that was to be assessed inside the ISS, both as a potential aid for automated repair tasks and an assistant for complex EVAs. This investigation could lead to advanced forms of robot capable of supporting more demanding work on the Moon, on asteroids, or on Mars. The two EVAs for the mission achieved a range of maintenance tasks on the exterior of the station, including placing ELC-4 on the truss. This final flight by Discovery was its thirteenth mission to the ISS and its thirty-ninth mission overall.

2011: The attachment of the Permanent Multipurpose Module that was the modified MPLM Leonardo.

STS-134, Endeavour: 36th ISS Assembly Flight ULF6 (May 16–June 1, 2011): The penultimate Shuttle flight of the program was also the twenty-fifth and final flight for Endeavour, which was on its twelfth visit to the ISS. Once Endeavour was docked, it provided a unique photo-opportunity, since this was the first and only time that all of the current types of resupply craft were present simultaneously: the American Shuttle OV-105 Endeavour, the Russian Progress M-10M and Soyuz TMA-21, the European ATV-2 Johannes Kepler, and the Japanese HTV-2 Kounotori. The historic images of this configuration were captured by ESA astronaut Paolo Nespoli while departing the station aboard Soyuz TMA-20. In addition to the Express Logistics Carrier 3 that was loaded with spares, Endeavour delivered an Alpha Magnetic Spectrometer, a particle physics experiment that was an improved version of one evaluated during the STS-91 mission to Mir in 1998. By observing cosmic rays, it was to investigate the nature of matter in the universe. Four EVAs were included in the flight plan, the last of which was the final EVA by members of a Shuttle crew (although via Quest rather than the Orbiter's airlock). This drew to a close the long sequence of Shuttle spacewalks that began in April 1983. STS-134 also saw the permanent relocation of the OBSS to the ISS to extend the reach of Canadarm2. The placing of AMS-02 on the main truss on May 19 officially marked the completion of the US segment of ISS. Several planned Russian modules had yet to be finished and a few outstanding large experiments and smaller items of hardware remained to be delivered but now the ISS was officially no longer an assembly site, it was a fully-fledged laboratory. Indeed, NASA declared the ISS to be a National Resource Laboratory for the benefit of the American people. This was in addition to it serving as an International Resource Laboratory as a result of the presence of the Russian segment and the European and Japanese facilities.

STS-135, Atlantis: 37th and final ISS Assembly Flight ULF7 (July 8–21, 2011): The end of the Shuttle era came thirty years and three months after the launch of Columbia on STS-1. It carried a crew of just four. The remaining operational MPLM, Raffaello, had over 9,000 lb (4,880 kg) of supplies, including sufficient food (2,677 lb or 1,214.3 kg) to sustain the ISS for a year, as well as other items and spares that would be of use in the future. This cargo was crammed into a total of seventeen racks – including eight Resupply Stowage Platforms (RSP), six Resupply Stowage Racks (RSR), and one Zero Stowage Rack. There was another 2,228 lb (1,010.6 kg) of materials on the mid-deck. The empty MPLM was then refilled with 5,666 lb (2,570.1 kg) of junk. With so much cargo to move, a review of the flight plan led to another day being added to the mission to finish off the operation. Also transferred across to the ISS was the Robotic Refueling Mission (RMM) experiment hardware, which was later to be evaluated by the residents to investigate the techniques, hardware, and procedures that were being developed for robotic satellite refueling and supporting EVA during servicing, even though the target spacecraft for this process had yet to be developed. The single planned EVA during the docked phase of was made by station crewmembers, mainly because the relatively late decision to add this mission to the manifest had provided little time for the Shuttle crew to train up. On 19 July, Atlantis undocked for the final time. The mission ended with an uneventful landing at the Cape two days later. The International Space Station had been assembled and the Shuttle passed into retirement.

Table 2.2 Space Shuttle Missions To The International Space Station 2005–2011

International Designation	STS Flight	Station Mission	Orbiter Vehicle (OV)	Shuttle Crew Number	Launch Date	KSC	Docking Date	Date Undocked	Docked Duration DD:HH:MM	Landing Date	Land on Orbit	Shuttle Mission Duration DD:HH:MM:SS	Miles (m)	Km (m)
SHUTTLE ISS ASSEMBLY AND RESUPPLY MISSIONS 2005-2011														
2005-026A	114	LF1	103	7	2005 Jul 26	39B	2005 Jul 28	2005 Aug 6	8:19:54	2005 Aug 9	219	13:21:32:48	5.8	9.3
2006-028A	121	ULF1.1	103	7 U/6D*	2006 Jul 4	39B	2006 Jul 6	2006 Jul 15	8:19:06	2006 Jul 17	202	12:18:37:54	5.3	8.5
2006-036A	115	12A	104	6	2006 Sep 9	39B	2006 Sep 11	2006 Sep 17	6:02:04	2006 Sep 21	187	11:19:07:24	4.8	7.8
2006-055A	116	12A.1	103	7 U/7D*	2006 Dec 9	39B	2006 Dec 12	2006 Dec 19	7:23:58	2006 Dec 22	204	12:20:45:16	5.3	8.5
2007-024A	117	13A	104	7 U/7D*	2007 Jun 8	39A	2006 Jun 10	2006 Jun 19	8:19:06	2007 Jun 22	219	13:20:12:44	5.8	9.3
2007-035A	118	13A.1	105	7	2007 Aug 8	39A	2007 Aug 10	2007 Aug 19	8:17:54	2007 Aug 21	201	12:17:55:34	5.2	8.4
2007-050A	120	10A	103	7 U/7D*	2007 Oct 23	39A	2007 Oct 25	2007 Nov 5	9:21:52	2007 Nov 7	238	15:02:24:02	6.2	10.0
2008-005A	122	1E	104	7 U/7D*	2008 Feb 7	39A	2008 Feb 9	2007 Feb 18	8:16:07	2008 Feb 20	202	12:18:21:50	5.3	8.5
2008-009A	123	1 J/A	105	7 U/7D*	2008 Mar 11	39A	2008 Mar 12	2008 Mar 26	11:20:36	2008 Mar 26	250	15:18:10:54	6.5	10.5
2008-027A	124	1 J	103	7 U/7D*	2008 May 31	39A	2008 Jun 2	2008 Jun 11	8:17:39	2008 Jun 14	217	13:18:13:07	5.7	9.2
2008-059A	126	ULF2	105	7 U/7D*	2008 Nov 14	39A	2008 Nov 16	2008 Nov 28	11:16:46	2008 Nov 30	251	15:20:29:27	6.6	10.6
2009-012A	119	15A	103	7 U/7D*	2009 Mar 15	39A	2009 Mar 17	2009 Mar 24	7:22:33	2009 Mar 28	202	12:19:29:33	5.3	8.5
2009-038A	127	2 J/A	105	7 U/7D*	2009 Jul 15	39A	2009 Jul 17	2009 Jul 28	10:23:41	2009 Jul 31	248	15:16:44:57	6.5	10.5
2009-045A	128	17A	103	7 U/7D*	2009 Aug 28	39A	2009 Aug 30	2008 Sep 8	8:18:32	2009 Sep12	219	13:20:53:43	5.7	9.2
2009-062A	129	ULF3	104	6 U/7D*	2009 Nov 16	39A	2009 Nov 18	2009 Nov 25	6:17:02	2009 Nov 27	171	10:19:16:13	4.9	7.2
2010-004A	130	20A	105	6	2010 Feb 8	39A	2010 Feb 9	2010 Feb 20	9:19:48	2010 Feb 21	217	13:18:06:22	5.7	9.2
2010-012A	131	19A	103	7	2010 Apr 5	39A	2010 Apr 7	2010 Apr 17	10:05:08	2010 Apr 20	238	15:02:47:10	6.2	10.0
2010-019A	132	ULF4	104	6	2010 May 14	39A	2010 May 16	2010 May 23	7:00:54	2010 May 26	186	11:18:29:09	4.8	7.8
2011-008A	133	ULF5	103	6	2011 Feb 24	39A	2011 Feb 26	2011 Mar 6	7:23:55	2011 Mar 9	202	12:19:03:51	5.3	8.5
2011-020A	134	ULF6	105	6	2011 May 16	39A	2011 May 18	2011 May 29	11:17:41	2011 Jun 1	249	15:17:38:22	6.5	10.4
2011-031A	135	ULF7	104	4	2011 Jul 8	39A	2011 Jul 10	2011 Jul 19	8:15:21	2011 Jul 21	200	12:18:27:52	5.2	8.5

(continued)

Table 2.2 (continued)

At conclusion of STS-135 on July 21, 2011 the Shuttle fleet was retired.

Key:
(*) Resident station crew member exchanged (See Table 3.2)
U/D Total crew members Up / total crew members Down

A = American mission
E = European mission
J = Japanese mission
UF = Utilization Flight
LF = Logistics Flight
ULF = Utilization & Logistics Flight

TOTAL SPACE SHUTTLE DOCKINGS WITH SPACE STATIONS (MIR & ISS)
103 Discovery [2 Mir missions (1 rendezvous 1 docking); 13 ISS dockings= 15 missions, 1 rendezvous and 14 dockings]
104 Atlantis [7 Mir dockings; 12 ISS dockings = 19 missions, 19 dockings]
105 Endeavour [1 Mir docking; 12 ISS dockings = 13 missions, 13 dockings]

Total of 47 space station missions [10 to Mir, 1 rendezvous and 9 dockings; and 37 dockings to ISS]

2011: This historic picture shows STS-135 Atlantis (right) docked to the ISS with the US segment complete. In the foreground is the recently attached AMS-02 experiment.

Shuttle Station Assembly: A Summary

The thirty-seven missions flown between December 1998 and July 2011 were the core of the effort to assemble the ISS. Remarkably, each mission flew without encountering major failures or requiring re-flights. This was a truly stunning achievement. Three of the four-Orbiter fleet undertook the work, with Discovery flying thirteen missions and Endeavour and Atlantis each making twelve flights. Columbia, being heavier, was not involved. The three Orbiters could have kept flying to resupply the station and perhaps to expand it with additional modules and hardware, but this was not to be.

Twelve years and seven months after Endeavour roared off to initiate the assembly process, Atlantis glided to its final landing with that task accomplished.

SHUTTLE AT STATION

If the ten Shuttle-Mir missions are added to the Shuttle-ISS missions, then fully one-third (34.81%) of the total of 135 launches over the thirty-year Shuttle program were associated with space stations. However, it was by no means apparent at the time that this focus would be practicable. Although the assembly of a space station was one of the tasks intended for the Shuttle when it was first conceived, it was unable to pursue this challenge until the second half of its operational lifetime.

But the story of the Shuttle at the ISS, and to a similar degree at Mir, is not simply about dockings by Atlantis, Discovery, and Endeavour. It is the story of hundreds of workers on the ground who prepared the hardware and controlled the flights, and the astronauts who applied the lessons learned during Shuttle-Mir to ensure that the ISS dockings were

2A (STS-88)

2A.1 (STS-96)

2A.2a (STS-101)

2A.2b (STS-106)

3A (STS-92)

4A (STS-97)

5A (STS-98)

5A.1 (STS-102)

6A (STS-100)

7A (STS-104)

7A.1 (STS-105)

UF1 (STS-108)

8A (STS-110)

UF2 (STS-111)

9A (STS-112)

11A (STS-113)

LF1 (STS-114)

ULF1.1 (STS-121)

12A (STS-115)

12A.1 (STS-116)

13A (STS-117)

13A.1 (STS-118)

10A (STS-120)

1E (STS-122)

1J/A (STS-123)

1J (STS-124)

ULF2 (STS-126)

15A (STS-119)

2J/A (STS-127)

17A (STS-128)

ULF3 (STS-129)

20A (STS-130)

19A (STS-131)

ULF4 (STS-132)

ULF5 (STS-133)

ULF6 (STS-134)

ULF7 (STS-135)

SPACE SHUTTLE ISS PAYLOAD EMBLEMS

Each Shuttle flight had its own mission emblem which is widely known. However, for ISS each mission also had a distinctive payload emblem which is reproduced here and are less well known. All images courtesy of Spacefacts.de from NASA originals

achieved without incident and that the tons of logistics were relocated safely and efficiently. The story also involves new developments in robotics and EVA, with a coordinated effort between the two skills to greatly expand and secure the final ISS configuration and hopefully facilitate years of research.

We are now far beyond the point at which the surviving Orbiters of the Shuttle fleet were retired, yet the ISS still operates around the clock thanks to the efforts of various players, including privately developed and operated space vehicles. However, without the Shuttle to bear the initial burden of the assembly process the ISS wouldn't exist as we know it today, and *that* must be one of the greatest legacies of the Shuttle program.

Notes

1. NASA News Release 02-256, December 20, 2002
2. Named after the American comedian and TV personality Stephen Colbert.

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