

The Space Shuttle and Its Operations

The Space Shuttle



Processing the Shuttle for Flight



Flight Operations



Extravehicular Activity Operations and Advancements



Shuttle Builds the International Space Station





The Space Shuttle

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The Space Shuttle design was remarkable. The idea of “wings in orbit” took concrete shape in the brilliant minds of NASA engineers, and the result was the most innovative, elegant, versatile, and highly functional vehicle of its time. The shuttle was indeed an engineering marvel on many counts. Accomplishing these feats required the design of a very complex system.

In several ways, the shuttle combined unique attributes not witnessed in spacecraft of an earlier era. The shuttle was capable of launching like a rocket, reentering Earth’s atmosphere like a capsule, and flying like a glider for a runway landing. It could rendezvous and dock precisely, and serve as a platform for scientific research within a range of disciplines that included biotechnology and radar mapping. The shuttle also performed satellite launches and repairs, bestowing an almost “perpetual youth” upon the Hubble Space Telescope through refurbishments.

The most impressive product that resulted from the shuttle’s capabilities and contributions is the International Space Station—a massive engineering assembly and construction undertaking in space.

No other crewed spacecraft to date has replicated these capabilities. The shuttle has left an indelible mark on our society and culture, and will remain an icon of space exploration for decades to come.



What Was the Space Shuttle?

Physical Characteristics

The Space Shuttle was the most complex space vehicle design of its time. It was comprised of four main components: the External Tank (ET); three Space Shuttle Main Engines; two Solid Rocket Boosters (SRBs); and the Orbiter vehicle. It was the first side-mounted space system dictated by the need to have a large

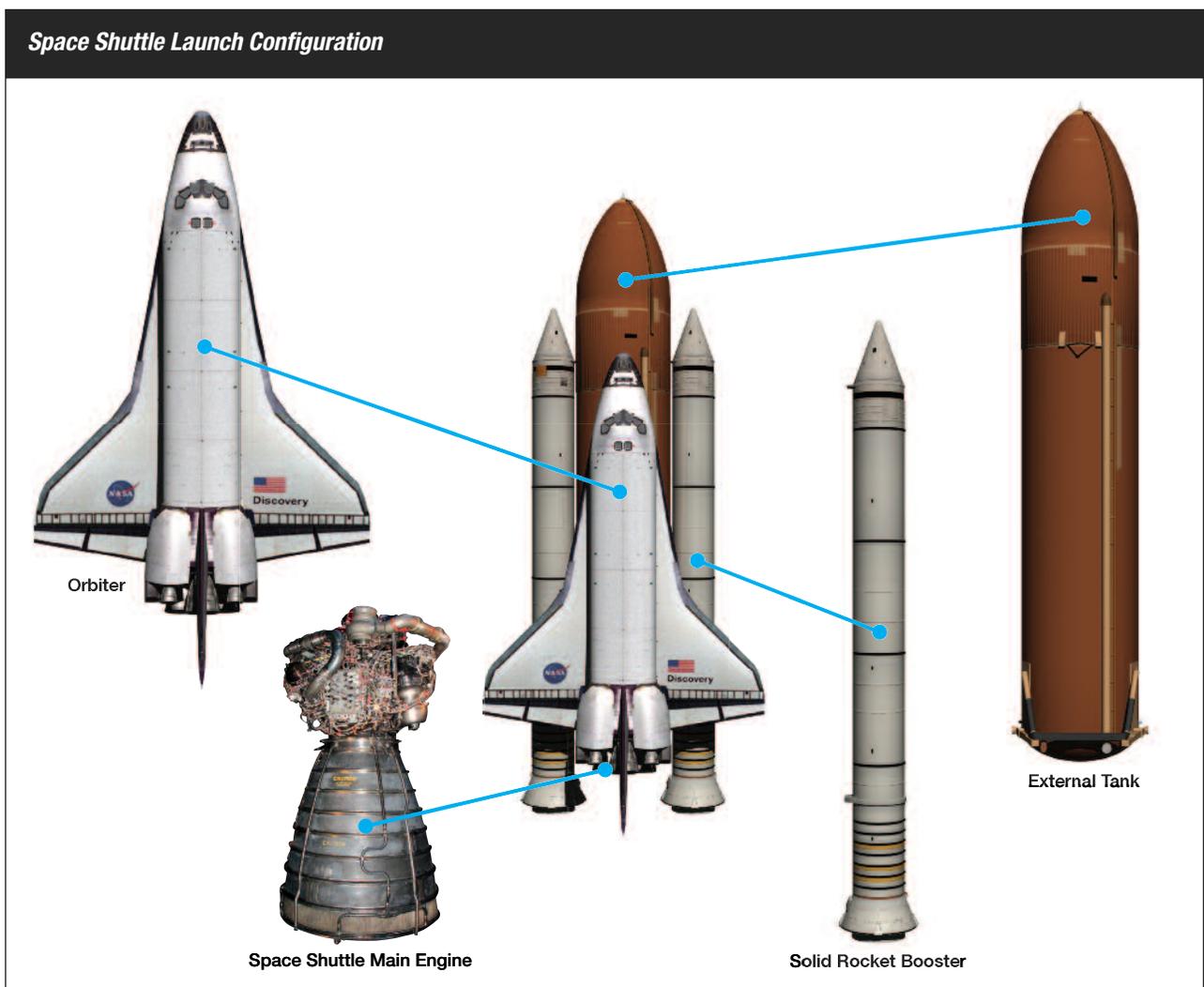
winged vehicle for cross-range capability for re-entry into Earth's atmosphere and the ability to land a heavyweight payload.

These four components provided the shuttle with the ability to accomplish a diverse set of missions over its flight history. The Orbiter's heavy cargo/payload carrying capability, along with the crew habitability and flexibility to operate in space, made this vehicle unique. Because of its lift capability and due-East inclination, the shuttle was able to launch a multitude of satellites, Spacelab modules, science

platforms, interplanetary probes, Department of Defense payloads, and components/modules for the assembly of the International Space Station (ISS).

The shuttle lift capability or payload decreased with increased operational altitude or orbit inclination because more fuel was required to reach the higher altitude or inclination.

Shuttle lift capability was also limited by total vehicle landing weight—different limits for different cases (nominal or abort landing). An abort landing was required if a system failure





during ascent caused the shuttle not to have enough energy to reach orbit or was a hazard to crew or mission. Abort landing sites were located around the world, with the prime abort landing sites being Kennedy Space Center (KSC) in Florida, Dryden Flight Research Center on the Edwards Air Force Base in California, and Europe.

The entire shuttle vehicle, fully loaded, weighed about 2 million kg (4.4 million pounds) and required a combined thrust of about 35 million newtons (7.8 million pounds-force) to reach orbital altitude. Thrust was provided by the boosters for the first 2 minutes and the main engines for the approximately 8 minutes and 30 seconds ascent required for the vehicle to reach orbital speed at the requisite altitude range of 185 to about 590 km (100 to 320 nautical miles).

Once in orbit, the Orbital Maneuvering System engines and Reaction Control System thrusters were used to perform all orbital operations, Orbiter maneuvers, and deorbit. Re-entry required orbital velocity decelerations of about 330 km/hr (204 mph) depending on orbital altitude, which caused the Orbiter to slow and fall back to Earth.

The Orbiter Thermal Protection System, which covered the entire vehicle, provided the protection needed to survive the extreme high temperatures experienced during re-entry. Primarily friction between the Orbiter and the Earth's atmosphere generated temperatures ranging from 927°C (1,700°F) to 1,600°C (3,000°F). The highest temperatures experienced were on the wing leading edge and nose cone.

The time it took the Orbiter to start its descent from orbital velocity of about 28,160 km/hr (17,500 mph) to

a landing speed of about 346 km/hr (215 mph) was 1 hour and 5 minutes.

During re-entry, the Orbiter was essentially a glider. It did not have any propulsion capability, except for the Reaction Control System thrusters required for roll control to adjust its trajectory early during re-entry.

Management of the Orbiter energy from its orbital speed was critical to allow the Orbiter to reach its desired runway target. The Orbiter's limited cross-range capability of about 1,480 km (800 nautical miles) made management of the energy during final phases of re-entry close to the ground—otherwise called terminal area energy management—critical for a safe landing.

The Orbiter performed as a glider during re-entry, thus its mass properties had to be well understood to ensure that the Flight Control System could control the vehicle and reach the required landing site with the right amount of energy for landing. One of the critical components of its aerodynamic flight was to ensure that the Orbiter center of gravity was correctly calculated and entered into the Orbiter flight design process. Because of the tight center of gravity constraints, the cargo bay payloads were placed in the necessary cargo bay location to protect the down weight and center of gravity of the Orbiter for landing. Considering the Orbiter's size, the center of gravity box was only 91 cm (36 in.) long, 5 cm (2 in.) wide, and 5 cm (2 in.) high.

External Tank

The ET was 46.8 m (153.6 ft) in length with a diameter of 8.4 m (27.6 ft), which made it the largest component of the shuttle. The ET contained two internal tanks—one for the storage of

liquid hydrogen and the other for the storage of liquid oxygen. The hydrogen tank, which was the bigger of the two internal tanks, held 102,737 kg (226,497 pounds) of hydrogen. The oxygen tank, located at the top of the ET, held 619,160 kg (1,365,010 pounds) of oxygen. Both tanks provided the fuel to the main engines required to provide the thrust for the vehicle to achieve a safe orbit. During powered flight and ascent to orbit, the ET provided about 180,000 L/min (47,000 gal/min) of hydrogen and about 67,000 L/min (18,000 gal/min) of oxygen to all three Space Shuttle Main Engines with a 6-to-1 mixture ratio of liquid hydrogen to liquid oxygen.

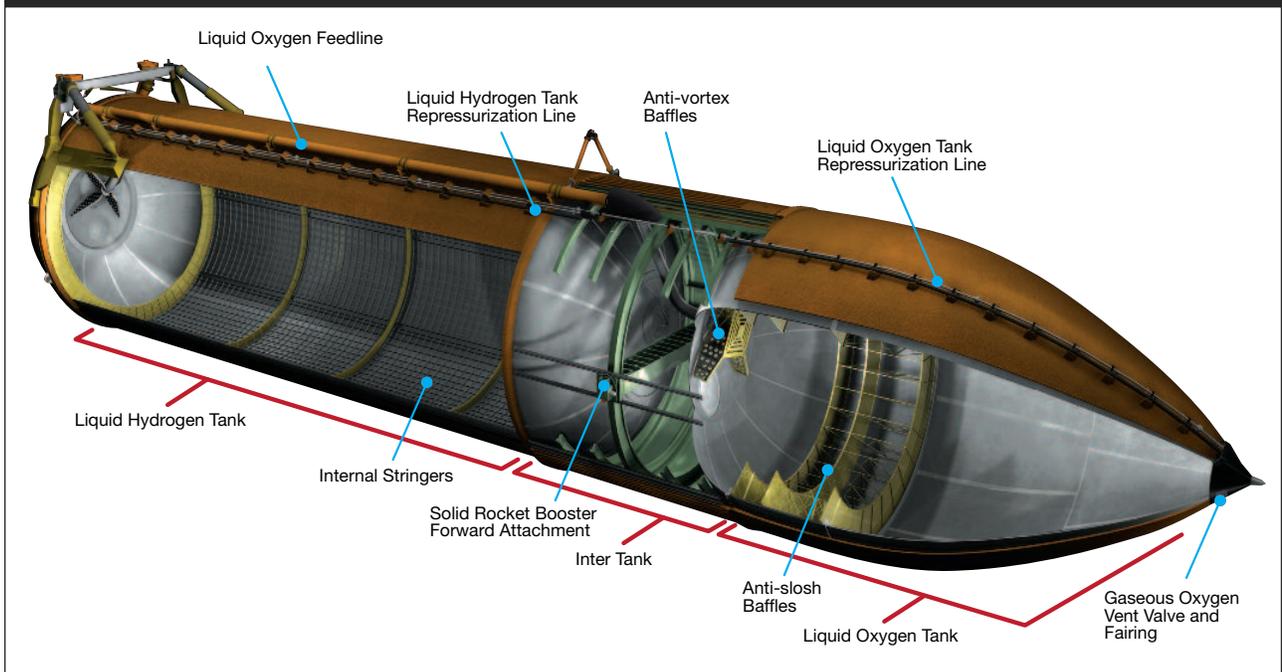
Solid Rocket Boosters

The two SRBs provided the main thrust to lift the shuttle off the launch pad. Each booster provided about 14.7 meganewtons (3,300,000 pounds-force) of thrust at launch, and they were only ignited once the three main engines reached the required 104.5% thrust level for launch. Once the SRBs were ignited, they provided about 72% of the thrust required of the entire shuttle at liftoff and through the first stage, which ended at SRB separation.

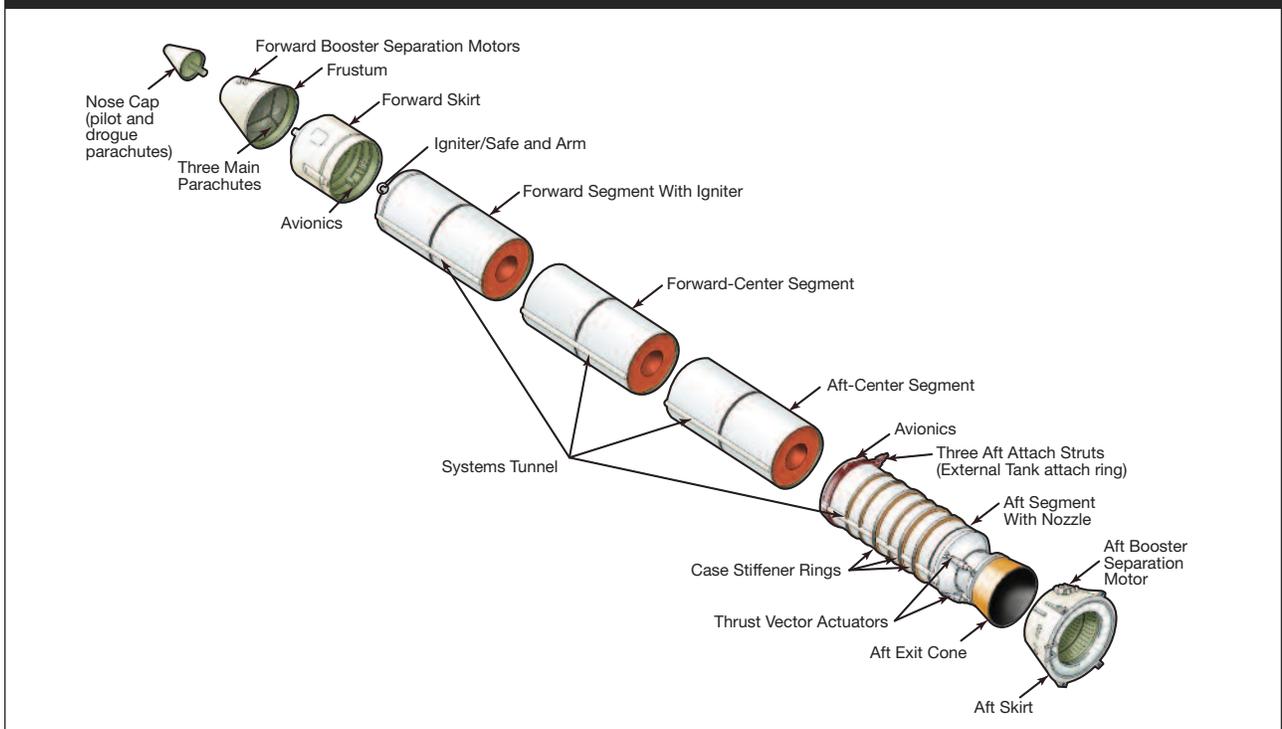
The SRB thrust vector control system enabled the nozzles to rotate, allowing the entire shuttle to maneuver to the required ascent trajectory during first stage. Two minutes after launch, the spent SRBs were jettisoned, having taken the vehicle to an altitude of about 45 km (28 miles). Not only were the boosters reusable, they were also the largest solid propellant motors in use then. Each measured about 45.4 m (149 ft) long and about 3.6 m (12 ft) in diameter.



External Tank



Solid Rocket Boosters





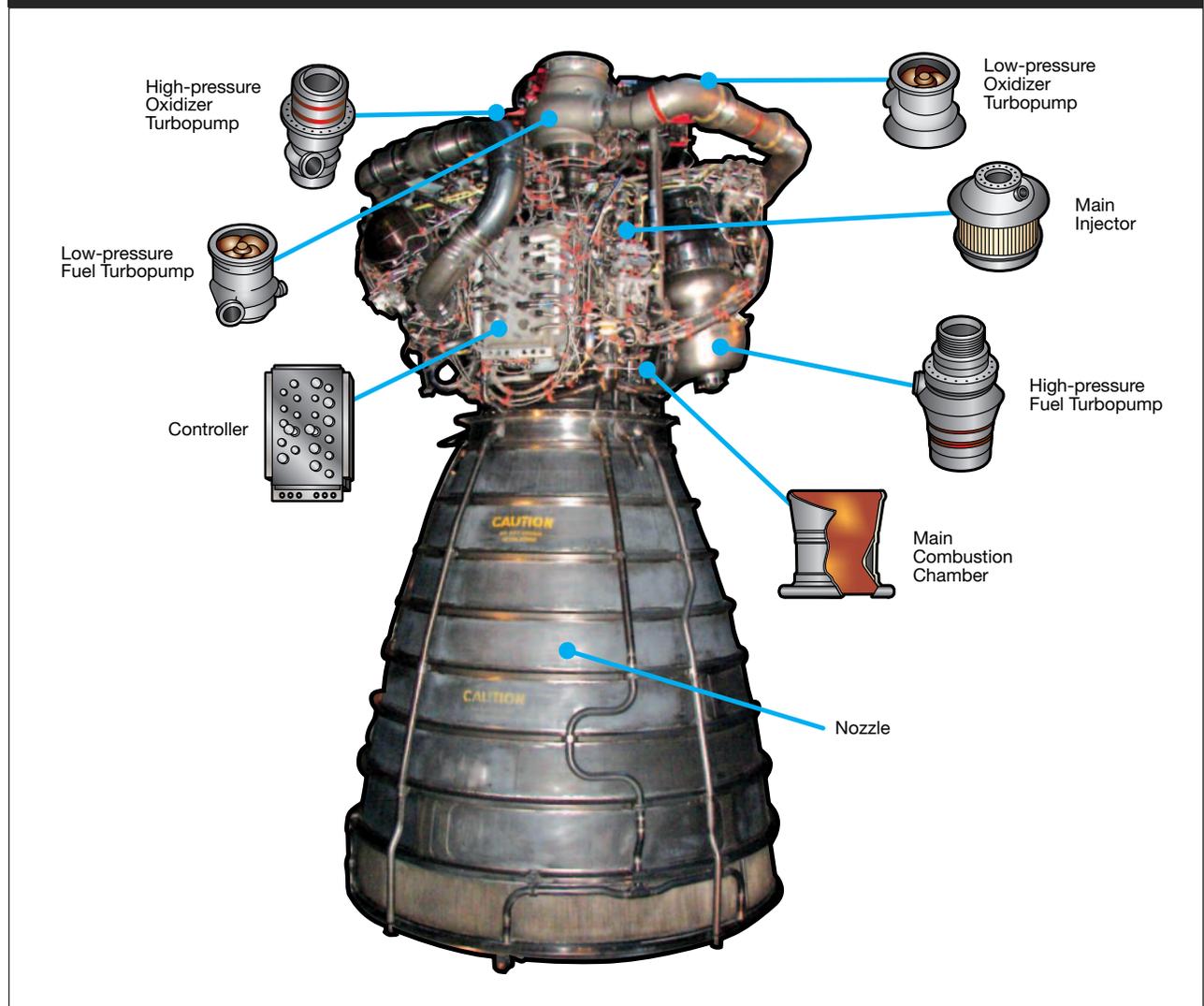
Space Shuttle Main Engines

After SRB separation, the main engines provided the majority of thrust required for the shuttle to reach orbital velocity. Each main engine weighed about 3,200 kg (7,000 pounds). With a total length of 4.3 m (14 ft), each engine, operating at the 104.5% power level, provided a thrust level of about 1.75 meganewtons (394,000 pounds-force) at sea level and about 2.2 meganewtons

(492,000 pounds-force) at vacuum throughout the entire 8 minutes and 30 seconds of powered flight. The engine nozzle by itself was 2.9 m (9.4 ft) long with a nozzle exit diameter of 2.4 m (7.8 ft). Due to the high heat generated by the engine thrust, each engine contained 1,082 tubes throughout its entire diameter, allowing circulation of liquid hydrogen to cool the nozzle during powered flight. The main engines were a complex piece of

machinery comprised of high- and low-pressure fuel and oxidizer pumps, engine controllers, valves, etc. The engines were under constant control by the main engine controllers. These consisted of an electronics package mounted on each engine to control engine operation under strict and critical performance parameters. The engines ran at 104.5% performance for much of the entire operation, except when they were throttled down to about

Space Shuttle Main Engine





James Thompson, Jr.
*Space Shuttle Main Engine project manager (1974-1982).
 Deputy NASA administrator (1989-1991).*



“A major problem we had to solve for the Space Shuttle Main Engine was called rotary stability subsynchronous whorl. After numerous theories and suggestions on turbo machinery, Joe Stangler at Rocketdyne and his team came up with the vortex and vaporizing theory down in the passages. He proposed putting a paddle in the flow stream and killing the vortex. Even though I thought Joe’s theory was crazy, 2 weeks before the program review they had success. Government, industries, and universities all contributed to its success.”

72% during first stage to preclude having the vehicle exceed structural limits during high dynamic pressure as well as close to main engine shutdown to preclude the vehicle from exceeding 3 gravitational force (3g) limits.

The only manual main engine control capability available to the crew was the manual throttle control, which allowed the crew to decrease engine performance from 104.5% to a level of 72% if required for vehicle control. The main engines had the capability to gimbal about 10.5 degrees up and down and 8.5 degrees to either side to change the thrust direction required for changes in trajectory parameters.

Orbiter

The Orbiter was the primary component of the shuttle; it carried the crew members and mission cargo/payload hardware to orbit. The Orbiter was about 37.1 m (122 ft) long with a wingspan of

about 23.8 m (78 ft). The cargo/payload carrying capacity was limited by the 18.3-m- (60-ft)-long by 4.6-m- (15-ft)-wide payload bay. The cargo/payload weighed up to 29,000 kg (65,000 pounds), depending on the desired orbital inclination. The Orbiter payload bay doors, which were constructed of graphite epoxy composite material, were 18.3 m (60 ft) in length and 4.5 m (15 ft) in diameter and rotated through an angle of 175 degrees. A set of radiator panels, affixed to each door, dissipated heat from the crew cabin avionics systems.

The first vehicle, Columbia, was the heaviest Orbiter fabricated due to the installation of additional test instrumentation required to gather data on vehicle performance. As each Orbiter was fabricated, the test instrumentation was deleted and system changes implemented, resulting in each subsequent vehicle being built lighter.

The Orbiter crew cabin consisted of the flight deck and the middeck and

could be configured for a maximum crew size of seven astronauts, including their required equipment to accomplish the mission objectives. The flight deck contained the Orbiter cockpit and aft station where all the vehicle and systems controls were located. The crew used six windows in the forward cockpit, two windows overhead, and two windows looking aft for orbit operations and viewing. The middeck was mostly the crew accommodations area, and it housed all the crew equipment required to live and work in space. The middeck also contained the three avionics bays where the Orbiter electronic boxes were installed. Due to their limited power generation capability, the Orbiter fuel cells consumables (power generation cryogenics) provided mission duration capability on the order of about 12 to 14 days, dependent on vehicle configuration.

In 2006, NASA put into place the Station-to-Shuttle Power Transfer System, which allowed the ISS to provide power to the Orbiter vehicle, thereby allowing the Orbiter to have a total mission duration of about 16 days. The Orbiter configuration (amount of propellant loaded in the forward and aft propellant tanks, payload mounting hardware in the payload bay, loading of cryogenic tanks required for power generation, crew size, etc.) was adjusted and optimized throughout the pre-mission process.

Because of its payload size and robotic arm capability, the Orbiter could be configured to perform as a platform for different cargo/payload hardware configurations. In the total 132 Space Shuttle missions (as of October 2010) over a period of 29 years,



the Orbiter deployed a multitude of satellites for Earth observation and telecommunications; interplanetary probes such as Galileo/Jupiter spacecraft and Magellan/Venus Radar Mapper; and great observatories that included the Hubble Space Telescope, Compton Gamma Ray Observatory, and Chandra X-ray Observatory. The Orbiter even functioned as a science platform/laboratory; e.g., Spacelab, Astronomy Ultraviolet Telescope, US Microgravity Laboratory, US Microgravity Payload, etc. Aside from the experiments and satellite deployments the shuttle performed, its most important accomplishment was the delivery and assembly of the ISS.

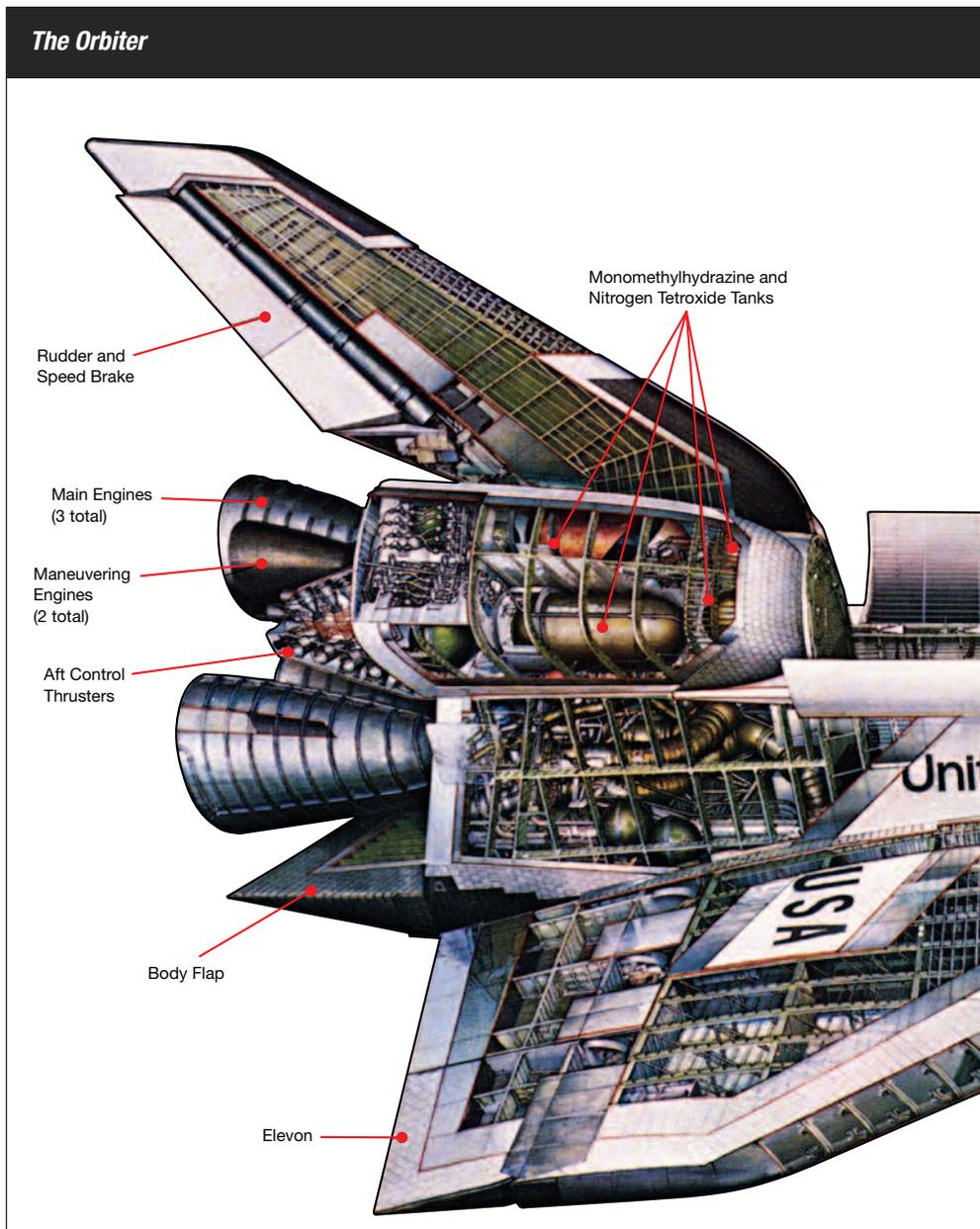
Space Shuttle Reusability

All components of the Space Shuttle vehicle, except for the ET, were designed to be reusable flight after flight. The ET, once jettisoned from the Orbiter, fell to Earth where atmospheric heating caused the tank to break up over the ocean.

The SRBs, once jettisoned from the tank, parachuted back to the ocean where they were recovered by special ships and brought back to KSC. With their solid propellant spent, the boosters were de-stacked and shipped back to aerospace and defense company Thiokol in Utah for refurbishment and reuse. The SRBs were thoroughly inspected after every mission to ensure that the components were not damaged and could be refurbished for another flight. Any damage found was either repaired or the component was discarded.

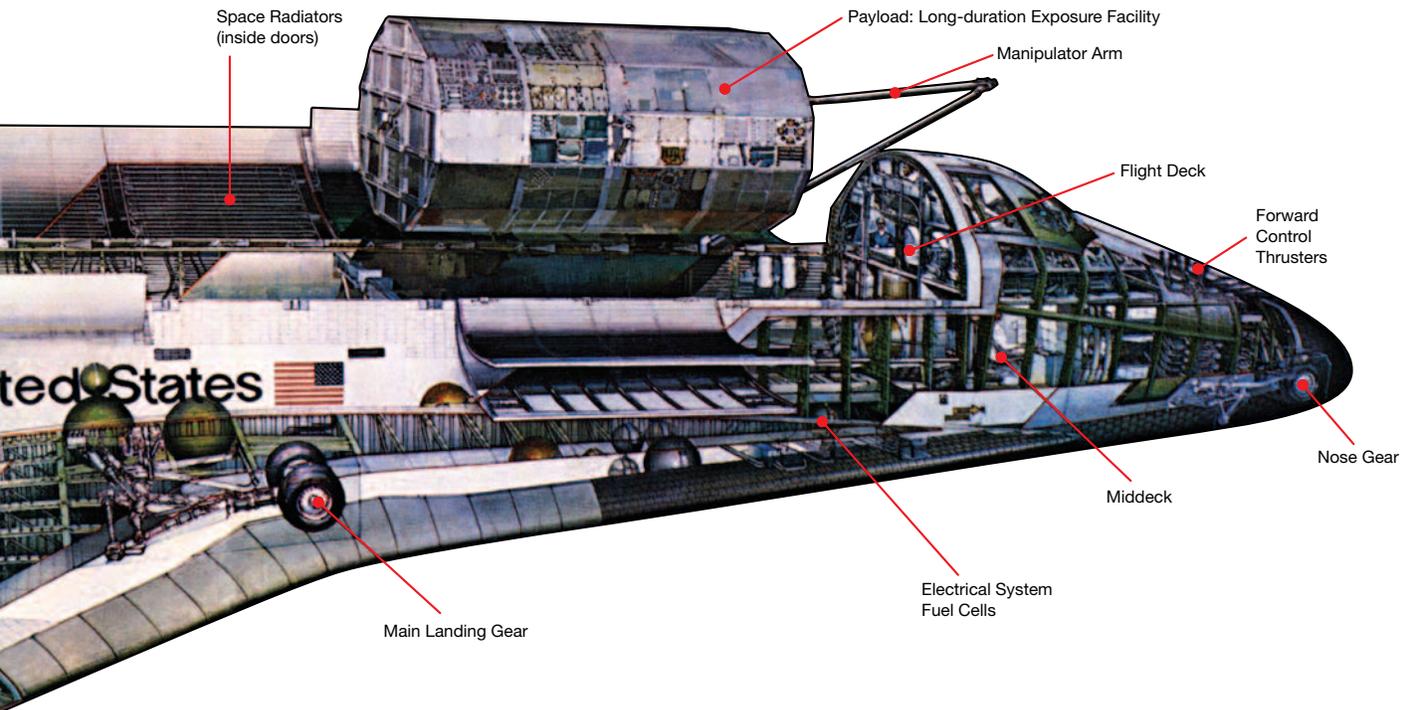
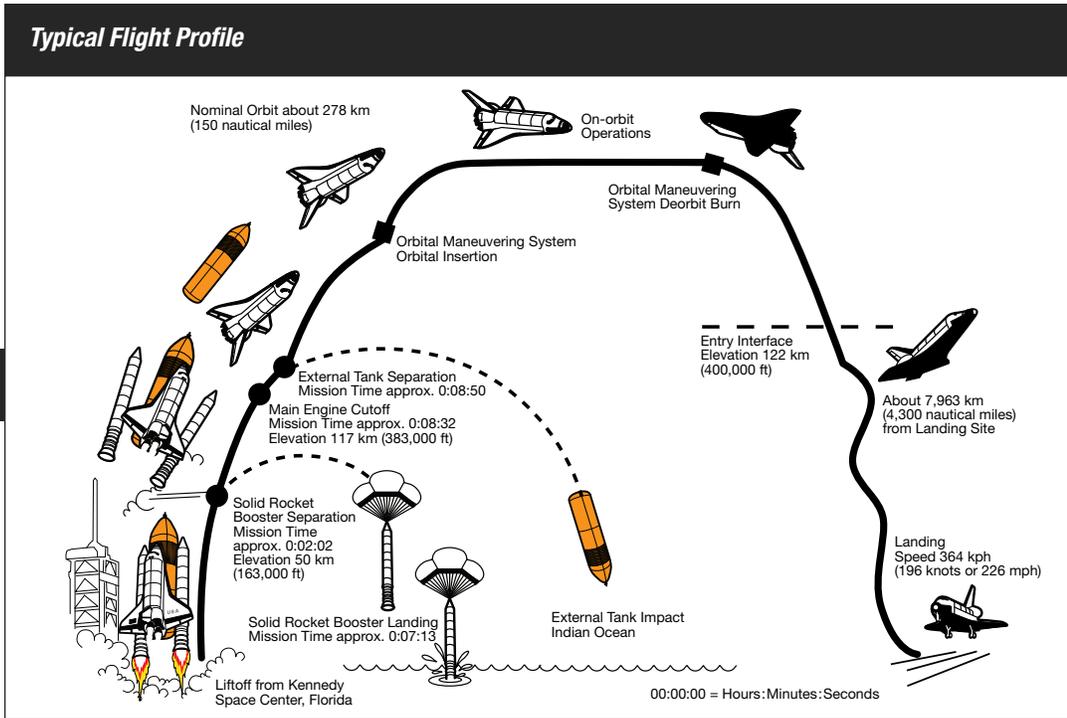
The Orbiter was the only fully reusable component of the shuttle system. Each Orbiter was designed and certified for 100 space missions and required about 5 months, once it landed, to service the different systems and configure the payload bay to support requirements for its next mission. NASA replaced the components only when they

sustained a system failure and could not be repaired. Even though certified for 100 missions, Discovery, Atlantis, and Endeavour completed 39, 32, and 25 missions, respectively, by October 2010. Challenger flew 10 missions and Columbia flew 28 missions before their loss on January 28, 1986, and February 1, 2003, respectively.





Typical Flight Profile





Automation, Autonomy, and Redundancy

The Space Shuttle was the first space vehicle to use the fly-by-wire computerized digital flight control system. Except for manual switch throws for system power-up and certain valve actuations, control of the Orbiter systems was through the general purpose computers installed in the forward avionics bay in the middeck.

Each Orbiter had five hardware-identical general purpose computers; four functioned as the primary means to control the Orbiter systems, and one was used as a backup should a software anomaly or problem cause the loss of the four primary computers. During ascent and re-entry—the critical phases of flight—four general purpose computers were used to control the spacecraft. The primary software, called the Primary Avionics Software System, was divided into two major systems: system software, responsible for computer operation, synchronization, and management of input and output operations; and applications software, which performed the actual duties required to fly the vehicle and operate the vehicle systems.

Even though simple in their architecture compared to today's computers, the general purpose computers had a complex redundancy management scheme in which all four primary computers were tightly coupled together and processed the same information at the same time. This tight coupling was achieved through synchronization steps and cross-check results of their processes about 440 times per second. The original International Business Machines computers had only about 424 kilobytes of memory each. The central processing unit could process

about 400,000 instructions per second and did not have a hard disk drive capability. These computers were replaced in April 1991 (first flight was STS-37) with an upgraded model that had about 2.5 times the memory capacity and three times the processor speed. To protect against corrupt software, the general purpose computers had a backup computer that operated with a completely different code independent of the Primary Avionics Software System. This fifth computer, called the Backup Flight System, operated in the background, processing the same critical ascent/re-entry functions in case the four general purpose computers failed or were corrupted by problems with their software. The Backup Flight System could be engaged at any moment only by manual crew command, and it also performed oversight and management of Orbiter noncritical functions. For the first 132 flights of the Space Shuttle Program, the Backup Flight System computer was never engaged and, therefore, was not used for Orbiter control.

The overall avionics system architecture that used the general purpose computer redundancy was developed with a redundancy requirement for fail-operational/fail-safe capability. These redundancy schemes allowed for the loss of redundancy in the avionics systems and still allowed continuation of the mission or safe landing of the Orbiter. All re-entry critical avionics functions, such as general purpose computers, aero surface actuators, rate gyro assemblies, accelerometer assemblies, air data transducer assemblies, etc., were designed with four levels of redundancy. This meant that each of these functions was controlled by four avionic boxes that performed the same specific function. The loss of the first box allowed for

safe continuation of the mission. The loss of the second box still allowed the function to work properly with only two remaining boxes, which subsequently allowed for safe re-entry and landing of the Orbiter. Other critical functions were designed with only triple redundancy, which meant that fail-operational/fail-safe reliability allowed the loss of two of the boxes before the function was lost.

The avionics systems redundancy management scheme was essentially controlled via computer software that operated within the general purpose computers. This scheme was to select the middle value of the avionics components when the systems had three or four avionics boxes executing the same function. On loss of the first box, the redundancy management scheme would down mode to the “average value” of the input received from the functioning boxes. Upon the second box failure, the scheme would further down mode to the “use value,” which essentially meant that the function was performed by using input data from only one remaining unit in the system. This robust avionics architecture allowed the loss of avionics redundancy within a function without impacting the ability of the Orbiter to perform its required mission.

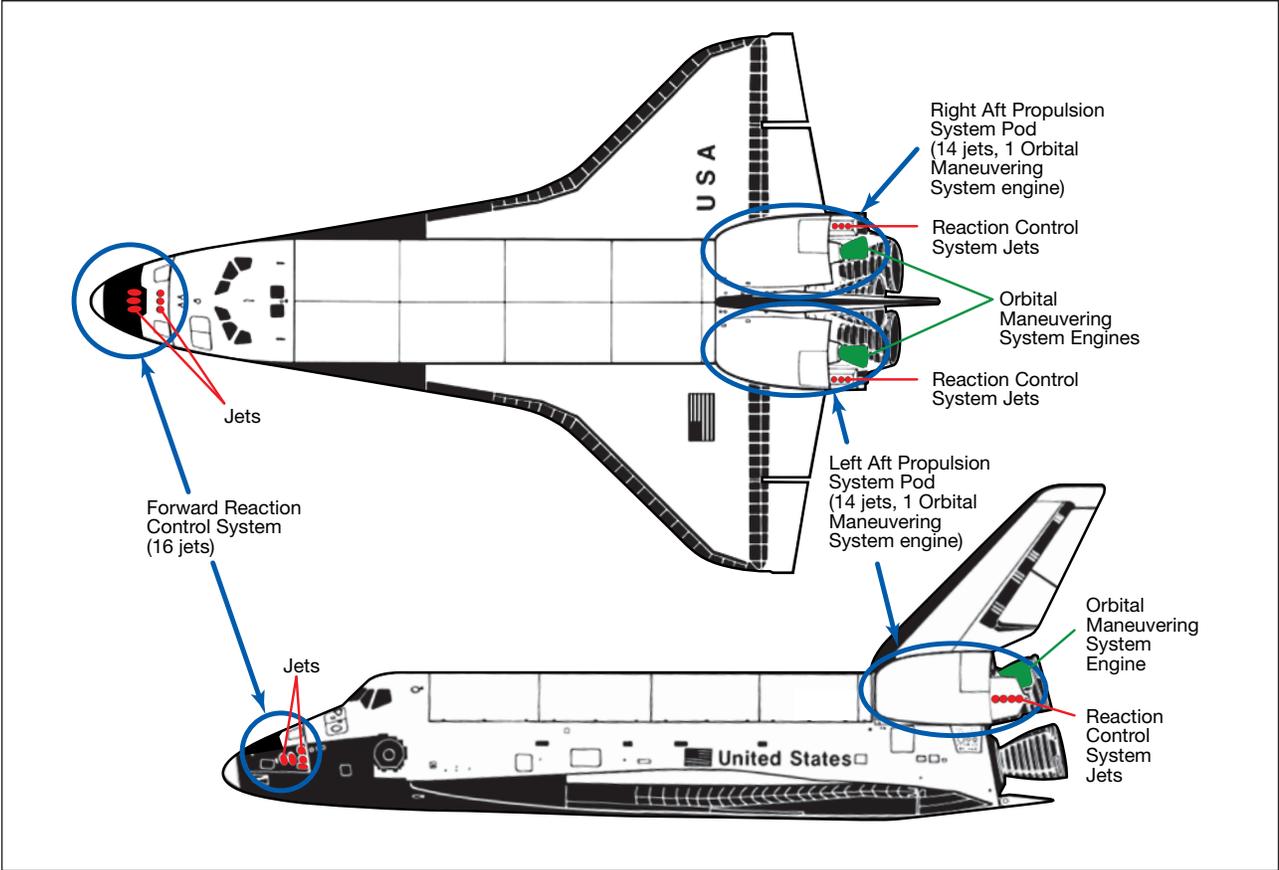
Maneuverability, Rendezvous, and Docking Capability

Maneuverability

The Orbiter was very maneuverable and could be tightly controlled in its pointing accuracy, depending on the objective it was trying to achieve. The Orbiter controllability and pointing capability was performed by the use of 44 Reaction Control System thrusters installed both in the forward and the aft portions of the



Reaction Control Thrusters and Orbital Maneuvering System



vehicle. Of the 44 thrusters, six were Reaction Control Systems and each had a thrust level of only 111 newtons (25 pounds-force). The remaining 38 thrusters were considered primary thrusters and each had a thrust level of 3,825 newtons (860 pounds-force).

The total thruster complement was divided between the forward thrusters located forward of the crew cabin, and the aft thrusters located on the two Orbital Maneuvering System pods in the tail of the Orbiter. The forward thrusters (total of 16) consisted of 14 primary thrusters and two vernier thrusters. Of the 28 thrusters in the aft, 24 were primary thrusters and four

were vernier thrusters. The thrusters were installed on the Orbiter in such a way that both the rotational and the translational control was provided to each of the Orbiter's six axes of control with each axis having either two or three thrusters available for control.

The Orbital Maneuvering System provided propulsion for the shuttle. During the orbit phase of the flight, it was used for the orbital maneuvers needed to achieve orbit after the Main Propulsion System had shut down. It was also the primary propulsion system for orbital transfer maneuvers and the deorbit maneuver.

The general purpose computers also controlled the tight Orbiter attitude and pointing capability via the Orbiter Digital Auto Pilot—a key piece of application software within the computers. During orbit operations, the Digital Auto Pilot was the primary means for the crew to control Orbiter pointing by the selection of different attitude and attitude rate deadbands, which varied between +/-1.0 and 5.0 degrees for attitude and +/-0.02 and 0.2 deg/sec for attitude rate. The Digital Auto Pilot could perform three-axis automatic maneuver, attitude tracking, and rotation about any axis or body vector. Crew interface to the Digital



Auto Pilot was via the Orbiter cathode ray tubes/keyboard interface, which allowed the crew to control parameters in the software. With very accurate control of its orientation, the Orbiter could provide a pointing capability to any part of the celestial sky as required to accomplish its mission objectives.

Rendezvous and Docking

The shuttle docked to, grappled, deployed, retrieved, and otherwise serviced a more diverse set of orbiting objects than any other spacecraft in history. It became the world's first general purpose space rendezvous vehicle. Astronauts retrieved payloads no larger than a refrigerator and docked to targets as massive as the ISS, despite the shuttle being designed without specific rendezvous targets in mind. In fact, the shuttle wasn't designed to physically dock with anything; it was intended to reach out and grapple objects with its robotic arm.

A rendezvous period lasted up to 4 days and could be divided into three phases: ground targeted; on-board targeted; and human-piloted proximity operations. The first phase began with launch into a lower orbit, which lagged the target vehicle. The Orbiter phased toward the target vehicle due to the different orbital rates caused by orbital altitude. Mission Control at Johnson Space Center tracked the shuttle via ground assets and computed orbital burn parameters to push the shuttle higher toward the target vehicle. As the shuttle neared the target, it transitioned to on-board targeting using radar and star trackers. These sensors provided navigation data that allowed on-board computers to calculate subsequent orbital burns to reach the target vehicle.

The final stage of rendezvous operations—proximity operations—began with the Orbiter's arrival within thousands of meters (feet) of the target orbital position. During proximity operations, the crew used their highest fidelity sensors (laser, radar, or direct measurement out the window with a camera) to obtain the target vehicle's relative position. The crew then transitioned to manual control and used the translational hand controller to delicately guide the Orbiter in for docking or grappling operations.

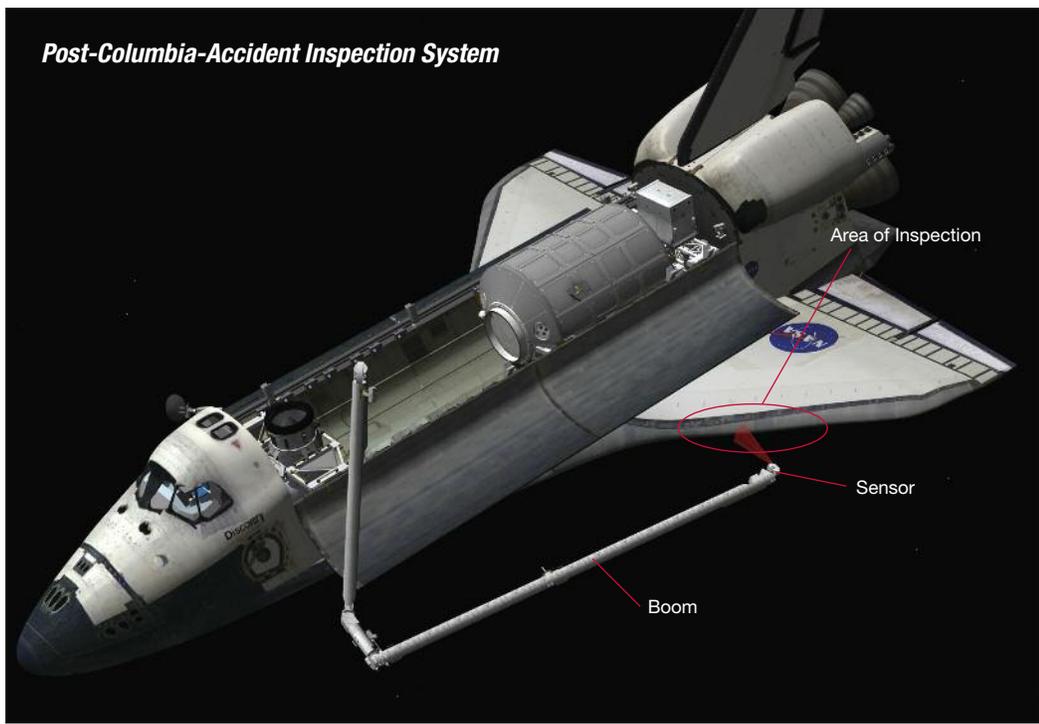
The first rendezvous missions targeted satellite objects less massive than the shuttle and grappled these objects with its robotic arm. During the proximity operations phase, the commander only had a docking camera view and accompanying radar information to guide the vehicle. Other astronauts aimed payload bay cameras at the target and recorded elevation angles, which were charted on paper to give the commander awareness of the Orbiter's position relative to the target. Once the commander maneuvered into a position where the target was above the payload bay, a mission specialist grappled the target with the robotic arm. This method proved highly reliable and applicable to a wide array of rendezvous missions.

Shuttle rendezvous needed a new strategy to physically dock with large vehicles: the Russian space station Mir and the ISS. Rendezvous with larger space stations required more precise navigation, stricter thruster plume limitations, and tighter tolerances during docking operations. New tools such as the laser sensors provided highly accurate range and range rate information for the crew. The laser was mounted in the payload bay and its data were routed into the shuttle cabin but could not be incorporated directly

into the shuttle guidance, navigation, and control software. Instead, data were displayed on and controlled by a laptop computer mounted in the aft cockpit. This laptop hosted software called the Rendezvous Proximity Operations Program that displayed the Orbiter's position relative to the target for increased crew situational awareness. This display was used extensively by the commander to manually fly the vehicle from 610 m (2,000 ft) to docking.

This assembly of hardware and software aptly met the increased accuracy required by delicate docking mechanisms and enabled crews to pilot the massive shuttle within amazing tolerances. In fact, during the final 0.9 m (3 ft) of docking with the ISS, the Orbiter had to maintain a 7.62-cm (3-in.) lateral alignment cylinder and the closing rate had to be controlled to within 0.02 m/sec (0.06 ft/sec). The commander could control this with incredibly discrete pulses of the Reaction Control System thrusters. Both the commander and the pilot were trained extensively in the art of shuttle proximity operations, learning techniques that allowed them to pilot the Orbiter to meet tolerances. The shuttle was never meant to be piloted to this degree of accuracy, but innovative engineering and training made these dockings uneventful and even routine.

The success of shuttle rendezvous missions was remarkable considering its operational complexity. Spacecraft rendezvous is an art requiring the highly scripted choreography of hardware systems, astronauts, and members of Mission Control. It is a precise and graceful waltz of billions of dollars of hardware and human decision making.



Post-Columbia-Accident Inspection System

The Orbiter Boom Sensor System inspects the wing leading edge. This system was built for inspections after the Columbia accident (STS-107 [2003]).

STS-88 (1998) Endeavour's Shuttle Robotic Arm grapples the Russian Module Zarya for berthing onto the International Space Station (ISS) Node 1, thus beginning the assembly sequence for the ISS.

Robotic Arm/Operational Capability

The Canadian Space Agency provided the Shuttle Robotic Arm. It was designed, built, and tested by Spar Aerospace Ltd., a Canadian Company. The electromechanical arm measured about 15 m (50 ft) long and 0.4 m (15 in.) in diameter with a six-degree-of-freedom rotational capability, and it consisted of a manipulator arm that was under the control of the crew via displays and control panels located in the Orbiter aft flight deck. The Shuttle Robotic Arm was comprised of six joints that corresponded roughly to the joints of a human arm and could handle a payload weighing up to 29,000 kg (65,000 pounds). An end effector was used to grapple a payload or any other fixture and/or component that had a grapple fixture for handling by the arm.





Even though NASA used the Shuttle Robotic Arm primarily for handling payloads, it could also be used as a platform for extravehicular activity (EVA) crew members to attach themselves via a portable foot restraint. The EVA crew member, affixed to the portable foot restraint grappled by the end effector, could then be maneuvered around the Orbiter vehicle as required to accomplish mission objectives.

Following the Return to Flight after the loss of Columbia, the Shuttle Robotic Arm was used to move around the Orbiter Boom Sensor System, which allowed the flight crew to inspect the Thermal Protection System around the entire Orbiter or the reinforced carbon-carbon panels installed on the leading edge of the wings.

During buildup of the ISS, the Shuttle Robotic Arm was instrumental in the handling of modules carried by the Orbiter—a task that would not have been possible without the use of this robotic capability.

Extravehicular Activity Capability

The Space Shuttle Program provided a dramatic expansion in EVA capability for NASA, including the ability to perform tasks in the space environment and ways to best protect and accommodate a crew member in that environment. The sheer number of EVAs performed during the course of the program resulted in a significant increase in knowledge of how EVA systems and EVA crew members perform.

Prior to the start of the program, a total of 38 EVAs were performed by all US

space programs combined, including Gemini, Apollo, and Skylab. During previous programs, EVAs focused primarily on simple tasks, such as the jettison of expended hardware or the collection of geology samples. The Space Shuttle Program advanced EVA capability to construction of massive space structures, high-strength maneuvers, and repair of complicated engineering components requiring a combination of precision and gentle handling of sensitive materials and structures. As of October 2010, the shuttle accomplished about 157 EVAs in 132 flights. Of those EVAs, 105 were dedicated to ISS assembly and repair tasks. Shuttle EVA crews succeeded in handling and manipulating elements as large as 9,000 kg (20,000 pounds); relocating and installing large replacement parts; capturing and repairing failed satellites; and performing surgical-like repairs of delicate solar arrays, rotating joints, and much more.

The Orbiter's EVA capability consisted of several key engineering components and equipment. For a crew member to step out of the shuttle and safely enter the harsh environment of space, that crew member had to use the integrated airlock, an extravehicular mobility unit spacesuit, a variety of EVA tools, and EVA translation and attachment aids attached to the vehicle or payload. EVA tools consisted of a suite of components that assisted in handling and translating cargo, translating and stabilizing at the work site, operating manual mechanisms, and attaching bolts and fasteners, often with relatively precise torque requirements. Photo and television operations provided documentation of the results for future troubleshooting, when necessary.

Extravehicular Mobility Unit

The extravehicular mobility unit was a fully self-sufficient individual spacecraft providing critical life support systems and protection from the harsh space environment. Unlike previous suits, the shuttle suit was designed specifically for EVA and was the cornerstone component for safe conduct of EVA during the shuttle era. It operated at 0.03 kgf/cm² (4.3 psi) pressure in the vacuum environment and provided thermal protection for interfacing with environments and components from -73°C (-100°F) to 177°C (350°F). It provided oxygen and removed carbon dioxide during an EVA, and it supplied battery power to run critical life support and ancillary extravehicular mobility unit systems, including support lights, cameras, and radio. The suit, which also provided crew members with critical feedback on system operations during EVA, was the first spacesuit controlled by a computer.

Future space programs will benefit tremendously from NASA's EVA experience during the shuttle flights. To ensure success, the goal has been and always will be to design for EVAs that are as simple and straightforward as possible. Fewer and less-complicated provisions will be required for EVA interfaces on spacecraft, and functions previously thought to require complicated and automated systems can now rely on EVA instead. During the shuttle era, NASA took the training wheels off of EVA capability and now has a fully developed and highly efficient operational resource in support of both scheduled and contingency EVA tasks.



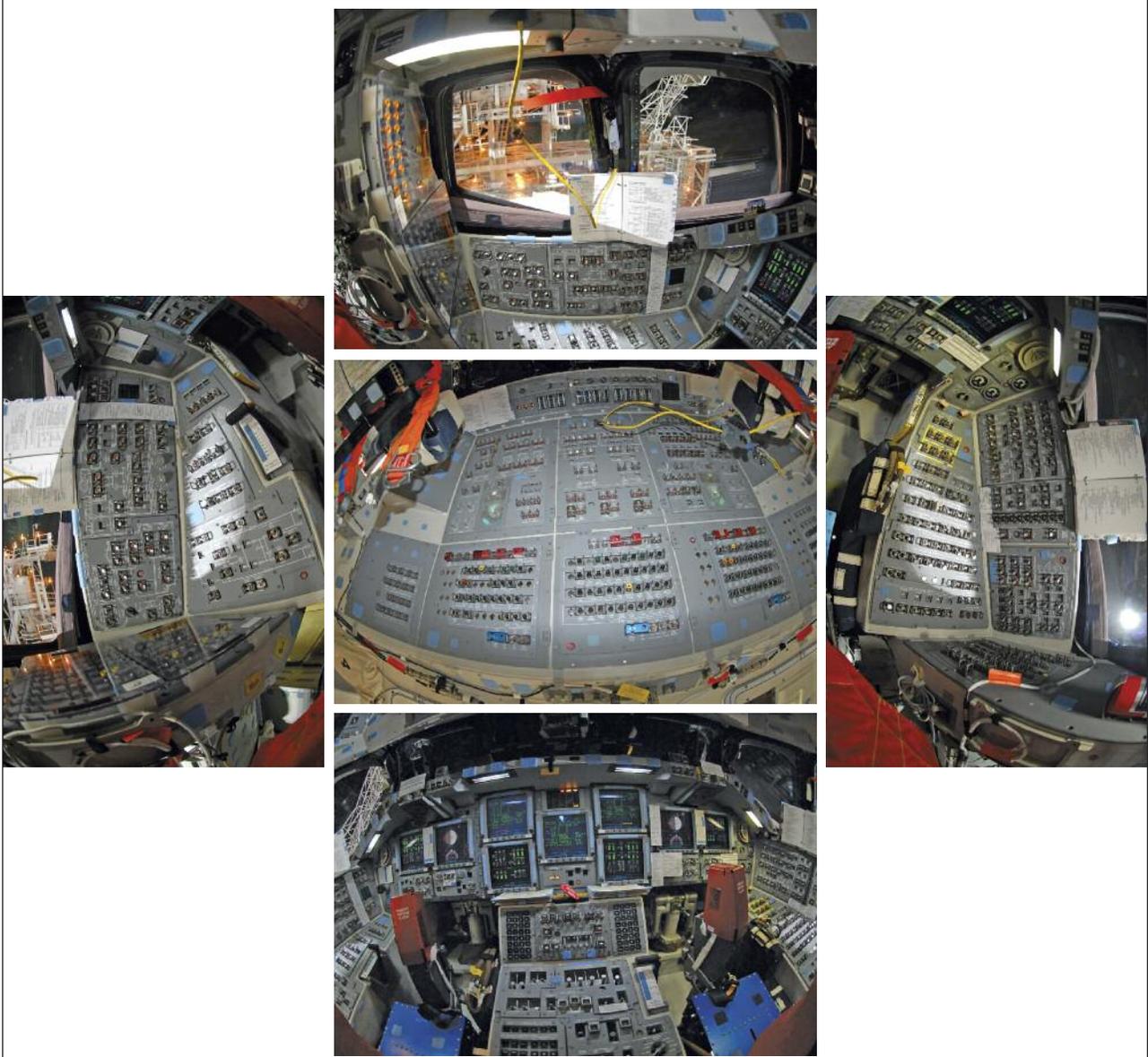
Crew Compartment Accommodation for Crew and Payloads

The Orbiter's crew cabin had a habitable volume of 71.5 m³ (2,525 ft³) and consisted of three levels: flight

deck, middeck, and utility area. The flight deck, located on the top level, accommodated the commander, pilot, and two mission specialists behind them. The Orbiter was flown and controlled from the flight deck. The middeck, located

directly below the flight deck, accommodated up to three additional crew members and included a galley, toilet, sleep locations, storage lockers, and the side hatch for entering and exiting the vehicle. The Orbiter airlock was also located

Flight Deck



Flight deck showing the commander and pilot seats, along with cockpit controls.

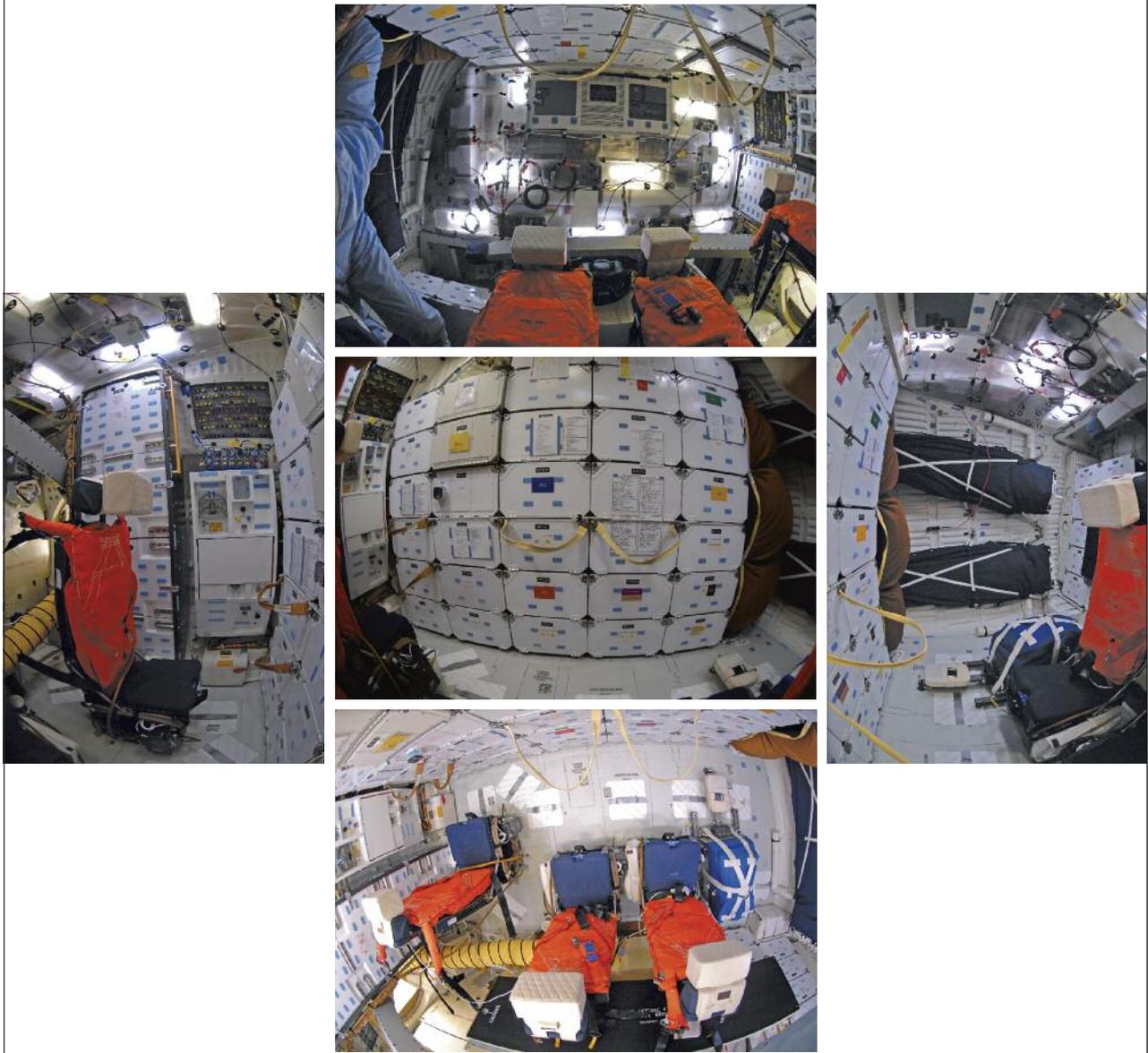


in the middeck area; it allowed up to three astronauts, wearing extravehicular mobility unit spacesuits, to perform an EVA in the vacuum of space. The standard practice was for only two crew members to perform an EVA.

Most of the day-to-day mission operations took place on the middeck. The majority of hardware required for crew members to live, work, and perform their mission objectives was stowed in stowage lockers and bags within the middeck volume. The entire

middeck stowage capability was equivalent to 127.5 middeck lockers in which each locker was about 0.06 m³ (2 ft³) in volume. This volume could accommodate all required equipment and supplies for a crew of seven for as many as 16 days.

Middeck



Crew compartment middeck configuration showing the forward middeck lockers in Avionics Bay 1 and 2, crew seats, and sleeping bags.



Performance Capabilities and Limitations

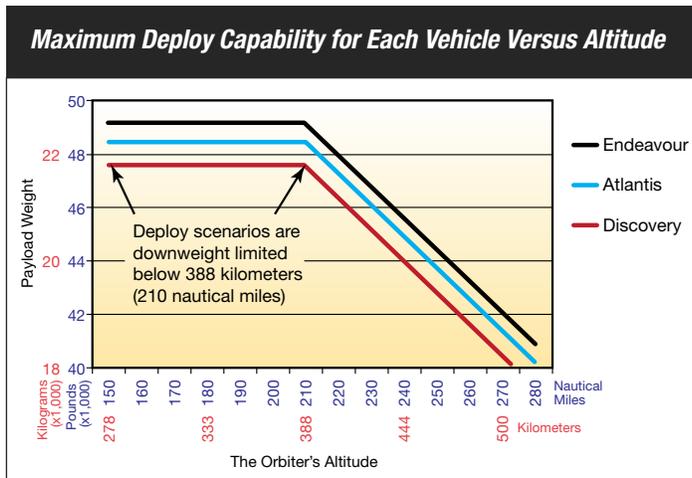
Throughout the history of the program, the versatile shuttle vehicle was configured and modified to accomplish a variety of missions, including: the deployment of Earth observation and communication satellites, interplanetary probes, and scientific observatories; satellite retrieval and repair; assembly; crew rotation; science and logistics resupply of both the Russian space station Mir and the ISS, and scientific research and operations. Each mission type had its own capabilities and limitations.

Deploying and Servicing Satellites

The largest deployable payload launched by the shuttle in the life of the program was the Chandra X-ray Observatory. Deployed in 1999 at an inclination of 28.45 degrees and an altitude of about 241 km (130 nautical miles), Chandra—and the support equipment deployed with it—weighed 22,800 kg (50,000 pounds).

In 1990, NASA deployed the Hubble Space Telescope into a 28.45-degree inclination and a 555-km (300-nautical-mile) altitude. Hubble weighed 13,600 kg (30,000 pounds). Five servicing missions were conducted over the next 19 years to upgrade Hubble’s science instrumentation, thereby enhancing its scientific capabilities. These subsequent servicing missions were essential in

Atlantis’ (STS-125 [2009]) robotic arm lifts Hubble from the cargo bay and is moments away from releasing the orbital observatory to start it on its way back home to observe the universe.



The up-mass capability of the shuttle decreased relative to the orbital altitude.





Kenneth Reightler

*Captain, US Navy (retired).
Pilot on STS-48 (1991) and
STS-60 (1994).*



"When I think about the legacy of the Space Shuttle Program in terms of scientific and engineering accomplishments, the word that comes to mind is versatility. Each of my flights involved so many projects and experiments, all involving such a wide variety of science and engineering, it seems almost impossible to catalog them. It is hard to imagine a spacecraft other than the Space Shuttle that could accommodate such an extensive list on just one flight.

"The shuttle's large cargo bay could hold large, complex structures or many small experiments, an amazing variety of experiments. We carried big, intricate satellites as well as smaller, simpler ones able to be deployed remotely or using robotic and/or human assistance.

"For me, as an engineer and a pilot, it was an unbelievable experience to now be conducting world-class science in a range of disciplines with the potential to benefit so many people back on Earth, such as experiments designed to help produce vaccines used to eradicate deadly diseases, to produce synthetic hormones, or to develop countermeasures for the effects of aging. I consider it to be a rare honor and privilege to have operated experiments to which so many scientists and engineers had devoted their time, energy, and thought. In some cases, people had spent entire careers preparing for the day when their experiments could be conducted, knowing that they could only work in space and there might be only one chance to try.

"Each of my flights brought moments of pride and satisfaction in such singular experiences."

correcting the Hubble mirror spherical aberration, thereby extending the operational life of the telescope and upgrading its science capability.

Assembling the International Space Station

The ISS Node 1/Unity module was launched on STS-88 (1998), thus beginning the assembly of the ISS, which required a total of 36 shuttle missions to assemble and provide logistical support for ISS vehicle operations. As of October 2010, Discovery had flown 12 missions and Atlantis and Endeavour had flown 11 missions to the ISS, with each mission carrying 12,700 to 18,600 kg (28,000 to 41,000 pounds) of cargo in the cargo bay and another 3,000 to 4,000 kg (7,000 to 9,000 pounds) of equipment stowed in the crew cabin. The combined total of ISS structure, logistics, crew, water, oxygen, nitrogen, and avionics delivered to the station for all shuttle visits totaled more than 603,300 kg (1,330,000 pounds). No other launch vehicle in the world could deliver these large 4.27-m- (14-ft)-diameter by 15.24-m- (50-ft)-long structures or have this much capability.

ISS missions required modifications to the three vehicles cited above—Discovery, Atlantis, and Endeavour—to dock to the space station. The docking requirement resulted in the Orbiter internal airlock being moved externally in the payload bay. This change, along with the inclusion of the docking mechanism, added about 1,500 kg (3,300 pounds) of mass to the vehicle weight.



A Platform for Scientific Research

The Orbiter was configured to accommodate many different types of scientific equipment, ranging from large pressurized modules called Spacelab or Spacehab where the crew conducted scientific research in a shirt-sleeve environment to the radars and telescopes for Earth mapping, celestial observations, and the study of solar, atmospheric, and space plasma physics. The shuttle was often used to deploy and retrieve science experiments and satellites. These science payloads were: deployed using the Shuttle Robotic Arm; allowed to conduct free-flight scientific operations; and then retrieved using the arm for return to Earth for further data analysis. This was a unique capability that only the Orbiter could perform.

The Orbiter was also unique because it was an extremely stable platform on which to conduct microgravity research studies in material, fundamental physics, combustion science, crystal growth, and biotechnology that required minimal movement or disturbance from the host vehicle. NASA studied the effect of space adaptation on both humans and animals. Crews of seven worked around the clock conducting research in these pressurized modules/laboratories that were packed with scientific equipment.

Much research was conducted with the international community. These missions brought together international academic, industrial, and governmental



The crew from the International Space Station captured this view of STS-97 (2000).



Franklin Chang-Díaz, PhD

Astronaut on STS-61C (1986), STS-34 (1989), STS-46 (1992), STS-60 (1994), STS-75 (1996), STS-91 (1998), and STS-111 (2002).

Memories of Wonder

"We have arrived at the base of the launch pad, dressed for the occasion in bright orange pressure suits that fit worse than they look. This is the day! As we enter the service elevator that will take us 193 feet up to the level of the shuttle cabin, we get to appreciate the size of this ship, the mighty solid rockets that hold the gargantuan External Tank and the seemingly fragile shuttle craft, poised on this unlikely contraption like a gigantic moth, gathering strength, for she knows full well where she is going today. One by one, between nervous smiles and sheer anticipation, we climb into our ship, aided by expert technicians who execute their tasks with seamless and clockwork precision, while soothing our minds with carefree conversation. The chatter over the audio channels reverberates, unemotional, precise, relentless, and the countdown clock is our master. We often say that, on launch day, the ship seems alive, hissing and creaking with the flow of the super-cold fluids that give her life. Over the course of 3 hours, waiting patiently for the hour of deliverance, we have each become one with the Orbiter. The chatter has subsided, the technicians have gone. It is just us now, our orange cocoons securely strapped and drawing the sap of the mother ship through multiple hoses and cables. It feels



cozy and safe, alas, our comfort is tempered by the knowledge of the machine and the job we are about to do. 'GLS is go for main engine start...' sounds the familiar female voice. The rumbling below signals the beginning of an earthquake. We feel a sudden jolt, the ship is free and she flies! We feel the shaking and vibration and the onset of the 'g' forces that build up uncomfortably, squeezing our chests and immobilizing our limbs as the craft escapes the pull of the Earth. And in less than 9 minutes, we are in space. The view is the most beautiful thing we ever saw and we will see this over and over from what is now our new home in the vacuum of space. The days will pass and this extraordinary vehicle will carry us to our destination...to our destiny. It has learned to dance in space, with exquisite precision and grace, first alone, then with other lonely dates, the Hubble telescope, the Russian Mir station and the International Space Station, and when the job was done, it returned to land softly, majestically, triumphant...and ready to do it all again."

partners to obtain maximum benefits and results. The facilities included middeck glove boxes for conducting research and testing science procedures and for developing new technologies in

microgravity. These boxes enabled crew members to handle, transfer, and manipulate experiment hardware and material that were not approved for use in the shuttle. There were furnaces to

study diffusion, and combustion modules for conducting research on the single most important chemical process in our everyday lives. The shuttle had freezers for sample return as well as the



capability to store large amounts of data for further analysis back on Earth. Scientists used spin tables to conduct biological and physiological research on the crew members.

The Orbiter provided all the power and active cooling for the laboratories. A typical Spacelab was provided approximately 6.3 kW (8.45 hp) of power, with peak power as high as 8.1 kW (10.86 hp). To cool the laboratories' electronics, the modules were tied into the Orbiter's cooling system so thermal control of the payload was the same as thermal control for the Orbiter avionics.

In an effort to share this national resource with industry and academia, NASA developed the Get Away Special Program, designed to provide inexpensive access to space for both novices and professionals to explore new concepts at little risk. In total, over 100 Get Away Special payloads were flown aboard the shuttle, and each payload often consisted of several individual experiments. The cylindrical payload canisters in which these experiments were flown measured 0.91 m (3 ft) in length with a 0.46-m (1.5-ft) diameter. They were integrated into the Orbiter cargo bay on the sill/sidewall and required minimal space and cargo integration engineering. The experiments could be confined inside a sealed canister, or the canister could be configured with a lid that could be opened for experiment pointing or deployment.

The shuttle was also an extremely accurate platform for precise pointing of scientific payloads at the Earth and celestial targets. These unpressurized payloads were also integrated into the cargo bay; however, unlike the

Spacelab and Spacehab science modules, these payloads were not accessible by the crew, but rather were exposed to the space environment. The crew activated and operated these experiments from the pressurized confines of the Orbiter flight deck. The Shuttle Radar Topography Mission was dedicated to mapping the Earth's topography between 60° North and 58° South, including the ocean floor. The result of the mission was a three-dimensional digital terrain map of 90% of the Earth's surface. The Orbiter provided about 10 kW (13.4 hp) of power to the Shuttle Radar Topography Mission payload during on-orbit operations and all of the cooling for the payloads' electronics.

An Enduring Legacy

The shuttle was a remarkable, versatile, complex piece of machinery that demonstrated our ingenuity for human exploration. It allowed the United States and the world to perform magnificent space missions for the benefit of all. Its ability to deploy satellites to explore the solar system, carry space laboratories to perform human/biological/material science, and carry different components to assemble the ISS were accomplishments that will not be surpassed for years to come.



Processing the Shuttle for Flight

Steven Sullivan

Preparing the Shuttle for Flight

Ground Processing

Jennifer Hall

Peter Nickolenko

Jorge Rivera

Edith Stull

Steven Sullivan

Space Operations Weather

Francis Merceret

Robert Scully

Terri Herst

Steven Sullivan

Robert Youngquist

When taking a road trip, it is important to plan ahead by making sure your vehicle is prepared for the journey. A typical road trip on Earth can be routine and simple. The roadways are already properly paved, service stations are available if vehicle repairs are needed, and food, lodging, and stores for other supplies can also be found. The same, however, could not be said for a Space Shuttle trip into space. The difficulties associated with space travel are complex compared with those we face when traveling here. Food, lodging, supplies, and repair equipment must be provided for within the space vehicle.

Vehicle preparation required a large amount of effort to restore the shuttle to nearly new condition each time it flew. Since it was a reusable vehicle with high technical performance requirements, processing involved a tremendous amount of “hands-on” labor; no simple tune-up here. Not only was the shuttle’s exterior checked and repaired for its next flight, all components and systems within the vehicle were individually inspected and verified to be functioning correctly. This much detail work was necessary because a successful flight was dependent on proper vehicle assembly. During a launch attempt, decisions were made within milliseconds by equipment and systems that had to perform accurately the first time—there was no room for hesitation or error. It has been said that a million things have to go right for the launch, mission, and landing to be a success, but it can take only one thing to go wrong for them to become a failure.

In addition to technical problems that could plague missions, weather conditions also significantly affected launch or landing attempts. Unlike our car, which can continue its road trip in cloudy, windy, rainy, or cold weather conditions, shuttle launch and landing attempts were restricted to occur only during optimal weather conditions. As a result, weather conditions often caused launch delays or postponed landings.

Space Shuttle launches were a national effort. During the lengthy processing procedures for each launch, a dedicated workforce of support staff, technicians, inspectors, engineers, and managers from across the nation at multiple government centers had to pull together to ensure a safe flight. The whole NASA team performed in unison during shuttle processing, with pride and dedication to its work, to make certain the success of each mission.



Preparing the Shuttle for Flight

Ground Processing

Imagine embarking on a one-of-a-kind, once-in-a-lifetime trip. Everything must be exactly right. Every flight of the Space Shuttle was just that way. A successful mission hinged on ground operations planning and execution.

Ground operations was the term used to describe the work required to process the shuttle for each flight. It included landing-to-launch processing—called a “flow”—of the Orbiter, payloads, Solid Rocket Boosters (SRBs), and External Tank (ET). It also involved many important ground systems. Three missions could be processed at one time, all at various stages in the flow. Each stage had to meet critical milestones or throw the entire flow into a tailspin.

Each shuttle mission was unique. The planning process involved creating a detailed set of mission guidelines, writing reference materials and manuals, developing flight software, generating a flight plan, managing configuration control, and conducting simulation and testing. Engineers became masters at using existing technology, systems, and equipment in unique ways to meet

the demands of the largest and most complex reusable space vehicle.

The end of a mission set in motion a 4- to 5-month process that included more than 750,000 work hours and literally millions of processing steps to prepare the shuttle for the next flight.

Landing

During each mission, NASA designated several landing sites—three in the Continental United States, three overseas contingency or transatlantic abort landing sites, and various emergency landing sites located in the shuttle’s orbital flight path. All of these sites had one thing in common: the commander got one chance to make the runway. The Orbiter dropped like a rock and there were no second chances. If the target was missed, the result was disaster.

Kennedy Space Center (KSC) in Florida and Dryden Flight Research Center (DFRC)/Edwards Air Force Base in California were the primary landing sites for the entire Space Shuttle Program. White Sands Space Harbor in New Mexico was the primary shuttle pilot training site and a tertiary landing site in case of unacceptable weather conditions at the other locations.

The initial six operational missions were scheduled to land at DFRC/Edwards Air Force Base because of the safety margins available on the lakebed runways. Wet lakebed conditions diverted one of those landings—Space Transportation System (STS)-3 (1982)—to White Sands Space Harbor. STS-7 (1983) was the first mission scheduled to land at KSC, but it was diverted to Edwards Air Force Base runways due to unfavorable Florida weather. The 10th shuttle flight—STS-41B (1984)—was the first to land at KSC.

Landing Systems

Similar to a conventional airport, the KSC shuttle landing facility used visual and electronic landing aids both on the ground and in the Orbiter to help direct the landing. Unlike conventional aircraft, the Orbiter had to land perfectly the first time since it lacked propulsion and landed in a high-speed glide at 343 to 364 km/hr (213 to 226 mph).

Following shuttle landing, a convoy of some 25 specially designed vehicles or units and a team of about 150 trained personnel converged on the runway. The team conducted safety checks for explosive or toxic gases, assisted the crew in leaving the Orbiter, and prepared the Orbiter for towing to the Orbiter Processing Facility.

The landing-to-launch ground operations “flow” at Kennedy Space Center prepared each shuttle for its next flight. This 4- to 5-month process required thousands of work hours and millions of individual processing steps.



Space Shuttle Atlantis landing, STS-129 (2009).



After landing, the Orbiter is moved to the Orbiter Processing Facility.

Landing

Orbiter Processing Facility: 120-130 days

Orbiter Processing

The Orbiter Processing Facility was a sophisticated aircraft hangar (about 2,700 m² [29,000 ft²]) with three separate buildings or bays. Trained personnel completed more than 60% of the processing work during the approximately 125 days the vehicle spent in the facility.

Technicians drained residual fuels and removed remaining payload elements or support equipment. More than 115 multilevel, movable access platforms could be positioned to surround the Orbiter and provide interior and exterior access. Engineers performed extensive checkouts involving some 6 million parts. NASA removed and transferred some elements to other facilities for servicing. The Orbiter Processing Facility also contained shops to support Orbiter processing.

Tasks were divided into forward, midbody, and aft sections and required mechanical, electrical, and Thermal Protection System technicians, engineers, and inspectors as well as planners and schedulers. Daily activities included test and checkout schedule meetings that required

coordination and prioritization among some 35 engineering systems and 32 support groups. Schedules ranged in detail from minutes to years.

Personnel removed the Orbital Maneuvering System pods and Forward Reaction Control System modules and modified or repaired and retested them in the Hypergolic Maintenance Facility. When workers completed modifications and repairs, they shipped the pods and modules back to the Orbiter Processing Facility for reinstallation.

Johnson Space Center Orbiter Laboratories

Several laboratories at Johnson Space Center supported Orbiter testing and modifications.

The Electrical Power Systems Laboratory was a state-of-the-art electrical compatibility facility that supported shuttle and International Space Station (ISS) testing. The shuttle breadboard, a high-fidelity replica of the shuttle electrical power distribution and control subsystem, was used early in the program for equipment development testing and later for ongoing payload and shuttle equipment upgrade testing.

During missions, the breadboard replicated flow problems and worked out solutions.

Engineers also tested spacecraft communications systems at the Electronic Systems Test Laboratory, where multielement, crewed spacecraft communications systems were interfaced with relay satellites and ground elements for end-to-end testing in a controlled radio-frequency environment.

The Avionics Engineering Laboratory supported flight system hardware and software development and evaluation as well as informal engineering evaluation and formal configuration-controlled verification testing of non-flight and flight hardware and software. Its real-time environment consisted of a vehicle dynamics simulation for all phases of flight, including contingency aborts, and a full complement of Orbiter data processing system line replacement units.

The Shuttle Avionics Integration Laboratory was the only program test facility where avionics, other flight hardware (or simulations), software, procedures, and ground support equipment were brought together for integrated verification testing.



Inside the Orbiter Processing Facility, technicians process the Space Shuttle Main Engine and install it into the Orbiter.

Orbiter Processing Facility (continued)



Kennedy Space Center Shuttle Logistics Depot

Technicians at the Shuttle Logistics Depot in Florida manufactured, overhauled and repaired, and procured Orbiter line replacement units. The facility was certified to service more than 85% of the shuttle's approximately 4,000 replaceable parts.



At the Shuttle Logistics Depot, Rick Zeitler assesses the cycling of a main propulsion fill and drain valve after a valve anomaly during launch countdown caused a scrub.

This facility established capabilities for avionics and mechanical hardware ranging from wire harnesses and panels to radar and communications systems, and from ducts and tubing to complex actuators, valves, and regulators. Capability included all aspects of maintenance, repair, and overhaul activities.

Kennedy Space Center Tile Processing

Following shuttle landing, the Thermal Protection System—about 24,000 silica tiles and about 8,000 thermal blankets—was visually inspected in the Orbiter Processing Facility.

Thermal Protection System products included tiles, gap fillers, and insulation blankets to protect the Orbiter exterior from the searing heat of launch, re-entry into Earth's atmosphere, and the cold soak of space. The materials were repaired and manufactured in the Thermal Protection Systems Facility.

Tile technicians and engineers used manual and automated methods to fabricate patterns for areas of the Orbiter that needed new tiles. Engineers used the automotive industry tool Optigo™ to take measurements in tile cavities. Optigo™ used optics to record the hundreds of data points needed to



Prior to the launch of STS-119 (2009), Discovery gets boundary layer transition tile, which monitors the heating effects of early re-entry at high Mach numbers.



At the Kennedy Space Center tile shop, a worker places a Boeing replacement insulation 18 tile in the oven to be baked at 1,200°C (2,200°F) to cure the ceramic coating.

manufacture tile accurate to 0.00254 cm (0.001 in.). Tile and external blanket repair and replacement processing included: removal of damaged tile and preparation of the cavity; machining, coating, and firing the replacement tile; and fit-checking, waterproofing, bonding, and verifying the bond.



Solid Rocket Boosters and the External Tank are delivered to Kennedy Space Center and transported to the Vehicle Assembly Building to be readied for the Space Shuttle.

Vehicle Assembly Building: 7-9 days

Space Shuttle Main Engine Processing

Trained personnel removed the three reusable, high-performance, liquid-fueled main engines from the Orbiter following each flight for inspection. They also checked engine systems and performed maintenance. Each engine had 50,000 parts, about 7,000 of which were life limited and periodically replaced.

Solid Rocket Booster Processing

The SRBs were repaired, refurbished, and reused for future missions. The twin boosters were the largest ever built and the first designed for refurbishment and reuse. They provided “lift” for the Orbiter to a distance of about 45 km (28 miles) into the atmosphere.

Booster Refurbishment

Following shuttle launch, NASA recovered the spent SRBs from the Atlantic Ocean, disassembled them, and transported them from Florida to ATK’s Utah facilities via specially designed rail cars—a trip that took about 3 weeks.

After refurbishment, the motor cases were prepared for casting. Each motor consisted of nine cylinders, an aft dome, and a forward dome. These elements were joined into four units

called casting segments. Insulation was applied to the inside of the cases and the propellant was bonded to this insulation.

The semiliquid, solid propellant was poured into casting segments and cured over 4 days. Approximately forty 2.7-metric-ton (3-ton) mixes of propellant were required to fill each segment.

The nozzle consisted of layers of glass- and carbon-cloth materials bonded to aluminum and steel structures. These materials were wound at specified angles and then cured to form a dense, homogeneous insulating material capable of withstanding temperatures reaching 3,300°C (6,000°F). The cured components were then adhesively bonded to their metal support structures and the metal sections were joined to form the complete nozzle assembly.

Transporting a flight set of two Solid Rocket Motors to KSC required four major railroads, nine railcars, and 7 days.

KSC teams refurbished, assembled, tested, and integrated many SRB elements, including the forward and aft skirts, separation motors, frustum, parachutes, and nose cap.

Technicians at the Rotation Processing and Surge Facility received, inspected, and offloaded the booster segments from rail cars, then rotated the segments from horizontal to vertical and placed them on pallets.

Many booster electrical, mechanical, thermal, and pyrotechnic subsystems were integrated into the flight structures. The aft skirt subassembly and forward skirt assembly were processed and then integrated with the booster aft segments.

After a complete flight set of boosters was processed and staged in the surge buildings, the boosters were transferred to the Vehicle Assembly Building for stacking operations.

External Tank Processing

The ET provided propellants to the main engines during launch. The tank was manufactured at the Michoud Assembly Facility in New Orleans and shipped to Port Canaveral in Florida. It was towed by one of NASA’s SRB retrieval ships. At the port, tugboats moved the barge upriver to the KSC turn basin. There, the



Inside the Vehicle Assembly Building, technicians complete the process of stacking the Solid Rocket Booster components.

Vehicle Assembly Building (continued)



tank was offloaded and transported to the Vehicle Assembly Building.

Payload Processing

Payload processing involved a variety of payloads and processing requirements.

The cargo integration test equipment stand simulated and verified payload/cargo mechanical and functional interfaces with the Orbiter before the spacecraft was transported to the launch pad. Payload processing began with power-on health and status checks, functional tests, computer and communications interface checks, and spacecraft command and monitor tests followed by a test to simulate all normal mission functions through payload deployment.

Hubble Space Telescope servicing missions provided other challenges. Sensitive telescope instruments required additional cleaning and hardware handling procedures. Payload-specific ground support equipment had to be installed and monitored throughout the pad flow, including launch countdown.

William Parsons
Space Shuttle program manager (2003-2005) and director of Kennedy Space Center (2007-2008).



"The shuttle is an extremely complex space system. It is surprising

In the firing room, William Parsons (left), director of Kennedy Space Center; and Dave King, director of Marshall Space Flight Center, discuss the imminent launch of STS-124 (2008).

how many people and vendors touch the vehicle. At the Kennedy Space Center, it is amazing to me how we are able to move a behemoth space structure, like the Orbiter, and mate to another structure with incredibly precise tolerances."

Following processing, payloads were installed in the Orbiter either horizontally at the Orbiter Processing Facility or vertically at the launch pad.

Space Station Processing Facility Checkout

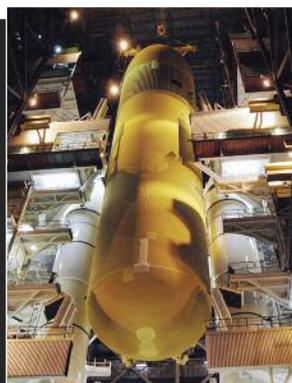
All space station elements were processed, beginning with Node 1 in 1997.

Most ISS payloads arrived at KSC by plane and were delivered to the Space Station Processing Facility

where experiments and other payloads were integrated.

ISS flight hardware was processed in a three-story building that had two processing bays, an airlock, operational control rooms, laboratories, logistic areas, and office space. For all payloads, contamination by even the smallest particles could impair their function in the space environment.

Payloads, including the large station modules, were processed in this



After the External Tank is mated to the Solid Rocket Booster, the Orbiter is brought to the Vehicle Assembly Building.

Vehicle Assembly Building (continued)

state-of-the-art, nonhazardous facility that had a nonconductive, air-bearing pallet compatible floor. This facility had a Class 100K clean room that regularly operated in the 20K range. Class 100K refers to the classification of a clean room environment in terms of the number of particles allowed. In a Class 100K, 0.03 m³ (1 ft³) of air is allowed to have 100,000 particles whose size is 0.5 micrometer (0.0002 in.).

Vehicle Assembly Integration for Launch

The SRB, ET, and Orbiter were vertically integrated in the Vehicle Assembly Building.

Mobile Launch Platform

Technicians inside the building stacked the shuttle on one of three mobile launcher platforms originally built in 1964 for the Apollo moon missions. These platforms were modified to accommodate the weight of the shuttle and still be transportable by crawler transporters, and to handle the increased pressure and heat caused by the SRBs. NASA

strengthened the platform deck and added an over-pressurization water deluge system. Two additional flame trenches accommodated the SRB exhaust. Tail service masts, also added, enabled cryogenic fueling and electrical umbilical interfaces.

Technology inside the mobile launcher platforms remained basically unchanged for the first half of the program, reusing much of the Apollo-era hardware. The Hazardous Gas Leak Detection System was the first to be updated. It enabled engineers in the firing room to monitor levels of hydrogen gas in and around the vehicle. Many manual systems also were automated and some could be controlled from remote locations other than the firing rooms.

Assembly

Massive Cranes

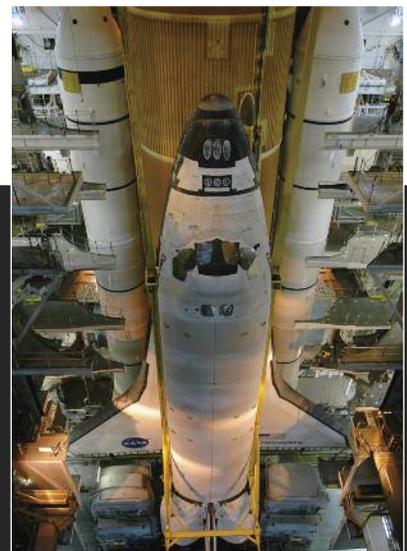
The size and weight of shuttle components required a variety of lifting devices to move and assemble the vehicle. Two of the largest and most critical were the 295-metric-ton (325-ton) and 227-metric-ton (250-ton) cranes.

The 295-metric-ton (325-ton) cranes lifted and positioned the Solid Rocket Motor sections, ET, and Orbiter. The 227-metric-ton (250-ton) cranes were backups.

Both cranes were capable of fine movements, down to 0.003 cm (0.001 in.), even when lifting fully rated loads. The 295-metric-ton (325-ton) cranes used computer controls and graphics and could be set to release the brakes and “float” the load, holding the load still in midair using motor control alone without overloading any part of the crane or its motors.

The cranes were located 140 m (460 ft) above the Vehicle Assembly Building ground floor. Crane operators relied on radio direction from ground controllers at the lift location.

The cranes used two independent wire ropes to carry the loads. Each crane carried about 1.6 km (1 mile) of wire rope that was reeved from the crane to the load block many times. The wire ropes were manufactured at the same time and from the same lot to ensure rope diameters were identical



The Orbiter is then mated with the External Tank and the Solid Rocket Booster.

Vehicle Assembly Building (continued)



and would wind up evenly on the drum as the load was raised.

Stacking the Orbiter, External Tank, and Solid Rocket Booster

SRB segments were moved to the Vehicle Assembly Building. A lifting beam was connected to the booster clevis using the 295-metric-ton (325-ton) crane hook. The segment was lifted off the pallet and moved into the designated high bay, where it was lowered onto the hold-down post bearings on the mobile launcher platform. Remaining segments were processed and mated to form two complete boosters.

Next in the stacking process was hoisting the ET from a checkout cell, lowering into the integration cell, and mating it to the SRBs. Additional inspections, tests, and component installations were then performed.

The Orbiter was towed from the Orbiter Processing Facility to the Vehicle Assembly Building transfer aisle, raised to a vertical position, lowered onto the mobile launcher platform, and mated. Following inspections, tests,

and installations, the integrated shuttle vehicle was ready for rollout to the launch pad.

Rollout to Launch Pad

Technicians retracted the access platforms, opened the Vehicle Assembly Building doors, and moved the tracked crawler transporter vehicle under the mobile launcher platform that held the assembled shuttle vehicle.

The transporter lifted the platform off its pedestals and rollout began. The trip to the launch pad took about 6 to 8 hours along the specially built crawlerway—two lanes of river gravel separated by a median strip. The rock surface supported the weight of the crawler and shuttle, and it reduced vibration. The crawler’s maximum unloaded speed was 3.2 km/hr (2 mph) and 1.6 km/hr (1 mph) loaded.

Engineers and technicians on the crawler, assisted by ground crews, operated and monitored systems during rollout while drivers steered the vehicle toward the pad. The crawler leveling system kept the top of the

shuttle vertical within +/-10 minutes of 1 degree of arc—the diameter of a basketball. The system also provided the leveling required to negotiate the 5% ramp leading to the launch pads and keep the load level when raised and lowered on pedestals at the pad.

Launch Pad Operations

Once the crawler lowered the mobile launcher platform and shuttle onto a launch pad’s hold-down posts, a team began launch preparations. These required an average of 21 processing days to complete.

The two steel towers of Launch Pads 39A and 39B stood 105.7 m (347 ft) above KSC’s coastline, atop 13-m- (42-ft)-thick concrete pads. Each complex housed a fixed service structure and a rotating service structure that provided access to electrical, pneumatic, hydraulic, hypergolic, and high-pressure gas lines to support vehicle servicing while protecting the shuttle from inclement weather. Pad facilities also included hypergolic propellant storage (nitrogen tetroxide and monomethylhydrazine),



Once the process is complete, the Space Shuttle is transported to the launch pad.



Crawler moving the shuttle stack to the launch pad.

Launch Pad: 28-30 days

cryogenic propellant storage (liquid hydrogen and liquid oxygen), a water tower, a slide wire crew escape system, and a pad terminal connection room.

Liquid Hydrogen/Liquid Oxygen— Tankers, Spheres

Chicago Bridge & Iron Company built the liquid hydrogen and liquid oxygen storage spheres in the 1960s for the Apollo Program. The tanks were two concentric spheres. The inner stainless-steel sphere was suspended inside the outer carbon-steel sphere using long support rods to allow thermal contraction and minimize heat conduction from the outside environment to the propellant. The space between the two spheres was insulated to keep the extremely cold propellants in a liquid state. For liquid hydrogen, the temperature is -253°C (-423°F); for liquid oxygen, the temperature is -183°C (-297°F).

The spheres were filled to near capacity prior to a launch countdown. A successful launch used about 1.7 million L (450,000 gal) of liquid hydrogen and about 830,000 L (220,000 gal) of liquid oxygen. A launch scrub consumed about



Technicians in the Payload Changeout Room at Launch Pad 39B process the Hubble Space Telescope for STS-31 (1990).

380,000 L (100,000 gal) of each commodity. The spheres contained enough propellant to support three launch attempts before requiring additional liquid from tankers.

Pad Terminal Connection Room

The Pad Terminal Connection Room was a reinforced-concrete room located on the west side of the flame trench, underneath the elevated

launch pad hardstand. It was covered with about 6 m (20 ft) of dirt fill and housed the equipment that linked elements of the shuttle, mobile launcher platform, and pad with the Launch Processing System in the Launch Control Center. NASA performed and controlled checkout, countdown, and launch of the shuttle through the Launch Processing System.

Payload Changeout Room

Payloads were transported to the launch pad in a payload canister. At the pad, the canister was lifted with a 81,647-kg (90-ton) hoist and its doors were opened to the Payload Changeout Room—an enclosed, environmentally controlled area mated to the Orbiter payload bay. The payload ground-handling mechanism—a rail-suspended, mechanical structure measuring 20 m (65 ft) tall—captured the payload with retention fittings that used a water-based hydraulic system with gas-charged accumulators as a cushion. The mechanism, with the payload, was then moved to the aft wall of the Payload Changeout Room, the main doors were closed, and the canister



The Space Shuttle arrives at the launch pad, where payloads are installed into the Orbiter cargo bay.



Payload Changeout Room at launch pad.

Launch Pad (continued)



was lowered and removed from the pad by the transporter.

Once the rotating service structure was in the mate position and the Orbiter was ready with payload bay doors open, technicians moved the payload ground-handling mechanism forward and installed the payload into the Orbiter cargo bay. This task could take as many as 12 hours if all went well. When installation was complete, the payload was electrically connected to the Orbiter and tested, final preflight preparations were made, and the Orbiter payload bay doors were closed for flight.

Sound Suppression

Launch pads and mobile launcher platforms were designed with a water deluge system that delivered high-volume water flows into key areas to protect the Orbiter and its payloads from damage by acoustic energy and rocket exhaust.

The water, released just prior to main engine ignition, flowed through pipes measuring 2.1 m (7 ft) in diameter for about 20 seconds. The mobile launcher platform deck water spray system was fed from



Water spray at the launch pad was used to suppress the acoustic vibration during launch.

six 3.7-m- (12-ft)-high water spray diffusers nozzles dubbed “rainbirds.”

Operational Systems— Test and Countdown

Launch Processing System

Engineers used the Launch Processing System computers to monitor thousands of shuttle measurements and control systems from a remote and safe location. Transducers, built into on-board systems and ground support equipment, measured each important function (i.e., temperature, pressure). Those measurements were converted into

engineering data and delivered to the Launch Processing System in the firing rooms, where computer displays gave system engineers detailed views of their systems.

The unique Launch Processing System software was specifically written to process measurements and send commands to on-board computers and ground support equipment to control the various systems. The software reacted either to measurements reaching predefined values or when the countdown clock reached a defined time.

Launch was done by the software. If there were no problems, the button to initiate that software was pushed at the designated period called T minus 9 minutes (T=time). One of the last commands sent to the vehicle was “Go for main engine start,” which was sent 10 seconds before launch. From that point on, the on-board computers were in control. They ignited the main engines and the SRBs.



In the firing room at Kennedy Space Center, NASA clears the Space Shuttle for launch.



STS-108 (2001) launch.

Launch Pad (continued)

Training and Simulations

Launch Countdown Simulation

The complexity of the shuttle required new approaches to launch team training. During Mercury, Gemini, and Apollo, a launch-day rehearsal involving the launch vehicle, flight crew, and launch control was adequate to prepare for launch. The shuttle, however, required more than just one rehearsal.

Due to processing and facility requirements, access to actual hardware in a launch configuration only occurred near the actual launch day after the vehicle was assembled and rolled to the launch pad. The solution was to write a computer program that simulated shuttle telemetry data with a computer math model and fed those data into launch control in place of the actual data sent by a shuttle on the pad.

Terminal Countdown Demonstration Test

The Terminal Countdown Demonstration Test was a dress rehearsal of the terminal portion of the launch countdown that included the flight crew suit-up and flight



Space Station Processing Facility for modules and other hardware at Kennedy Space Center.

crew loading into the crew cabin.

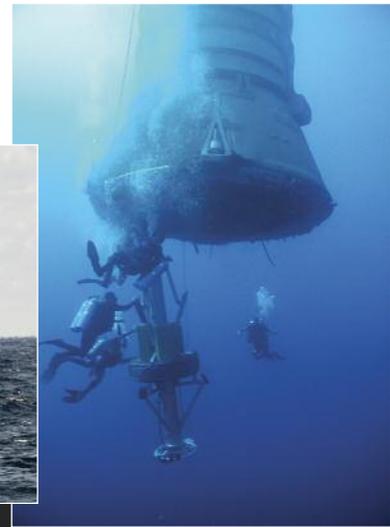
The Orbiter was configured to simulate a launch-day posture, giving the flight crew the opportunity to run through all required procedures. The flight crew members also was trained in emergency egress from the launch pad, including use of emergency equipment, facility fire-suppression systems, egress routes, slidewire egress baskets, emergency bunker, emergency vehicles, and the systems available if they needed to egress the launch pad.

Special Facilities and Tools

Facility Infrastructure

Although the types of ground systems at KSC were common in many large-scale industrial complexes, KSC systems often were unique in their application, scale, and complexity.

The Kennedy Complex Control System was a custom-built commercial facility control system that included



After launch, Solid Rocket Boosters separate from the Space Shuttle and are recovered in the Atlantic Ocean, close to Florida's East Coast.

Solid Rocket Booster Recovery



about 15,000 monitored parameters, 800 programs, and 300 different displays. In 1999, it was replaced with commercial off-the-shelf products.

The facility heating, ventilating, and air conditioning systems for Launch Pads 39A and 39B used commercial systems in unique ways. During launch operations that required hazard proofing of the mobile launcher platform, a fully redundant fan—149,140 W (200 hp), 1.12 m (44 in.) in diameter—pressurized the mobile launcher platform and used more than 305 m (1,000 ft) of 1.2- by 1.9-m (48- by 75-in.) concrete sewer pipe as ductwork to deliver this pressurization air.

Facility systems at the Orbiter Processing Facility high bays used two fully redundant, spark-resistant air handling units to maintain a Class 100K clean work area in the 73,624-m³ (2.6-million-ft³) high bay. During hazardous operations, two spark-resistant exhaust fans, capable of exhausting 2,492 m³/min (88,000 ft³/min), worked in conjunction with high bay air handling units and could

replace the entire high bay air volume in fewer than 30 minutes.

The launch processing environment included odorless and invisible gaseous commodities that could pose safety threats. KSC used an oxygen-deficiency monitoring system to continuously monitor confined-space oxygen content. If oxygen content fell below 19.5%, an alarm was sounded and beacons flashed, warning personnel to vacate the area.

Communications and Tracking

Shuttle communications systems and equipment were critical to safe vehicle operation. The communications and tracking station in the Orbiter Processing Facility provided test, checkout, and troubleshooting for Orbiter preflight, launch, and landing activities. Communications and tracking supported Orbiter communications and navigations subsystems.

Following landing at KSC, the communications and tracking station monitored the Orbiter and Merritt Island Launch Area communications transmissions during tow and spotting

of the vehicle in the Orbiter Processing Facility. In that facility, the station was configured as a passive repeater to route the uplink and downlink radio frequency signals to and from the Orbiter Processing Facility and Merritt Island Launch Area using rooftop antennas.

Operations Planning Tools

Requirements and Configuration Management

Certification of Flight Readiness was the process by which the Space Shuttle Program manager determined the shuttle was ready to fly. This process verified that all design requirements were properly approved, implemented, and closed per the established requirements and configuration management processes in place at KSC.

Requirements and configuration management involved test requirements and modifications. Test requirements ensured shuttle integrity, safety, and performance. Modifications addressed permanent hardware or software changes, which improved the safety of flight or vehicle performance, and mission-specific hardware or software changes required to support the payload and mission objectives.



The recovered Solid Rocket Boosters are returned to Kennedy Space Center for refurbishment and reusability.



NASA generated planning, executing, and tracking products to ensure the completion of all processing flow steps. These included: process and support plans; summary and detailed assessments; milestone, site, maintenance, and mini schedules; and work authorization documents. Over time, many operations tools evolved from pen and paper, to mainframe computer, to desktop PC, and to Web-based applications.

Work authorization documents implemented each of the thousands of requirements in a flow. Documents included standard procedures performed every flow as well as nonstandard documents such as problem and discrepancy reports, test preparation sheets, and work orders.

Kennedy Space Center Integrated Control Schedule

The KSC Integrated Control Schedule was the official, controlling schedule for all work at KSC's shuttle processing sites. This integration tool reconciled conflicts between sites and resources among more than a dozen independent sites and multiple shuttle missions in work simultaneously. Work authorization documents could not be performed unless they were entered on this schedule, which distributed the required work authorization documents over time and sequenced the work in the proper order over the duration of the processing flow. The schedule, published on the Web every workday, contained the work schedule for the following 11 days for each of the 14

shuttle processing sites, including the three Orbiter Processing Facility bays, Vehicle Assembly Building, launch pads, Shuttle Landing Facility, and Hypergolic Maintenance Facility.

Space Shuttle Launch Countdown Operations

Launch countdown operations occurred over a period of about 70 hours during which NASA activated, checked out, and configured the shuttle vehicle systems to support launch. Initial operations configured shuttle data and computer systems. Power Reactant Storage and Distribution System loading was the next major milestone in the countdown operation. Liquid oxygen and liquid hydrogen had to be transferred from tanker trucks on the launch pad surface, up the fixed service structure, across the rotating service structure, and into the on-board storage tanks, thus providing the oxygen and hydrogen gas that the shuttle fuel cells required to supply power and water while on orbit.

The next major milestones were activation of the communication equipment and movement of the rotating service structure from the mate position (next to the shuttle) to the park position (away from the shuttle), which removed much access to the vehicle.

The most hazardous operation, short of launch, was loading the ET with liquid oxygen and liquid hydrogen. This was performed remotely from the Launch Control Center. The Main

Propulsion System had to be able to control the flow of cryogenic propellant through a wide range of flow rates. The liquid hydrogen flow through the vehicle was as high as 32,550 L/min (8,600 gal/min). While in stable replenish, flow rates as low as 340 L/min (90 gal/min) had to be maintained with no adverse effects on the quality of the super-cold propellant.

Once the tank was loaded and stable, NASA sent teams to the launch pad. One team inspected the vehicle for issues that would prevent launch, including ice formation and cracks in the ET foam associated with the tank loading. Another team configured the crew cabin and the room used to access the shuttle cabin. Flight crew members, who arrived a short time later, were strapped into their seats and the hatch was secured for launch.

The remaining operations configured the vehicle systems to support the terminal countdown. At that point, the ground launch sequencer sent the commands to perform the remaining operations up to 31 seconds before launch, when the on-board computers took over the countdown and performed the main engine start and booster ignition.

Solid Rocket Booster Recovery

Following shuttle launch, preparations continued for the next mission, beginning with SRB recovery.

Approximately 1 day before launch, the two booster recovery ships—Freedom Star and Liberty Star—left Cape Canaveral Air Force Station and



Port Canaveral to be on station prior to launch to retrieve the boosters from the Atlantic Ocean.

Approximately 6½ minutes after launch, the boosters splashed down 258 km (160 miles) downrange. Divers separated the three main parachutes from each booster and the parachutes were spun onto reels on the decks of each ship. The divers also retrieved drogue chutes and frustums and lifted them aboard the ships.

For the boosters to be towed back to KSC, they were repositioned from vertical to horizontal. Divers placed an enhanced diver-operated plug into the nozzle of the booster, which was 32 m (105 ft) below the ocean surface. Air was pumped into the boosters, displacing the water inside them and repositioning the boosters to horizontal. The boosters were then moved alongside the ships for transit to Cape Canaveral Air Force Station where they were disassembled and refurbished. Nozzles and motor segments were shipped to the manufacturer for further processing.

Following recovery, the segments were taken apart and the joints were inspected to make sure they had performed as expected. Booster components were inspected and hydrolased—the ultimate pressure cleaning—to remove any residual fuel and other contaminants. Hydrolasing was done manually with a gun operating at 103,421 kPa (15,000 psi) and robotically at up to 120,658 kPa (17,500 psi). Following cleaning, the frustum and forward skirt were media-blasted and repainted.

Parachutes

SRB main parachute canopies were the only parachutes in their size class that were refurbished. NASA removed the parachutes from the retrieval ships and transported them to the Parachute Refurbishment Facility.

At the facility, technicians unspooled, defouled, and inspected the parachutes. Following a preliminary damage mapping to assess the scope of repairs required, the parachutes were hung on a monorail system that facilitated movement through the facility. The first stop was a 94,635-L (25,000-gal) horizontal wash tank where each parachute underwent a 4- to 6-hour fresh water wash cycle to remove all foreign material. The parachutes were transferred to the drying room and

exposed to 60°C (140°F) air for 10 to 12 hours, after which they were inspected, repaired, and packed into a three-part main parachute cluster and transferred to the Assembly and Refurbishment Facility for integration into a new forward assembly.

Summary

In conclusion, the success of each shuttle mission depended, without exception, on ground processing. The series of planning and execution steps required to process the largest and most complex reusable space vehicle was representative of NASA's ingenuity, dedicated workforce, and unmatched ability, thus contributing immensely to the legacy of the Space Shuttle Program.



Technicians assemble a Solid Rocket Booster parachute at Kennedy Space Center.

Space Operations Weather: How NASA, the National Weather Service, and the Air Force Improved Predictions

Weather was the largest single cause of delays or scrubs of launch, landing, and ground operations for the Space Shuttle.

The Shuttle Weather Legacy

NASA and the US Air Force (USAF) worked together throughout the program to find and implement solutions to weather-related concerns. The Kennedy Space Center (KSC) Weather Office played a key role in shuttle weather operations. The National Weather Service operated the Spaceflight Meteorology Group at Johnson Space Center (JSC) to support on-orbit and landing operations for its direct customers—the shuttle flight directors. At Marshall Space Flight Center, the Natural Environments Branch provided expertise in climatology and analysis of meteorological data for both launch and landing operations with emphasis on support for engineering analysis and design. The USAF 45th Weather Squadron provided the operational weather observations and forecasting for ground operations and launch at the space launch complex. This collaborative community, which worked effectively as a team across the USAF, NASA, and the National Weather Service, not only improved weather prediction to support the Space Shuttle Program and spaceflight worldwide in general, it also contributed much to our understanding of the atmosphere and how to observe and predict it. Their efforts not only



Rollout of Space Shuttle Discovery, STS-128 (2009), was delayed by onset of lightning in the area of Launch Pad 39A at Kennedy Space Center. Photo courtesy of Environmental Protection Agency.

enabled safe ground launch and landing, they contributed to atmospheric science related to observation and prediction of lightning, wind, ground and atmosphere, and clouds.

By the late 1980s, 50% of all launch scrubs were caused by adverse weather conditions—especially the destructive effects of lightning, winds, hail, and temperature extremes. So NASA and their partners developed new methods to improve the forecasting of weather phenomena that threatened missions, including the development of technologies for lightning, winds, and other weather phenomena. The Space Shuttle Program led developments and innovations that addressed weather conditions specific to Florida, and largely supported and enhanced launch capability from the Eastern Range. Sensor technologies developed were used by, and shared with, other meteorological organizations throughout the country.

Living With Lightning, a Major Problem at Launch Complexes Worldwide

Naturally occurring lightning activity associated with thunderstorms occurs at all launch complexes, including KSC and Cape Canaveral Air Force Station. Also, the launch itself can trigger lightning—a problem for launch complexes that have relatively infrequent lightning may have a substantial potential for rocket-triggered lightning. The launch complex at Vandenberg Air Force Base, California, is a primary example.

Natural lightning discharges may occur within a single thundercloud, between thunderclouds, or as cloud-to-ground strikes. Lightning may also be triggered by a conductive object, such as a Space Shuttle, flying into a region of atmosphere where strong electrical charge exists but is not strong enough by itself to discharge as a lightning strike.

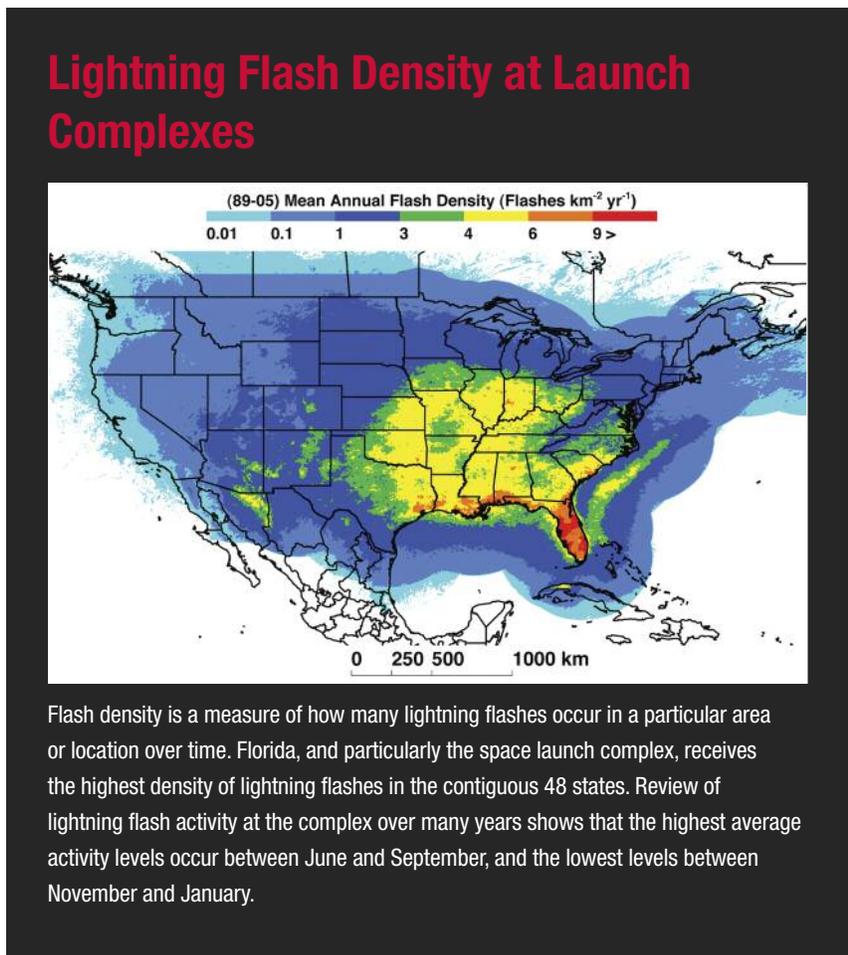


Natural lightning is hazardous to all aerospace operations, particularly those that take place outdoors and away from protective structures. Triggered lightning is only a danger to vehicles in flight but, as previously described, may occur even when natural lightning is not present.

Lightning Technology at the Space Launch Complex

Crucial to the success of shuttle operations were the activities of the USAF 45th Weather Squadron, which provided all launch and landing orbit weather support for the space launch complex. Shuttle landing support was provided by the National Weather Service Spaceflight Meteorology Group located at JSC. The 45th Weather Squadron operated from Range Weather Operations at Cape Canaveral Air Force Station. The Spaceflight Meteorology Group housed weather system computers for forecast and also analyzed data from the National Centers for Environmental Prediction, weather satellite imagery, and local weather sensors as well as assisted in putting together KSC area weather forecasts.

Another key component of shuttle operations was the KSC Weather Office, established in the late 1980s. The KSC Weather Office ensured all engineering studies, design proposals, anomaly analyses, and ground



processing and launch commit criteria for the shuttle were properly considered. It coordinated all weather research and development, incorporating results into operations.

Launch Pad Lightning Warning System data helped forecasters determine when surface electric fields may have been of sufficient magnitude to create triggered lightning during launch. The data also helped determine when to issue and cancel lightning advisories and warnings. The original Lightning Detection and Ranging System, developed by NASA at KSC, sensed electric fields produced by the processes of breakdown and channel formation in both cloud lightning and cloud-to-ground flashes. The locational accuracy of this system was on the order of +/-100 m (328 ft). In 2008, a USAF-owned system replaced the

Lightning Evaluation Tools	System Network
Launch Pad Lightning Warning System	Thirty-one electric-field mills that serve as an early warning system for electrical charges building aloft due to a storm system.
Lightning Detection and Ranging	Nine antennas that detect and locate lightning in three dimensions within 185 km (100 nautical miles) using a "time of arrival" computation on signals.
National Lightning Detection Network	One-hundred ground-based sensing stations that detect cloud-to-ground lightning activity across the continental US. The sensors instantaneously detect the electromagnetic signal given off when lightning strikes the ground.
Cloud-to-Ground Lightning Surveillance System	Six sensors spaced much closer than in the National Lightning Detection Network.
Weather Radar	Two radars that provide rain intensity and cloud top information.

Systems used for weather and thunderstorm prediction and conditions.



original KSC Lightning Detection and Ranging System, which served the space launch complex for about 20 years.

The National Lightning Detection Network plots cloud-to-ground lightning nationwide and was used to identify cloud-to-ground strikes at KSC and to ensure safe transit of the Orbiter atop the Shuttle Carrier Aircraft. A National Lightning Detection Network upgrade in 2002-2003 enabled the system to provide a lightning flash-detection efficiency of approximately 93% of all flashes with a location accuracy on the order of +/-500 to 600 m (1,640 to 1,968 ft).

The Cloud-to-Ground Lightning Surveillance System is a lightning detection system designed to record cloud-to-ground lightning strikes in the vicinity of the space launch complex. A Cape Canaveral Air Force Station upgrade in 1998 enabled the system to provide a lightning flash-detection efficiency within the sensor array of approximately 98% of all flashes and with a location accuracy on the order of +/-250m (820 ft).

The Lightning Detection and Ranging System was completely upgraded during the shuttle era with new sensors positioned in nine locations around the space launch complex proper. Along with a central processor, the system was referred to as the Four-Dimensional Lightning Surveillance System. This new central processor was also capable of processing the Cloud-to-Ground Lightning Surveillance System sensor data at the same time and, moreover, produced full cloud-to-ground stroke data rather than just the first stroke in real time. The synergistic combination of the upgraded Four-Dimensional Lightning Surveillance System and the Cloud-to-Ground Lightning Surveillance System provided a more

accurate and timely reporting capability over that of the upgraded Cloud-to-Ground Lightning Surveillance System or the older Lightning Detection and Ranging System individually, and it allowed for enhanced space launch operations support.

Launch and landing forecasters located in Texas, and Cape Canaveral, Florida, accessed displays from two different Florida radar sites—one located at Patrick Air Force Base, and a NEXRAD (next-generation weather radar) Doppler, located in Melbourne at the National Weather Service.

Lightning Operational Impacts; Warning Systems

The likelihood of sustaining damage from natural lightning was reduced by minimizing exposure of personnel and hardware during times when lightning threatened. To accomplish this, it was necessary to have in place a balanced warning system whereby lightning activity could be detected and reported far enough in advance to permit protective action to be taken. Warnings needed to be accurate to prevent harm yet not stop work unnecessarily. Lightning advisories were important for ground personnel, launch systems, and the transport of hardware, including the 6- to 8-hour transport of the Space Shuttle to the launch pad.

The original deployment of the Lightning Detection and Ranging System pioneered a two-phase lightning policy. In Phase I, an advisory was issued that lightning was forecast within 8 km (5 miles) of the designated site within 30 minutes of the effective time of the advisory. The 30-minute warning gave personnel time to get to a protective shelter and gave personnel working on lightning-sensitive tasks time to secure operations in a safe and

orderly manner. A Phase II warning was issued when lightning was imminent or occurring within 8 km (5 miles) of the designated site. All lightning-sensitive operations were terminated until the Phase II warning was lifted. This two-phase policy provided adequate lead time for sensitive operations without shutting down less-sensitive operations until the hazard became immediate. Much of this activity was on the launch pads, which were tall, isolated, narrow structures in wide-open areas and were prime targets for lightning strikes. Lightning advisories were critical for the safety of over 25,000 people and resource protection of over \$18 billion in facilities. Several more billion dollars could be added to this value, depending on what payloads and rockets were at the launch pads or in transit outside. This policy ultimately reduced ground processing downtime by as much as 50% compared to the older system, saving millions of dollars annually.

Operationally, warnings were sometimes not sufficient, for example during launch operations when real-time decisions had to be made based on varying weather conditions with a potentially adverse effect on flight. Following a catastrophic lightning-induced failure of an Atlas/Centaur rocket in 1987, a blue-ribbon “Lightning Advisory Panel” comprising top American lightning scientists was convened to assist the space program. The panel recommended a set of “lightning launch commit criteria” to avoid launching into an environment conducive to either natural or triggered lightning. These criteria were adopted by NASA for the Space Shuttle Program, and also by the USAF for all military and civilian crewless launches from the Eastern and Western Ranges.



Hail Damage to the External Tank

On the afternoon of February 26, 2007, during STS-117 prelaunch processing at Kennedy Space Center (KSC) Launch Pad A, a freak winter thunderstorm with hail struck the launch complex and severely damaged the External Tank (ET) (ET-124) Thermal Protection System foam insulation. The hail strikes caused approximately 7,000 divots in the foam material. The resulting damage revealed that the vehicle stack would have to be returned to the Vehicle Assembly Building to access the damage. This would be the second time hail caused the shuttle to be returned to the building. To assess the damage, NASA built customized scaffolding.

The design and installation of the scaffolding needed to reach the sloping forward section of the tank was a monumental task requiring teams of specialized riggers called “High Crew” to work 24 hours a day for 5 straight days. A hand-picked engineering assessment team evaluated the damage. The ET liquid oxygen tank forward section was the most severely damaged area and required an unprecedented repair effort. There were thousands of damaged areas that violated the ET engineering acceptance criteria for flight. NASA assembled a select repair team of expert technicians, quality inspectors, and engineers to repair the damage. This team was assisted by manufacturing specialists from Lockheed Martin, the ET manufacturer, and Marshall Space Flight Center.

KSC developed an inexpensive, unique hail monitoring system using a piezoelectric device and sounding board to characterize rain and hail. While the shuttle was at the pad, three remote devices constantly monitored the storms for potential damage to the vehicle.



ET-124 damage repairs, post storm.

The lightning launch commit criteria, as initially drafted, were very conservative as electrical properties of clouds were not well understood. Unfortunately, this increased the number of launches that had to be postponed or scrubbed due to weather conditions. The program undertook a series of field research initiatives to learn more about cloud electrification in hopes that the criteria could safely be made less restrictive.

These field research initiatives used aircraft instrumented with devices called electric field mills that could measure the strength of the electric field in clouds as the aircraft flew through them. The research program was known as Airborne Field Mill. Data collected by the Airborne Field Mill program were subjected to extensive quality control, time-synchronized, and consolidated into a carefully documented, publicly

accessible online archive. This data set is the largest, most comprehensive of its kind.

The Airborne Field Mill science team developed a quantity called Volume Averaged Height Integrated Radar Reflectivity that could be observed with weather radar. This quantity, when small enough, assured safe electric fields aloft. As a result, the Lightning Advisory Panel was able to recommend changes to the lightning launch commit criteria to make them both safer and less restrictive. The new criteria are used by all US Government launch facilities, and the Federal Aviation Administration is including them in its regulations governing the licensing of private spaceports. These criteria were expressed in detailed rules that described weather conditions likely to produce or be associated with lightning activity, the existence of which precluded launch.

Lightning Protection and Instrumentation Systems

Physical lightning protection for the shuttle on the pad was provided by a combination of a large, loose network of wiring known as a counterpoise beneath the pad structure and surrounding environs and a large wire system comprising a 2.5-cm- (1-in.-), 610-m- (2,000-ft)-long steel cable anchored and grounded at either end and supported in the middle by a 24.4-m- (80-ft)-tall nonconductive mast. The mast also served to prevent currents—from lightning strikes to the wire—from passing into the pad structure. A 1.2-m (4-ft) air terminal, or lightning rod, was mounted atop the mast and electrically connected to the steel cable. The cable arrangement assumed a characteristic curved shape to either side of the pad described mathematically as a catenary and therefore called the Catenary Wire System.



A grounded stainless-steel cable extends from the lightning mast to provide a zone of protection for the launch vehicle.

Additional lightning protection devices at the launch pads included a grounded overhead shield cable that protected the crew emergency egress slide wires attached to the fixed service structure. Grounding points on the pad surface and the mobile launcher platform and electrical connections in contact with the shuttle completed the system that conducted any lightning-related currents safely away from the vehicle. Overhead grid-wire systems protected hypergolic fuel and oxidizer storage areas. The huge 3,407,000-L (900,000-gal) liquid hydrogen and liquid oxygen tanks at each pad were constructed of metal and did not need overhead protection.

The shuttle and its elements were well protected from both inclement weather and lightning away from the pad while in the Vehicle Assembly Building. This 160-m- (525-ft)-high structure had eleven 8-m- (25-ft)-high lightning conductor towers on its roof. When lightning hit the building's air terminal system, wires conducted the charge to the towers, which directed the current down the Vehicle Assembly Building's sides and into bedrock through the building's foundation pilings.

In addition to physical protection features, the Space Shuttle Program employed lightning monitoring systems to determine the effects of lightning strikes to the catenary system, the immediate vicinity of the launch pad, and the shuttle itself. The shuttle used two specific lightning monitoring systems—the Catenary Wire Lightning Instrumentation System and the Lightning Induced Voltage Instrumentation System. The Catenary Wire Lightning Instrumentation System used sensors located at either end of the Catenary Wire System to sense currents in the catenary wire induced by nearby or direct lightning strikes. The data were then used to evaluate the potential for damage to sensitive electrical equipment on the shuttle. The Lightning Induced Voltage Instrumentation System used voltage taps and current sensors located in the shuttle and the mobile launcher platform to detect and record voltage or current transients in the shuttle Electrical Power System.

After STS-115, NASA performed a system review and decided to upgrade the two systems. The Ground Lightning Monitoring System was implemented.

It was comprised of both voltage monitoring on the Orbiter power busses and magnetic field sensing internal to the Orbiter middeck, the aft avionics bay, the Payload Changeout Room, and locations on the pad structure. The collected voltage and magnetic field data were used to determine induced current and voltage threats to equipment, allowing direct comparison to known, acceptable maximum levels for the vehicle and its equipment.

The elaborate lightning detection and personnel protection systems at KSC proved their worth the hard way. The lightning masts at Launch Pads 39A and 39B were struck many times with a shuttle on the pad, with no damage to equipment. No shuttle was endangered during launch, although several launches were delayed due to reported weather conditions.

Ultimately, one of the biggest contributions to aerospace vehicle design for lightning protection was the original standard developed by NASA for the shuttle. New standards developed by the Department of Defense, the Federal Aviation Administration, and

Lightning Delays Launch

In August 2006, while STS-115 was on the pad, the lightning mast suffered a 50,000-ampere attachment, much stronger than the more typical 20,000- to 30,000-ampere events, resulting in a 3-day launch delay while engineers and managers worked feverishly to determine the safety of flight condition of the vehicle. The vehicle, following extensive data review and analysis, was declared safe to fly.



commercial organizations over the years have leveraged this pioneering effort, and the latest of these standards is now applicable for design of the new spacecraft.

Working With Winds

Between the Earth's surface and about 18 km (10 nautical miles) altitude, the Earth's atmosphere is dense enough that winds can have a big effect on an ascending spacecraft. Not only can the wind blow a vehicle toward an undesirable direction, the force of the wind can cause stress on the vehicle. The steering commands in the vehicle's guidance computer were based on winds measured well before launch time. If large wind changes occurred between the time the steering commands were calculated and launch time, it was difficult for the vehicle to fly the desired trajectory or the vehicle would be stressed beyond its limits and break up. Therefore, frequent measurements of wind speed and direction as a function of height were made during countdown.

The Space Shuttle Program measured upper air winds in two ways: high-resolution weather balloons and a Doppler radar wind profiler. Both had a wind speed accuracy of about 1 m/sec (3.3 ft/sec). Balloons had the advantage of being able to detect atmospheric features as small as 100 m (328 ft) in vertical extent, and have been used since the beginning of the space program. Their primary disadvantages were that they took about 1 hour to make a complete profile from the surface to 18 km (11 miles), and they blew downwind. In the winter at KSC, jet stream winds could blow a balloon as much as 100 km (62 miles) away from the launch site before the balloon reached the top of its trajectory.

The wind profiler was located near the Shuttle Landing Facility, close to the

Hurricane Damage

Space Shuttle processing during Florida's hurricane season was a constant challenge to ground processing. Hurricane weather patterns were constantly monitored by the team. If the storms could potentially cause damage to the vehicle, the stack was rolled back to the Vehicle Assembly Building for protection. During Hurricane Frances in September 2004, Kennedy Space Center suffered major damage resulting from the storm. The Vehicle Assembly Building lost approximately 820 aluminum side panels and experienced serious roof damage.



Damage to Vehicle Assembly Building at Kennedy Space Center during Hurricane Frances.

launch pad. The profiler scattered radar waves off turbulence in the atmosphere and measured their speed in a manner similar to a traffic policeman's radar gun. It produced a complete profile of wind speed and direction every 5 minutes. This produced profiles 12 times faster than a balloon and much closer to the flight path of the vehicle. Its only technical disadvantage was that the smallest feature in the atmosphere it could distinguish was 300 m (984 ft) in vertical extent. The Doppler radar wind profiler was first installed in the late 1980s.

When originally delivered, the profiler was equipped with commercial software that provided profiles with unknown accuracy every 30 minutes. For launch support, NASA desired a higher rate of measurement and accuracy as good as the high-resolution balloons. Although the Median Filter First Guess software, used in a laboratory to evaluate the potential value of the Doppler radar wind profiler, significantly outperformed any commercially available signal processing methodology for wind

profilers, it was sufficiently complex and its run time too long for operational use to be practical.

To use wind profiler data, NASA developed algorithms for wind profiles that included the ground wind profile, high-altitude weather balloons, and Doppler radar. This greatly enhanced the safety of space launches.

Landing Weather Forecasts

The most important shuttle landing step occurred just prior to the deorbit burn decision. The National Weather Service Spaceflight Meteorology Group's weather prediction was provided to the JSC flight director about 90 minutes prior to the scheduled landing. This forecast supported the Mission Control Center's "go" or "no-go" deorbit burn decision. The deorbit burn occurred about 60 minutes prior to landing. The shuttle had to land at the specified landing site. The final 90-minute landing forecast had to be precise, accurate, and clearly communicated for NASA to make a safe landing decision.



Flight Operations

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For nearly 3 decades, NASA's Johnson Space Center (JSC) Mission Operations organization planned, trained, and managed the on-orbit operations of all Space Shuttle missions. Every mission was unique, and managing a single mission was an extremely complex endeavor. At any one time, however, the agency simultaneously handled numerous flights (nine in 1985 alone). Each mission featured different hardware, payloads, crew, launch date, and landing date. Over the years, shuttle missions became more complicated—even more so when International Space Station (ISS) assembly flights began. Besides the JSC effort, Kennedy Space Center managed all launches while industry, the other centers, and other countries managed many of the payloads.

NASA defined the purpose of each mission several years before the mission's flight. Types of missions varied from satellite releases, classified military payloads, science missions, and Hubble Space Telescope repair and upgrades to construction of the ISS. In addition to completion of the primary mission, all flights had secondary payloads such as education, science, and engineering tests. Along with executing mission objectives, astronauts managed Orbiter systems and fulfilled the usual needs of life such as eating and sleeping. All of these activities were integrated into each mission.

This section explains how NASA accomplished the complicated tasks involved in flight operations. The Space Transportation System (STS)-124 (2008) flight provides examples of how mission operations were conducted.



Plan, Train, and Fly

Planning the Flight Activities

NASA's mission operations team planned flight activities to assure the maximum probability of safe and complete success of mission objectives for each shuttle flight. The planning process encompassed all aspects of preflight assessments, detailed preflight planning and real-time replanning, and postflight evaluations to feed back into subsequent flights. It also included facility planning and configuration requirements. Each vehicle's unique characteristics had to be considered in all flight phases to remain within defined constraints and limitations. The agency made continual efforts to optimize each flight's detailed execution plan, including planning for contingencies to maximize safety and performance margins as well as maximizing mission content and probability of mission success.

During the initial planning period, NASA selected the flight directors and determined the key operators for the Mission Control Team. This team then began planning and training. The flight crew was named 1 to 1½ years prior to launch. The commander acted as the leader for the flight crew through all planning, training, and execution of the mission while the flight directors led the mission operations team.

Approximately 14 months before launch, the mission operations team developed a detailed flight plan. To create the comprehensive timeline, team members worked closely with technical organizations like engineering, the astronaut office, specific NASA contractors, payload suppliers, government agencies, international partners, and other NASA

Collaboration Paved the Way for a Successful Mission... of International Proportions

In 2000, Mission Operations Directorate worked with Japan in preparation for the flight of STS-124 in 2008. To integrate Japan Aerospace Exploration Agency (JAXA) into the program, the US flight team worked closely with the team from Japan to assimilate JAXA's Japanese Experiment Module mission with the requirements deemed by the International Space Station Program. The team of experts taught Japanese flight controllers how Mission Operations Directorate handled flight operations—the responsibilities of mission controllers, dealing with on-orbit failures, writing mission rules and procedures, structuring flight control teams—to help them determine how to plan future missions and manage real-time operations. The downtime created by the Columbia accident (2003) provided additional time to the Japanese to develop necessary processes, since this was the first time JAXA commanded and controlled a space station module.

In addition to working closely with Japan on methodology and training, flight designers integrated the international partners (Russian Federal Space Agency, European Space Agency, Canadian Space Agency, and JAXA) in their planning process. The STS-124 team worked closely with JAXA's flight controllers in the Space Station Integration and Promotion Center at Tsukuba, Japan, to decide the sequence of events—from unberthing the module to activating the science lab. Together, they determined plans and incorporated these plans into the extensive timeline.

centers including Kennedy Space Center (KSC) and Marshall Space Flight Center (MSFC). Crew timeline development required balancing crew task completion toward mission objectives and the individual's daily life needs, such as nutrition, sleep, exercise, and personal hygiene. The timeline was in 5-minute increments to avoid overextending the crew, which could create additional risks due to crew fatigue. Real-time changes to the flight plan were common; therefore, the ground team had to be prepared to accommodate unexpected deviations. Crew input was vital to the process.

Initial Planning: Trajectory Profile

Planning included the mission's trajectory profile. This began with identifying the launch window, which involved determining the future time at which the planes from the launch site and the targeted orbit intersect. The latitude of the launch site was important in determining the direction of launch because it defined the minimum inclination that could be achieved, whereas operational maximum inclinations were defined by range safety limits to avoid landmass. For International Space Station (ISS) missions, the shuttle launched from the



launch site's 28.5-degree latitude into a 51.6-degree inclination orbit, so the launch ground track traveled up the East Coast. For an orbit with a lower inclination, the shuttle headed in a more easterly direction off the launch pad. Imagine that, as the ISS approached on an ascending pass, the shuttle launched along a path that placed it into an orbit just below and behind the ISS orbit. NASA optimized the fuel usage (for launch and rendezvous) by selecting an appropriate launch time. The optimal time to launch was when the ISS orbit was nearest the launch site. Any other time would have resulted in an inefficient use of expensive fuel and resources; however, human factors and mission objectives also influenced mission design and could impose additional requirements on the timing of key mission events. The availability of launch days was further constrained by the angle between the orbital plane and the sun vector. That angle refers to the amount of time the spacecraft spends in sunlight. When this angle exceeded 60 degrees, it was referred to as a "beta cutout." This variable, accounted for throughout a shuttle mission, limited the availability of launch days.

Operational Procedures Development

NASA developed crew procedures and rules prior to the first shuttle flight—Space Transportation System (STS)-1 in 1981—and refined and modified them after each flight, as necessary. A basic premise was that the crew should have all requisite procedures to operate the vehicle safely with respect to the completion of launch, limited orbit operations, and deorbit without ground involvement in the event of a loss of communication. This was not as simple as it might sound. Crew members had no independent knowledge of ground site



During the early flights, NASA established the core elements of the mission operations shuttle processes. The emblem for Johnson Space Center Mission Operations included a sigma to indicate that the history of everything learned was included in planning for the next missions.

status, landing site weather, or on-board sensor drift, and they had considerably less insight into the total set of vehicle telemetry available to the ground.

Each flight increased NASA's experience base with regard to actual vehicle, crew, and ground operations performance. Each mission's operational lessons learned were incorporated into the next mission's crew procedures, flight team training, Flight Rules modifications, and facilities modifications (mostly software).

Flight Control Team

Flight controllers were a vital part of every mission. For each flight control position in the flight control room, one or more supporting positions were in the back room, or the multipurpose support room. For example, the flight dynamics officer and the guidance procedures officer, located in "the trench" of the flight control room, relied on a team of flight controllers sitting just a few feet away in the multipurpose support room to provide them with recommendations. These back room flight controllers provided specialized support in areas such as aborts, navigation, and weather as well

as communications with external entities (i.e., Federal Aviation Administration, US State Department).

Back room support had more time and capabilities to perform quick analyses while front room flight controllers were working higher level issues and communicating with the other front room controllers (i.e., propulsion engineer, booster engineer) and the flight director. This flow of communications enabled analyses to be performed in real time, with appropriate discussions among all team players to result in a recommended course of action that was then passed on to the front room. The front room remained involved in back room discussions when feasible and could always redirect their support if they received new information from another front room flight controller, the flight director, or the capsule communicator (responsible for all communications with the on-orbit crew).

It can easily be surmised that being a flight controller required a quick and decisive mindset with an equally important team player attitude. The pressure to make immediate decisions was greatest during the launch phase and similarly so during the re-entry phase. During those times, flight controllers worked under a high level of pressure and had to trust their counterparts to work together through any unplanned challenges that may have occurred.

Flight Controller Preparation

Preparations for any off-nominal situations were regularly practiced prior to any mission through activities that simulated a particular phase of flight and any potential issue that could occur during that timeframe. These simulated activities, simply referred to as "Sims," involved both the front room



Flight Rules

Part of the planning process included writing Flight Rules. Flight Rules were a key element of the real-time flight control process and were predefined actions to be taken, given certain defined circumstances. This typically meant that rules were implemented, as written, during critical phases such as launch and re-entry into Earth's atmosphere. Generally, during the orbit phase, there was time to evaluate exact circumstances. The Flight Rules defined authorities and responsibilities between the crew and ground, and consisted of generic rules, such as system loss definition, system management, and mission consequence (including early mission termination) for defined failures.

For each mission, lead flight directors and their teams identified flight-specific mission rules to determine how to proceed if a failure occurred. These supplemented the larger book of generic flight rules. For instance, how would the team respond if the payload bay doors failed to open in orbit? The rules minimized real-time rationalization because the controllers thoroughly reviewed and simulated requirements and procedures before the flight.

and the back room flight controllers, just as if the Sim were the real thing. Sims allowed the flight control team and the astronauts to familiarize themselves with the specifics of the missions and with each other. These activities were just as much team-building exercises as they were training exercises in what steps to take and the decisions required for a variety of issues, any of which could have had catastrophic results. Of course, the best part of a simulation was that it was not real. So if a flight controller or an astronaut made a mistake, he or she could live and learn while becoming better prepared for the real thing.

Training to become a flight controller began long before a mission flew. Flight controllers had to complete a training flow and certification process before being assigned to a mission. The certification requirements varied depending on the level of responsibility

of the position. Most trainees began by reading technical manuals related to their area of flight control (i.e., electrical, environmental, consumables manager or guidance, navigation, and controls system engineer), observing currently certified flight controllers during simulations, and performing other hands-on activities appropriate to their development process. As the trainee became more familiar with the position, he or she gradually began participating in simulations until an examination of the trainee's performance was successfully completed to award formal certification. Training and development was a continually improving process that all flight controllers remained engaged in whether they were assigned to a mission or maintaining proficiency. A flight controller also had the option to either remain in his or her current position or move on to a more challenging flight control position

with increased responsibilities, such as those found in the front room. An ascent phase, front room flight control position was typically regarded as having the greatest level of responsibility because this flight controller was responsible for the actions of his or her team in the back room during an intense and time-critical phase of flight. Similarly, the flight director was responsible for the entire flight control team.

Flight Techniques

The flight techniques process helped develop the procedures, techniques, and rules for the vehicle system, payload, extravehicular activities (EVAs), and robotics for the flight crew, flight control team, flight designers, and engineers. NASA addressed many topics over the course of the Space Shuttle Program, including abort modes and techniques, vehicle power downs, system loss integrated manifestations and responses, risk assessments, EVA and robotic procedures and techniques, payload deployment techniques, rendezvous and docking or payload capture procedures, weather rules and procedures, landing site selection criteria, and others. Specific examples involving the ISS were the development of techniques to rendezvous, conduct proximity operations, and dock the Orbiter while minimizing plume impingement contamination and load imposition.

Crew Procedures

Prior to the first shuttle flight, NASA developed and refined the initial launch, orbit, and re-entry crew procedures, as documented in the Flight Data File. This document evolved and expanded over time, especially early in the program, as experience in the real operational environment increased rapidly.

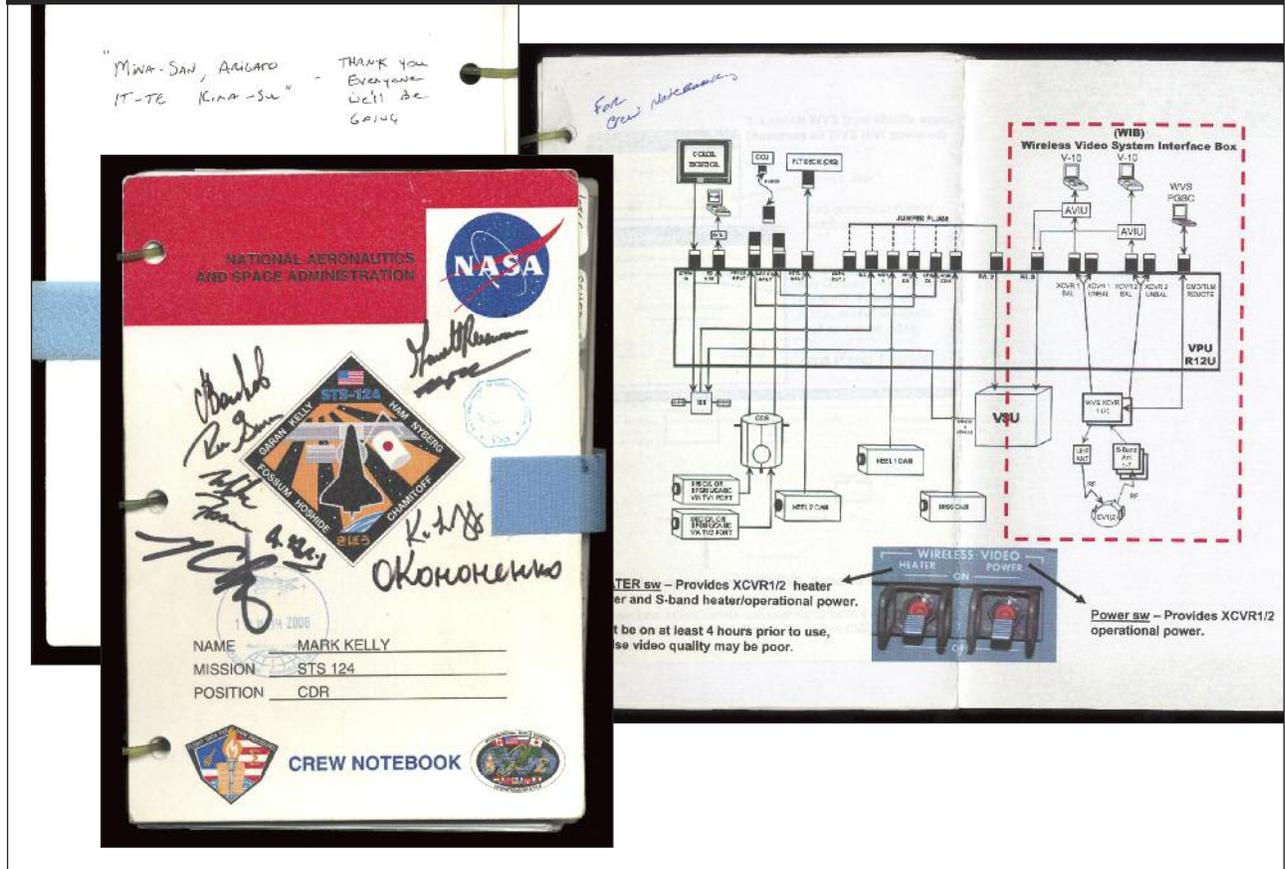


A "fish-eye" lens on a digital still camera was used to record this image of the STS-124 and International Space Station (ISS) Expedition 17 crew members as they share a meal on the middeck of the Space Shuttle Discovery while docked with the ISS. Pictured counterclockwise (from the left bottom): Astronaut Mark Kelly, STS-124 commander; Russian Federal Space Agency Cosmonaut Sergei Volkov, Expedition 17 commander; Astronaut Garrett Reisman; Russian Federal Space Agency Cosmonaut Oleg Kononenko, Astronaut Gregory Chamitoff, Expedition 17 flight engineers; Astronaut Michael Fossum, Japan Aerospace Exploration Agency Astronaut Akihiko Hoshide, Astronaut Karen Nyberg; and Astronaut Kenneth Ham, pilot.



The three major flight phases— ascent, orbit, and re-entry—often required different responses to the same condition, many of which were time critical. This led to the development of different checklists for these phases. New vehicle features such as the Shuttle Robotic Arm and the airlock resulted in additional Flight Data File articles. Some of these, such as the malfunction procedures, did not change unless the underlying system changed or new knowledge was gained, while flight-specific articles, such as the flight plan, EVA, and payload operations checklists, changed for each flight. The Flight Data File included in-flight maintenance

Commander Mark Kelly's personal crew notebook from STS-124.





procedures based on experience from the previous programs. Checklist formats and construction standards were developed and refined in consultation with the crews. NASA modeled the pocket checklists, in particular, after similar checklists used by many military pilots for their operations. Flight versions of the cue cards were fitted with Velcro® tabs and some were positioned in critical locations on the various cockpit panels for instantaneous reference.

In addition, the crew developed quick-reference, personal crew notebooks that included key information the crew member felt important, such as emails or letters from individuals or organizations. During ISS missions, the crews established a tradition where the shuttle crew and the ISS crew signed or stamped the front of each other's notebook.

Once the official Flight Data File was completed, crew members reviewed the flight version one last time and often added their own notes on various pages. All information was then copied and the flight versions of the Flight Data File were loaded on the shuttle. Multiple copies of selected Flight Data File books were often flown to enhance on-board productivity.

All flight control team members and stakeholders, including the capsule communicator and flight director, had nearly identical copies of the Flight Data File at their consoles. This was to ensure the best possible communications between the space vehicle and the flight control team. The entire flown Flight Data File with crew annotations, both preflight and in-flight, was recovered Postflight and archived as an official record.

Detailed Trajectory Planning

Trajectory planning efforts, both preflight and in real time, were major activities. Part of the preflight effort involved defining specific parameters called I-loads, which defined elements of the ascent trajectory control software, some of which were defined and loaded on launch day via the Day-of-Launch I-Load Update system. The values of these parameters were uniquely determined for each flight based on the time of year, specific flight vehicle, specific main engines, mass properties including the specific Solid Rocket Boosters (SRBs), launch azimuth, and day-of-launch wind measurements. It was a constant optimization process for each flight to minimize risk and maximize potential success. Other constraints were space radiation events, predictable conjunctions, and predictable meteoroid events, such as the annual Perseid meteor shower period in mid August. The mission operations team developed the Flight Design Handbook to document, in detail, the process for this planning.

Re-entry trajectory planning was initially done preflight and was continuously updated during a mission. NASA evaluated daily landing site opportunities for contingency deorbit purposes, and continuously tracked mass properties and vehicle center of gravity to precisely predict deorbit burn times and re-entry maneuvers. After the Columbia accident (STS-107) in 2003, the agency established new ground rules to minimize the population overflow for normal entries.

Planning also involved a high level of NASA/Department of Defense coordination, particularly following the Challenger accident (STS-51L) in 1986. This included such topics

as threat and warning, orbital debris, and search and rescue.

Orbiter and Payload Systems Management

Planning each mission required management of on-board consumables for breathing oxygen, fuel cell reactants, carbon dioxide, potable water and wastewater, Reaction Control System and Orbital Maneuvering System propellants, Digital Auto Pilot, attitude constraints, thermal conditioning, antenna pointing, Orbiter and payload data recording and dumping, power downs, etc. The ground team developed and validated in-flight maintenance activities, as required, then put these activities in procedure form and uplinked the activity list for crew execution. There was an in-flight maintenance checklist of predefined procedures as well as an in-flight maintenance tool kit on board for such activities. Unique requirements for each flight were planned preflight and optimized during the flight by the ground-based flight control team and, where necessary, executed by the crew on request.

Astronaut Training

Training astronauts is a continually evolving process and can vary depending on the agency's objectives. Astronaut candidates typically completed 1 year of basic training, over half of which was on the shuttle. This initial year of training was intended to create a strong foundation on which the candidates would build for future mission assignments. Astronaut candidates learned about the shuttle systems, practiced operation of the shuttle in hands-on mock-ups, and trained in disciplines such as space



Shuttle Training Aircraft

Commanders and pilots used the Shuttle Training Aircraft—a modified Gulfstream-2 aircraft—to simulate landing the Orbiter, which was often likened to landing a brick, especially when compared with the highly maneuverable high-speed aircraft that naval aviators and pilots had flown. The Shuttle Training Aircraft mimicked the flying characteristics of the shuttle, and the left-hand flight deck resembled the Orbiter.

Trainers even blocked the windows to simulate the limited view that a pilot experienced during the landing. During simulations at the White Sands Space Harbor in New Mexico, the instructor sat in the right-hand seat and flew the plane into simulation. The commander or pilot, sitting in the left-hand seat, then took the controls. To obtain the feel of flying a brick with wings, he or she lowered the main landing gear and used the reverse thrusters. NASA requirements stipulated that commanders complete a minimum of 1,000 Shuttle Training Aircraft approaches before a flight. Even Commander Mark Kelly—a pilot for two shuttle missions, a naval aviator, and a test pilot with over 5,000 flight hours—recalled that he completed at least “1,600 approaches before [he] ever landed the Orbiter.” He conceded that the training was “necessary because the Space Shuttle doesn’t have any engines for landing. You only get one chance to land it. You don’t want to mess that up.”



Two aircraft stationed at Ellington Air Force Base for Johnson Space Center are captured during a training and familiarization flight over White Sands, New Mexico. The Gulfstream aircraft (bottom) is NASA's Shuttle Training Aircraft and the T-38 jet serves as a chase plane.

Flight Simulation Training

For every hour of flight, the STS-124 crew spent 6 hours training on the ground for a total of about 1,940 hours per crew member. This worked out to be nearly a year of 8-hour workdays.

Commander Mark Kelly and Pilot Kenneth Ham practiced rendezvousing and docking with the space station on the Shuttle Engineering Simulator, also known as the dome, numerous times (on weekends and during free time) because the margin of error was so small.

and life sciences, Earth observation, and geology. These disciplines helped develop them into “jacks-of-all-trades.”

Flight assignment typically occurred 1 to 1½ years prior to a mission. Once assigned, the crew began training for the specific objectives and specialized needs for that mission. Each crew had a training team that ensured each crew member possessed an accurate understanding of his or her assignments. Mission-specific training was built off of past flight experience, if any, and basic training knowledge. Crew members also received payload training at the principal investigator’s facility. This could be at a university, a national facility, an international facility, or another NASA facility. Crew members were the surrogates for the scientists and engineers who designed the payloads, and they trained extensively to ensure a successfully completed mission. As part of their training for the payloads, they may have actually spent days doing the operations required for each day’s primary objectives.

Crew members practiced mission objectives in simulators both with and without the flight control teams in Mission Control. Astronauts trained in Johnson Space Center’s (JSC’s) Shuttle Mission Simulator, shuttle mock-ups, and the Shuttle Engineering Simulator. The Shuttle Mission Simulator contained both a fixed-base and a motion-based high-fidelity station. The motion-based simulator duplicated, as closely as possible, the experience of launch and landing, including the release of the SRBs and External Tank (ET) and the views seen out the Orbiter windows. Astronauts practiced aborts and disaster scenarios in this simulator. The fixed-base simulator included a flight deck and middeck, where crews practiced on-orbit activities. To replicate the feeling of



space, the simulator featured views of space and Earth outside the mock-up's windows. Astronauts used the full-fuselage mock-up trainer for a number of activities, including emergency egress practice and EVA training. Crew compartment trainers (essentially the flight deck and the middeck) provided training on Orbiter stowage and related subsystems.

A few months before liftoff, the crew began integrated simulations with the flight control teams in the Mission Control Center. These simulations prepared the astronauts and the flight control teams assigned to the mission to safely execute critical aspects of the mission. They were a crucial step in flight preparation, helping to identify any problems in the flight plan.

With the exception of being in Earth environment, integrated simulations were designed to look and feel as they would in space, except equipment did not malfunction as frequently in space as it did during simulations. Elaborate scripts always included a number of glitches, anomalies, and failures. Designed to bring the on-orbit and Mission Control teams together to work toward a solution, integrated simulations tested not only the crews and controllers but also the mission-specific Flight Rules.

An important part of astronaut crew training was a team-building activity completed through the National Outdoor Leadership School. This involved a camping trip that taught astronaut candidates how to be leaders as well as followers. They had to learn to depend on one another and balance each other's strengths and weaknesses. The astronaut candidates needed to learn to work together as a crew and eventually recognize that their crew was their family. Once a crew was assigned to a mission, these team-building

Team Building

Commander Mark Kelly took his crew and the lead International Space Station flight director to Alaska for a 10-day team-building exercise in the middle of mission training. These exercises were important, Kelly explained, as they provided crews with the "opportunity to spend some quality time together in a stressful environment" and gave the crews an opportunity to develop leadership skills. Because shuttle missions were so compressed, Kelly wanted to determine how his crew would react under pressure and strain. Furthermore, as a veteran, he knew the crew members had to work as a team. They needed to learn more about one another to perform effectively under anxious and stressful circumstances. Thus, away from the conveniences of everyday life, STS-124's crew members lived in a tent, where they could "practice things like team building, Expedition behavior, and working out conflicts." Building a team was important not only to Kelly, but also to the lead shuttle flight director who stressed the importance of developing "a friendship and camaraderie with the crew." To build that support, crew members frequently gathered together for social events after work. A strong relationship forged between the flight control team and crews enabled Mission Control to assess how the astronauts worked and how to work through stressful situations.



The STS-124 crew members celebrate the end of formal crew training with a cake-cutting ceremony in the Jake Garn Simulation and Training Facility at Johnson Space Center. Pictured from the left: Astronauts Mark Kelly, commander; Ronald Garan, mission specialist; Kenneth Ham, pilot; Japan Aerospace Exploration Agency Astronaut Akihiko Hoshide, Astronauts Michael Fossum, Karen Nyberg, and Gregory Chamitoff, all mission specialists. The cake-cutting tradition shows some of the family vibe between the training team and crew as they celebrate key events in an assigned crew training flow.



Prior to launch, astronauts walk around their launch vehicle at Kennedy Space Center.

activities became an important part of the mission-specific training flow. Teamwork was key to the success of a shuttle mission.

When basic training was complete, astronauts received technical assignments; participated in simulations, support boards, and meetings; and made public appearances. Many also began specialized training in areas such as EVA and robotic operations. Extensive preflight training was performed when EVAs were required for the mission.

Each astronaut candidate completed an EVA skills program to determine his or her aptitude for EVA work. Those continuing on to the EVA specialty completed task training and systems training, the first of which was specific to the tasks completed by an astronaut during an EVA while the latter focused on suit operations. Task training included classes on topics such as the familiarization and operation of tools. For their final EVA training, the astronauts practiced in a swimming pool that produced neutral buoyancy, which mimicked some aspect of

microgravity. Other training included learning about their EVA suits, the use of the airlock in the Orbiter or ISS, and the medical requirements to prevent decompression sickness.

Mission-specific EVA training typically began 10 months before launch. An astronaut completed seven neutral buoyancy training periods for each spacewalk that was considered complex, and five training periods for noncomplex or repeat tasks.

The last training runs before launch were usually completed in the order in which they would occur during the mission. Some astronauts found that the first EVA was more intimidating than the others simply because it represented that initial hurdle to overcome before gaining their rhythm. This concern was eased by practicing an additional Neutral Buoyancy Laboratory training run for their first planned spacewalk as the very last training run before launch.

EVA and robotic operations were commonly integrated, thereby creating the need to train both specialties together and individually. The robotic arm operator received specialized training with the arm on the ground using skills to mimic microgravity and coordination through a closed-circuit television.

EVA training was also accomplished in the Virtual Reality Laboratory, which was similarly used for robotic training. The Virtual Reality Laboratory complemented the underwater training with a more comfortable and flexible environment for reconfiguration changes. Virtual reality software was also used to increase an astronaut's situational awareness and develop effective verbal commands as well as to familiarize him or her with mass handling on the arm and r-bar pitch maneuver photography training.

T-38 aircraft training was primarily used to keep astronauts mentally conditioned to handle challenging, real-time situations. Simulators were an excellent training tool, but they were limited in that the student had the comfort of knowing that he or she was safely on the ground. The other benefit of T-38 training was that the aircraft permitted frequent and flexible travel, which was necessary to accommodate an astronaut's busy training schedule.

In Need of a Plumber

Just a few days before liftoff of STS-124, the space station's toilet broke. This added a wrinkle to the flight plan redrafted earlier. Russia delivered a spare pump to Kennedy Space Center, and the part arrived just in time to be added to Discovery's middeck. Storage space was always at a premium on missions. The last-minute inclusion of the pump involved some shifting and the removal of 15.9 kg (35 pounds) of cargo, including some wrenches and air-scrubber equipment. This resulted in changes to the flight plan—Discovery's crew and the station members would use the shuttle's toilet until station's could be used. If that failed, NASA packed plenty of emergency bags typically used by astronauts to gather in-flight urine specimens for researchers.

When the crew finally arrived and opened the airlock, Commander Mark Kelly joked, "Hey, you looking for a plumber?" The crews, happy to see each other, embraced one another.



Crew Prepares for Launch

With all systems “go” and launch weather acceptable, STS-124 launched on May 31, 2008, marking the 26th shuttle flight to the International Space Station. Three hours earlier, technicians had strapped in seven astronauts for NASA’s 123rd Space Shuttle mission. Commander Mark Kelly was a veteran of two shuttle missions. By contrast, the majority of his crew consisted of rookies—Pilot Kenneth Ham along with Astronauts Karen Nyberg, Ronald Garan, Gregory Chamitoff, and Akihiko Hoshide of the Japan Aerospace Exploration Agency. Although launch typically represented the beginning of a flight, more than 2 decades of work went into the coordination of this single mission.

After suiting up, STS-124 crew members exited the Operations and Checkout Building to board the Astrovan, which took them to Launch Pad 39A for the launch of Space Shuttle Discovery. On the right (front to back): Astronauts Mark Kelly, Karen Nyberg, and Michael Fossum. On the left (front to back): Astronauts Kenneth Ham, Ronald Garan, Akihiko Hoshide, and Gregory Chamitoff.

There were roughly two dozen T-38 aircraft at any time, all of which were maintained and flown out of Ellington Field in Houston, Texas. As part of astronaut candidate training, they received T-38 ground school, ejection seat training, and altitude chamber training. Mission specialists frequently did not have a military flying background, so they were sent to

Pensacola, Florida, to receive survival training from the US Navy. As with any flight certification, currency requirements were expected to be maintained. Semiannual total T-38 flying time minimum for a pilot was 40 hours. For a mission specialist, the minimum flight time was 24 hours. Pilots were also required to meet approach and landing minimum flight times.

Launching the Shuttle

Launch day was always exciting. KSC’s firing room controlled the launch, but JSC’s Mission Operations intently watched all the vehicle systems. The Mission Control Center was filled with activity as the flight controllers completed their launch checklists. For any shuttle mission, the weather was the most common topic of discussion

The Countdown Begins

The primary objective of the STS-124 mission was to deliver Japan’s Kibo module to the International Space Station. As Commander Mark Kelly said, “We’re going to deliver Kibo, or hope, to the space station, and while we tend to live for today, the discoveries from Kibo will certainly offer hope for tomorrow.” The Japanese module is an approximately 11-m (37-ft), 14,500-kg (32,000-pound) pressurized science laboratory, often referred to as the Japanese Pressurized Module. This module was so large that the Orbiter Boom Sensor System had to be left on orbit during STS-123 (2008) to accommodate the extra room necessary in Discovery’s payload bay.

During the STS-124 countdown, the area experienced some showers. By launch time, however, the sea breeze had pushed the showers far enough away to eliminate any concerns. The transatlantic abort landing weather proved a little more challenging, with two of the three landing sites forecasted to have weather violations. Fortunately, Moron Air Base, Spain, remained clear and became the chosen transatlantic abort landing site.



Space Shuttle Discovery and its seven-member STS-124 crew head toward low-Earth orbit and a scheduled link-up with the International Space Station.



and the most frequent reason why launches and landings were delayed. Thunderstorms could not occur too close to the launch pad, crosswinds had to be sufficiently low, cloud decks could not be too thick or low, and visibility was important. Acceptable weather needed to be forecast at the launch site and transatlantic abort landing sites as well as for each ascent abort option.

Not far from the launch pad, search and rescue forces were always on standby for both launch and landing. This included pararescue jumpers to retrieve astronauts from the water if a bailout event were to occur. The more well-known assets were the support ships, which were also supported by each of the military branches and the US Coast Guard. This team of search-and-rescue support remained on alert throughout a mission to ensure the safe return of all crew members.

Shortly before a launch, the KSC launch director polled the KSC launch control room along with JSC Mission Control for a “go/no go” launch decision. The JSC front room flight controllers also polled their back room flight

controllers for any issues. If no issues were identified, the flight controllers, representing their specific discipline, responded to the flight director with a “go.” If an issue was identified, the flight controller was required to state “no go” and why. Flight Rules existed to identify operational limitations, but even with these delineations the decision to launch was never simple.

Fly

Ground Facilities Operations

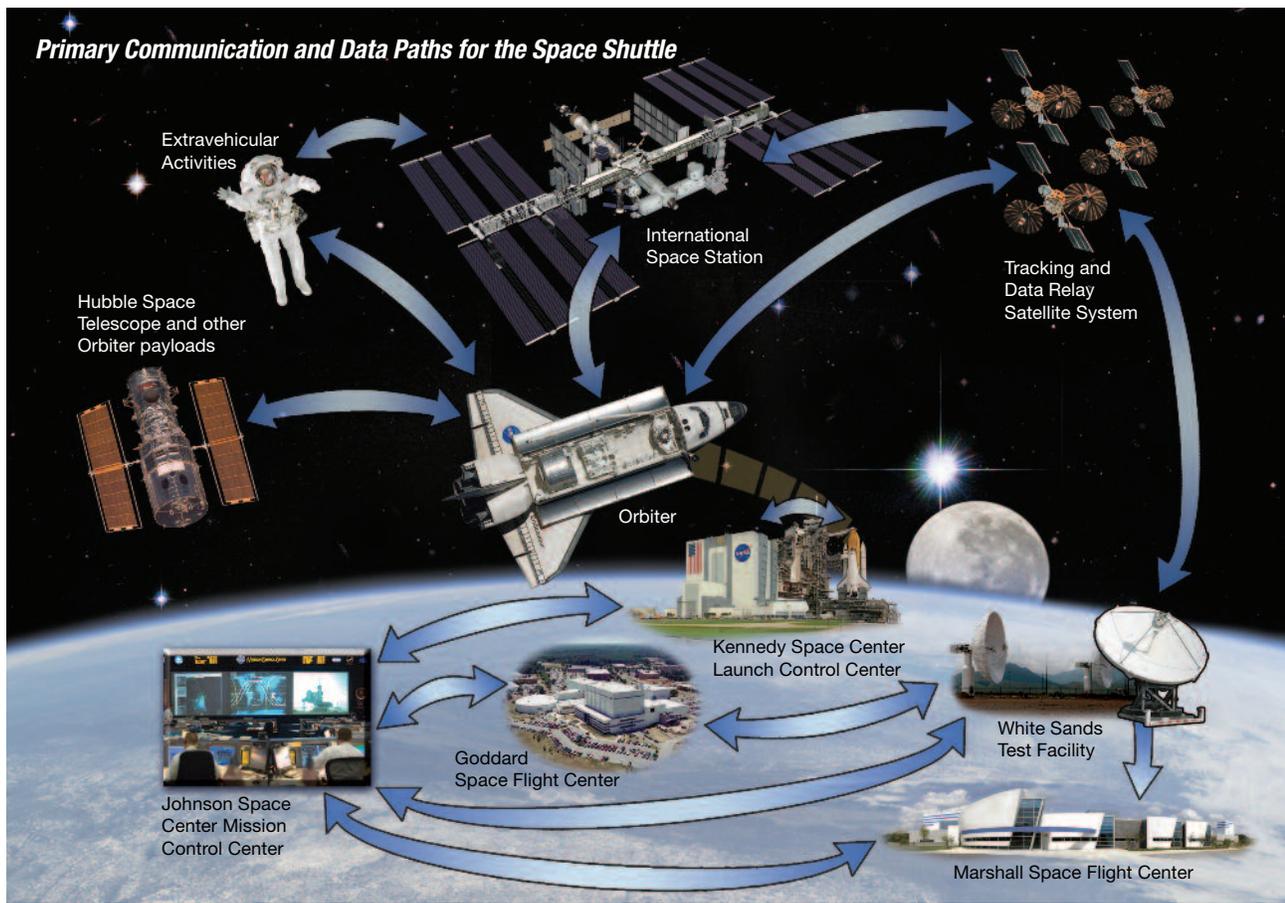
The Mission Control Center relied on the NASA network, managed by Goddard Space Flight Center (GSFC), to route the spacecraft downlink telemetry, tracking, voice, and television and uplink voice, data, and command. The primary in-flight link was to/from the Mission Control Center to the White Sands Ground Terminal up to the tracking and data relay satellites and then to/from the Orbiter. In addition, there were still a few ground sites with a direct linkage to/from the Orbiter as well as specific C-band tracking sites for specific phases as needed. The preflight planning

function included arranging for flight-specific support from all these ground facilities and adjusting them, as necessary, based on in-flight events. The readiness of all these support elements for each flight was certified by the GSFC network director at the Mission Operations Flight Readiness Review.

The Mission Control Center was the focus of shuttle missions during the flight phase. Control of the mission and communication with the crew transferred from the KSC firing room to the JSC Mission Control Center at main engine ignition. Shuttle systems data, voice communications, and television were relayed almost instantaneously to the Mission Control Center through the NASA ground and space networks. In many instances, external facilities such as MSFC and GSFC as well as US Air Force and European Space Agency facilities also provided support for specific payloads. The facility support effort, the responsibility of the operations support team, ensured the Mission Control Center and all its interfaces were ready with the correct software, hardware, and interfaces to support a particular flight.



The Mission Control Center front room houses the capsule communicator, flight director and deputy, and leads for all major systems such as avionics, life support, communication systems, guidance and navigation, extravehicular activity lead and robotic arm, propulsion and other expendables, flight surgeon, and public affairs officer. These views show the extensive support and consoles. Left photo: At the front of the operations center are three screens. The clocks on the left include Greenwich time, mission elapsed time, and current shuttle commands. A map of the world with the shuttle position-current orbit is in the center. The right screen shows shuttle attitude. Center photo: Flight Director Norman Knight (right) speaks with one of the leads at the support console. Right photo: Each console in the operations center has data related to the lead's position; e.g., the life support position would have the data related to Orbiter air, water, and temperature readings and the support hardware functions.



Just before shuttle liftoff, activity in the Mission Control Center slowed and the members of the flight control team became intently focused on their computer screens. From liftoff, the performance of the main engines, SRBs, and ET were closely observed with the team ready to respond if anything performed off-nominally. If, for example, a propulsion failure occurred, the flight control team would identify a potential solution that may or may not require the immediate return of the Orbiter to the ground. If the latter were necessary, an abort mode (i.e., return to launch site, transatlantic abort landing) and a landing site would be selected. The electrical systems and the crew environment also had to function correctly while the Orbiter was guided into orbit. For the entire climb to orbit,

personnel in the Mission Control Center remained intensely focused. Major events were called out during the ascent. At almost 8½ minutes, when target velocity was achieved, main engine cutoff was commanded by the on-board computers and flight controllers continued verifying system performance. Every successful launch was an amazing accomplishment.

Before and after a shuttle launch, KSC personnel performed walkdowns of the launch pad for a visual inspection of any potential debris sources. Shuttle liftoff was a dynamic event that could cause ice/frost or a loose piece of hardware to break free and impact the Orbiter. Finding these debris sources and preventing potential damage was important to the safety of the mission.

Debris Impact on the Orbiter

Debris from launch and on orbit could make the Orbiter unable to land. The Orbiter could also require on-orbit repair.

Ascent Inspection

After the Columbia accident (2003), the shuttle was closely observed during the shuttle launch and for the duration of the ascent phase by a combination of ground and vehicle-mounted cameras, ground Radio Detection and Ranging, and the Wing Leading Edge Impact Detection System. The ground cameras were located on the fixed service structure, the mobile launch platform, around the perimeter of the launch pad, and on short-, medium-, and long-range trackers located along the Florida coast. The ground cameras



Orbiter Survey

The Orbiter survey included the Orbiter's crew cabin Thermal Protection System and the wing leading edge and nose cap reinforced carbon-carbon using the Shuttle Robotic Arm and the Orbiter Boom Sensor System. The survey involved detailed scanning in a specified pattern and required most of the day to complete. A focused inspection was only performed when a suspect area was identified and more detailed information was required to determine whether a repair or alternative action was necessary.

Due to the unique nature of the STS-124 mission, the Shuttle Robotic Arm was used instead of the Orbiter Boom Sensor System. Astronaut Karen Nyberg operated the robotic arm for the inspection of the Thermal Protection System. The nose cap and wing leading edge reinforced carbon-carbon survey was scheduled for post undock after the Orbiter Boom Sensor System had been retrieved during a Flight Day 4 extravehicular activity.



Astronaut Karen Nyberg, STS-124, works the controls on the aft flight deck of Space Shuttle Discovery during Flight Day 2 activities.

provided high-resolution imagery of liftoff and followed the vehicle through SRB separation and beyond. The vehicle-mounted cameras were strategically placed on the tank, boosters, and Orbiter to observe the condition of specific areas of interest and any debris strikes. The crew took handheld video and still imagery of the tank following separation when lighting conditions permitted. This provided another source of information to confirm a clean separation or identify any suspect areas on the tank that might potentially represent a debris concern for the Orbiter Thermal Protection System. The Wing Leading Edge Impact Detection System used accelerometers mounted within the Orbiter's wing leading edge to monitor for impacts throughout the ascent and orbit phases, power permitting.

The world's largest C-band radar and two X-band radars played an integral role in the ascent debris observation through a valuable partnership with the US Navy. The C-band radar watched for falling debris near the Orbiter, and the X-band radar further interpreted the velocity characteristics of any debris events with respect to the vehicle's motion. The X-band radars were on board an SRB recovery ship located downrange of the launch site and a US Army vessel south of the groundtrack. The US Navy C-band radar sat just north of KSC.

Data collected from ground and vehicle-mounted cameras, ground radar, and the Wing Leading Edge Impact Detection System created a comprehensive set of ascent data. Data were sent to the imagery analysis teams at JSC, KSC, and MSFC for

immediate review. Each team had its area of specialty; however, intentional overlap of the data analyses existed as a conservative measure. As early as 1 hour after launch, these teams of imagery specialists gathered in a dark room with a large screen and began reviewing every camera angle captured. They watched the videos in slow motion, forward, and backward as many times as necessary to thoroughly analyze the data. The teams were looking for debris falling off the vehicle stack or even the pad structure that may have impacted the Orbiter. If the team observed or even suspected a debris strike on the Orbiter, the team reported the location to the mission management team and the Orbiter damage assessment team for on-orbit inspection. The damage assessment team oversaw the reported findings of the on-orbit imagery analysis and delivered a recommendation to the Orbiter Project Office and the mission management team stating the extent of any damage and the appropriate forward action. This cycle of obtaining imagery, reviewing imagery, and recommending forward actions continued throughout each phase of the mission.

On-orbit Inspections

The ISS crew took still images of the Orbiter as it approached the station and performed maneuvers, exposing the underside tiles. Pictures were also taken of the ET umbilical doors to verify proper closure as well as photos of the Orbiter's main engines, flight deck windows, Orbital Maneuvering System pods, and vertical stabilizer. The shuttle crew photographed the pods and the leading edge of the vertical stabilizer from the windows of the flight deck. The ISS crew took still images of the Orbiter. All images were downlinked for review by the damage assessment team.



For all missions to the ISS that took place after the Columbia accident, late inspection was completed after the Orbiter undocked. This activity included a survey of the reinforced carbon-carbon to look for any micrometeoroid orbital debris damage that may have occurred during the time on orbit. Since the survey was only of the reinforced carbon-carbon, it took less time to complete than did the initial on-orbit survey. As with the Flight Day 2 survey, the ground teams compared the late inspection imagery to Flight Day 2 imagery and either cleared the Orbiter for re-entry or requested an alternative action.

On-orbit Activities

Extravehicular Activity Preparation

For missions that had EVAs, the day after launch was reserved for extravehicular mobility unit checkout and the Orbiter survey. EVA suit checkout was completed in the airlock where the suit systems were verified to be operating correctly. Various procedures developed over the nearly 30-year history for an EVA mission were implemented to prevent decompression sickness and ensure the crew and all the hardware were ready. The day of the EVA, both crew members suited up with the assistance of the other crew members and then left the airlock. EVAs involving the Shuttle Robotic Arm required careful coordination between crew members. This was when the astronauts applied the meticulously practiced verbal commands.

For missions to the ISS, the primary objective of Flight Day 3 was to rendezvous and dock with the ISS. As the Orbiter approached the ISS, it performed a carefully planned series of burns to adjust the orbit for a smooth approach to docking.

A Flawless Rendezvous

On day three, STS-124 rendezvoused and docked with the space station. About 182 m (600 ft) below the station, Commander Mark Kelly flipped Discovery 360 degrees so that the station crew members could photograph the underbelly of the shuttle. Following the flip, Kelly conducted a series of precise burns with the Orbital Maneuvering System, which allowed the shuttle—flying about 28,200 km/hr (17,500 mph)—to chase the station, which was traveling just as fast. Kelly, who had twice flown to the station, described the moment: “It’s just incredible when you come 610 m (2,000 ft) underneath it and see this giant space station. It’s just an amazing sight.” Once the Orbiter was in the same orbit with the orbiting lab, Kelly nudged the vehicle toward the station. As the vehicle moved, the crew encountered problems with the Trajectory Control System, a laser that provided range and closure rates. This system was the primary sensor, which the crew members used to gauge how far they were from the station. Luckily, the crew had simulated this failure numerous times, so the malfunction had no impact on the approach or closure. The lead shuttle flight director called the rendezvous “absolutely flawless.” Upon docking ring capture, the crew congratulated Kelly with a series of high fives.

Trust and Respect Do Matter

During activation of the Japanese Experiment Module, the flight controllers in Japan encountered a minor hiccup. As the crew attached the internal thermal control system lines, ground controllers worried that there was an air bubble in the system’s lines, which could negatively impact the pump’s performance. Controllers in Houston, Texas, and Tsukuba, Japan, began discussing options. The International Space Station (ISS) flight director noticed that the relationship she had built with the Japanese “helped immensely.” The thermal operations and resource officer had spent so many years working closely with his Japan Aerospace Exploration Agency counterpart that, when it came time to decide to use the nominal plan or a different path, “the respect and trust were there,” and the Japanese controllers agreed with his recommendations to stay with the current plan. “I think,” the ISS flight director said, “that really set the mission on the right course, because then we ended up proceeding with activation.”

On-orbit Operations

Within an hour of docking with the ISS, the hatch opened and the shuttle crew was welcomed by the ISS crew. For missions consisting of a crew change, the first task was to transfer

the custom Soyuz seat liners to crew members staying on station. Soyuz is the Russian capsule required for emergency return to Earth and for crew rotations. Completion of this task marked the formal change between the shuttle and ISS crews.



Every mission included some housekeeping and maintenance. New supplies were delivered to the station and old supplies were stowed in the Orbiter for return to Earth. Experiments that completed their stay on board the ISS were also returned home for analyses of the microgravity environment's influence.

Returning Home

If necessary, a flight could be extended to accommodate extra activities and weather delays. The mission management team decided on flight extensions for additional activities where consideration was given for impacts to consumables, station activities, schedule, etc. Landing was typically allotted 2 days with multiple opportunities to land. NASA's preference was always to land at KSC since the vehicle could be processed at that facility; however, weather would sometimes push the landing to Dryden Flight Research Center/Edwards Air Force Base. If the latter occurred, the Orbiter was flown back on a modified Boeing 747 in what was referred to as a "ferry flight."

Once the Orbiter landed and rolled to a stop, the Mission Control Center turned control back to KSC. After landing, personnel inspected the Orbiter for any variations in Thermal Protection System and reinforced carbon-carbon integrity. More imagery was taken for comparison to on-orbit imagery. Once the Orbiter was at the Orbiter Processing Facility, its cameras were removed for additional imagery analysis and the repairs began in preparation for another flight.

Returning to Earth



Space Shuttle Discovery's drag chute is deployed as the spacecraft rolls toward a stop on runway 15 of the Shuttle Landing Facility at Kennedy Space Center, concluding the 14-day STS-124 mission to the International Space Station.

After nearly 9 days at the space station, the crew of STS-124 undocked and said farewell to Gregory Chamitoff, who would be staying on as the flight engineer for the Expedition crew, and the two other crew members. When watching the goodbyes on video, it appeared as if the crew said goodbye, closed the hatch, and dashed away from the station. "It's more complicated than that," Commander Mark Kelly explained. "You actually spend some time sitting on the Orbiter side of the hatch." About 1 hour passed before the undocking proceeded. Afterward, the crew flew around the station and then completed a full inspection of the wing's leading edge and nose cap with the boom.

The crew began stowing items like the Ku-band antenna in preparation for landing on June 15. On the day of landing, the crew suited up and reconfigured the Orbiter from a spaceship to an airplane. The re-entry flight director and his team worked with the crew to safely land the Orbiter, and continually monitored weather conditions at the three landing sites. With no inclement weather at Kennedy Space Center, the crew of STS-124 was "go" for landing. The payload bay doors were closed several minutes before deorbit burn. The crew then performed checklist functions such as computer configuration, auxiliary power unit start, etc. Sixty minutes before touchdown the deorbit burn was performed. After the Columbia accident, the re-entry profiles for the Orbiter changed so that the crew came across the Gulf of Mexico, rather than the United States. As the Orbiter descended, the sky turned from pitch black to red and orange. Discovery hit the atmosphere at Mach 25 and a large fireball surrounded the glider. It rapidly flew over Mexico. By the time it passed over Orlando, Florida, the Orbiter slowed. As they approached the runway, Kelly pulled the nose up and lowered the landing gear. On touchdown—after main gear touchdown but before nose gear touchdown—he deployed a parachute, which helped slow the shuttle as it came to a complete stop.



The Shuttle Carrier Aircraft transported the Space Shuttle Endeavour from Dryden Research Center, California, back to Kennedy Space Center, Florida.

Solid Foundations Assured Success

Two pioneers of flight operations, Christopher Kraft and Gene Kranz, established the foundations of shuttle mission operations in the early human spaceflight programs of Mercury, Gemini, and Apollo. Their “plan, train, fly” approach made controllers tough and competent, “flexible, smart, and quick on their feet in real time,” recalled the lead flight director for STS-124 (2008). That concept, created in the early 1960s, remained the cornerstone of mission operations throughout the Space Shuttle Program, as exemplified by the flight of STS-124.



Endeavour touches down at Dryden Flight Research Center located at Edwards Air Force Base in California to end the STS-126 (2008) mission.



Extravehicular Activity Operations and Advancements

Nancy Patrick
Joseph Kosmo
James Locke
Luis Trevino
Robert Trevino

A dramatic expansion in extravehicular activity (EVA)—or “spacewalking”—capability occurred during the Space Shuttle Program; this capability will tremendously benefit future space exploration. Walking in space became almost a routine event during the program—a far cry from the extraordinary occurrence it had been. Engineers had to accommodate a new cadre of astronauts that included women, and the tasks these spacewalkers were asked to do proved significantly more challenging than before. Spacewalkers would be charged with building and repairing the International Space Station. Most of the early shuttle missions helped prepare astronauts, engineers, and flight controllers to tackle this series of complicated missions while also contributing to the success of many significant national resources—most notably the Hubble Space Telescope. Shuttle spacewalkers manipulated elements up to 9,000 kg (20,000 pounds), relocated and installed large replacement parts, captured and repaired failed satellites, and performed surgical-like repairs of delicate solar arrays, rotating joints, and sensitive Orbiter Thermal Protection System components. These new tasks presented unique challenges for the engineers and flight controllers charged with making EVAs happen.

The Space Shuttle Program matured the EVA capability with advances in operational techniques, suit and tool versatility and function, training techniques and venues, and physiological protocols to protect astronauts while providing better operational efficiency. Many of these advances were due to the sheer number of EVAs performed. Prior to the start of the program, 38 EVAs had been performed by all prior US spaceflights combined. The shuttle astronauts accomplished 157 EVAs.

This was the primary advancement in EVA during the shuttle era—an expansion of capability to include much more complicated and difficult tasks, with a much more diverse Astronaut Corps, done on a much more frequent basis. This will greatly benefit space programs in the future as they can rely on a more robust EVA capability than was previously possible.



Spacewalking: Extravehicular Activity

If We Can Put a Human on the Moon, Why Do We Need to Put One in the Payload Bay?

The first question for program managers at NASA in regard to extravehicular activities (EVAs) was: Are they necessary? Managers faced the challenge of justifying the added cost, weight, and risk of putting individual crew members outside and isolated from the pressurized cabin in what is essentially a personal spacecraft. Robotics or automation are often considered alternatives to sending a human outside the spacecraft; however, at the time the shuttle was designed, robotics and automation were not advanced enough to take the place of a human in all required external tasks. Just as construction workers and cranes are both needed to build skyscrapers, EVA crew members and robots are needed to work in space.

Early in the Space Shuttle Program, safety engineers identified several shuttle contingency tasks for which EVA was the only viable option. Several shuttle components could not meet redundancy requirements through automated means without an untenable increase in weight or system complexity. Therefore, EVA was employed as a backup. Once EVA capability was required, it became a viable and cost-effective backup option as NASA identified other system problems. Retrieval or repair of the Solar Maximum Satellite (SolarMax) and retrieval of the Palapa

Gregory Harbaugh
Astronaut on STS-39 (1991), STS-54 (1993), and STS-82 (1997).
Manager, Extravehicular Activity (EVA) Office (1997-2001).

“In my opinion, one of the major achievements of the Space Shuttle era was the dramatic enhancement in productivity, adaptability, and efficiency of EVA, not to mention the numerous EVA-derived accomplishments. At the beginning of the shuttle era, the extravehicular mobility unit had minimal capability for tools, and overall utility of EVA was limited. However, over the course of the program EVA became a planned event on many missions and ultimately became the fallback option to address a multitude of on-orbit mission objectives and vehicle anomalies. Speaking as the EVA program manager for 4 years (1997-2001), this was the result of incredible reliability of the extravehicular mobility unit thanks to its manufacturers (Hamilton Sundstrand and ILC Dover), continuous interest and innovation led by the EVA crew member representatives, and amazing talent and can-do spirit of the engineering/training teams. In my 23 years with NASA, I found no team of NASA and contractor personnel more technically astute, more dedicated, more innovative, or more ultimately successful than the EVA team.

EVA became an indispensable part of the Space Shuttle Program. EVA could and did fix whatever problems arose, and became an assumed tool in the holster of the mission planners and managers. In fact, when I was EVA program manager we had shirts made with the acronym WOBTSYA—meaning ‘we’ve only begun to save your Alpha’ (the ISS name at the time). We knew when called upon we could handle just about anything that arose.”

B2 and Westar VI satellites were EVA tasks identified very early in the program. Later, EVA became a standard

backup option for many shuttle payloads, thereby saving cost and resolving design issues.



Automation and Extravehicular Activity

EVA remained the preferred method for many tasks because of its efficiency and its ability to respond to unexpected failures and contingencies. As amazing and capable as robots and automation are, they are typically efficient for anticipated tasks or those that fall within the parameters of known tasks. Designing and certifying a robot to perform tasks beyond known requirements is extremely costly and not yet mature enough to replace humans.

Robots and automation streamlined EVA tasks and complemented EVA, resulting in a flexible and robust capability for building, maintaining, and repairing space structures and conducting scientific research.

Designing the Spacesuit for the Space Shuttle

Once NASA established a requirement for EVA, engineers set out to design and build the hardware necessary to provide this capability. Foremost, a spacesuit was required to allow a crew member to venture outside the pressurized cabin. The Gemini and Apollo spacesuits were a great starting point; however, many changes were needed to create a workable suit for the shuttle. The shuttle suit had to be reusable, needed to fit many different crew members, and was required to last for many years of repeated use. Fortunately, engineers were able to take advantage of advanced technology and lessons learned from earlier programs to meet these new requirements.

The cornerstone design requirement for any spacesuit is to protect the crew member from the space environment.

Suit Environment as Compared to Space Environment

Atmosphere	Suit Environment Requirements	Space Environment
Pressure:	23.44 kPa-27.57 kPa (3.4 - 4.4 psi)	1 Pa (1.45 x 10 ⁻⁴ psi)
Oxygen:	100%	0%
Temperature:	10°C-27°C (50°F-80°F)	-123°C-+232°C (-190°F- +450°F)

The target suit pressure was an exercise in balancing competing requirements. The minimum pressure required to sustain human life is 21.4 kPa (3.1 psi) at 100% oxygen. Higher suit pressure allows better oxygenation and decreases the risk of decompression sickness to the EVA crew member. Lower suit pressure increases crew member flexibility and dexterity, thereby reducing crew fatigue. This is similar to a water hose. A hose full of water is difficult to bend or twist, while an empty hose is much easier to move around. Higher suit pressures also require more structural stiffening to maintain suit integrity (just as a thicker balloon is required to hold more air). This further exacerbates the decrease in flexibility and dexterity. The final suit pressure selected was 29.6 kPa (4.3 psi), which has proven to be a reasonable compromise between these competing constraints.

The next significant design requirements came from the specific mission applications: what EVA tasks



Contingency extravehicular activity: Astronaut Scott Parazynski, atop the Space Station Robotic Arm and the Shuttle Robotic Arm extension, the Orbiter Boom Sensor System, approaches the International Space Station solar arrays to repair torn sections during STS-120 (2009).

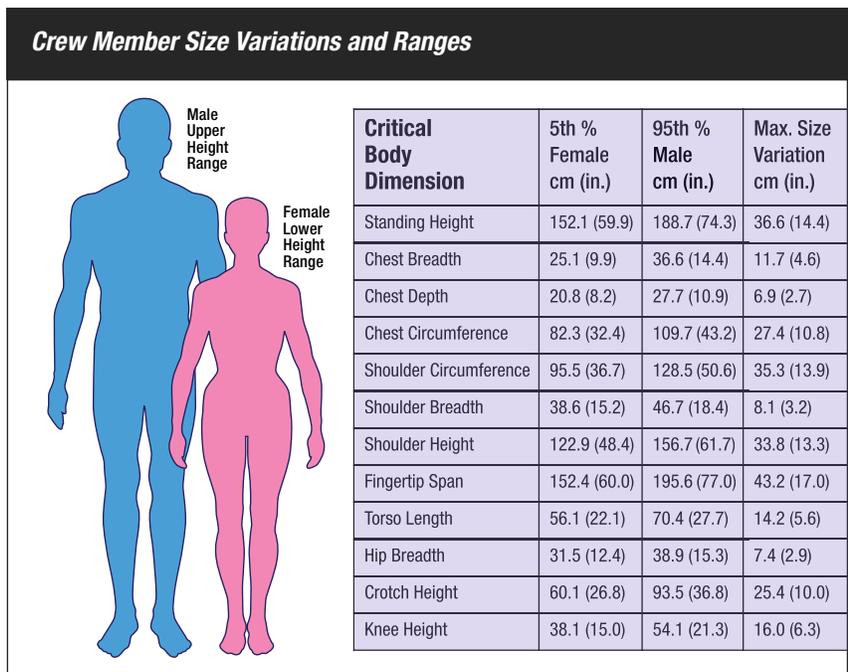


were required, who would perform them, and to what environmental conditions the spacewalkers would be exposed. Managers decided that the shuttle spacesuit would only be required to perform in microgravity and outside the shuttle cabin. This customized requirement allowed designers to optimize the spacesuit. The biggest advantage of this approach was that designers didn't have to worry as much about the mass of the suit.

Improving mobility was also a design goal for the shuttle extravehicular mobility unit (i.e., EVA suit). Designers added features to make it more flexible and allow the crew member greater range of motion than with previous suits. Bearings were included in the shoulder, upper arm, and waist areas to provide a useful range of mobility. The incorporation of the waist bearing enabled the EVA crew member to rotate.

Shuttle managers decided that, due to the duration of the program, the suit should also be reusable and able to fit many different crew members. Women were included as EVA crew members for the first time, necessitating unique accommodations and expanding the size range required. The range had to cover from the 5% American Female to the 95% American Male with variations in shoulders, waist, arms, and legs.

A modular “tuxedo” approach was used to address the multi-fit requirement. Tuxedos use several different pieces, which can be mixed and matched to best fit an individual—one size of pants can be paired with a different size shirt, cummerbund, and shoes to fit the individual. The EVA suit used a



modular design, thereby allowing various pieces of different sizes to achieve a reasonably good fit. The design also incorporated a custom-tailoring capability using inserts, which allowed a reasonably good fit with minimal modifications.

While the final design didn't accommodate the entire size range of the Astronaut Corps, it was flexible enough to allow for a wide variety of crew members to perform spacewalks, especially those crew members who had the best physical attributes for work on the International Space Station (ISS).

One notable exception to this modular approach was the spacesuit gloves. Imagine trying to assemble a bicycle while wearing ski gloves that are too large and are inflated like a balloon. This is similar to attempting EVA tasks

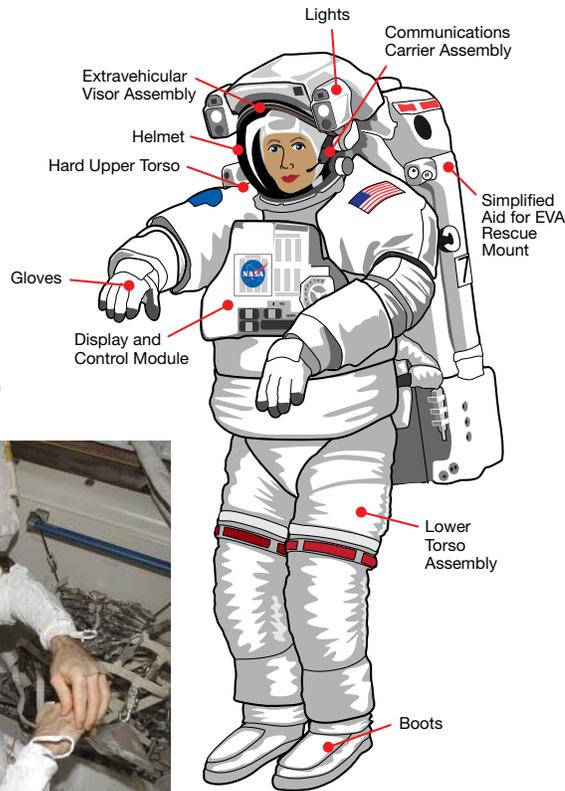
like driving bolts and operating latches while wearing an ill-fitting glove. Laser-scanning technology was used to provide a precise fit for glove manufacture patterns. Eventually, it became too expensive to maintain a fully customized glove program. Engineers were able to develop a set of standard sizes with adjustments at critical joints to allow good dexterity at a much lower cost. In contrast, a single helmet size was deemed sufficient to fit the entire population without compromising a crew member's ability to perform tasks.

The responsibility for meeting the reuse requirement was borne primarily by the Primary Life Support System, or “backpack,” which included equipment within the suit garment to control various life functions. The challenge



Extravehicular Mobility Unit

February 8, 2007: Astronaut Michael Lopez-Alegria, International Space Station Expedition 14 commander, dons a liquid cooling and ventilation garment to be worn under the extravehicular mobility unit. Here, he is preparing for the final of three sessions of extravehicular activity (EVA) in 9 days.



for Primary Life Support System designers was to provide a multiyear, 25-EVA system. This design challenge resulted in many innovations over previous programs.

One area that had to be improved to reduce maintenance was body temperature control. Both the Apollo and the shuttle EVA suit used a water cooling system with a series of tubes that carried chilled water and oxygen around the body to cool and

ventilate the crew member. The shuttle EVA suit improved on the Apollo design by removing the water tubes from the body of the suit and putting them in a separate garment—the liquid cooling ventilation garment. This garment was a formfitting, stretchable undergarment (think long johns) that circulated water and oxygen supplied by the Primary Life Support System through about 91 m (300 ft) of flexible tubing. This component of the suit was easily replaceable,

inexpensive, easy to manufacture, and available in several sizes.

Materials changes in the Primary Life Support System also helped to reduce maintenance and refurbishment requirements. Shuttle designers replaced the tubing in the liquid cooling ventilation garment with ethylene vinyl acetate to reduce impurities carried by the water into the system. The single change that likely contributed the most toward increasing component life and reducing maintenance requirements was the materials selection for the Primary Life Support System water tank bladder. The water tank bladder expanded and contracted as the water quantity changed during the EVA, and functioned as a barrier between the water and the oxygen system. Designers replaced the molded silicon bladder material with Flourel™, which leached fewer and less-corrosive effluents and was half as permeable to water, resulting in dryer bladder cavities. This meant less corrosion and cleaner filters—all resulting in longer life and less maintenance.

Using the Apollo EVA suit as the basis for the shuttle EVA suit design saved time and money. It also provided a better chance for success by using proven design. The changes that were incorporated, such as using a modular fit approach, including more robust materials, and taking advantage of advances in technology, helped meet the challenges of the Space Shuttle Program. These changes also resulted in a spacesuit that allowed different types of astronauts to perform more difficult EVA tasks over a 30-year program with very few significant problems.



Extravehicular Activity Mission Operations and Training—All Dressed Up, Time to Get to Work

If spacesuit designers were the outfitters of spacewalks, flight controllers, who also plan the EVAs and train the crew members, were the choreographers. Early in the program, EVAs resembled a solo dancer performing a single dance. As flights became more complicated, the choreography became more like a Broadway show—several dancers performing individual sequences, before coming together to dance in concert. On Broadway, the individual sequences have to be choreographed so that dancers come together at the right time. This choreography is similar to developing EVA timelines for a Hubble repair or an ISS assembly mission. The tasks had to be scheduled so that crew members could work individually when only one person was required for a task, but allow them to come together when they had a jointly executed task.

The goal was to make timelines as efficient as possible, accomplish as many tasks as possible, and avoid one crew member waiting idle until the other crew member finished a task. The most significant contribution of EVA operations during the shuttle era was the development of this ability to plan and train for a large number of interdependent and challenging EVA tasks during short periods of time. Over time, the difficulty increased to require interdependent spacewalks within a flight and finally interdependent spacewalks between flights. This culminated in the

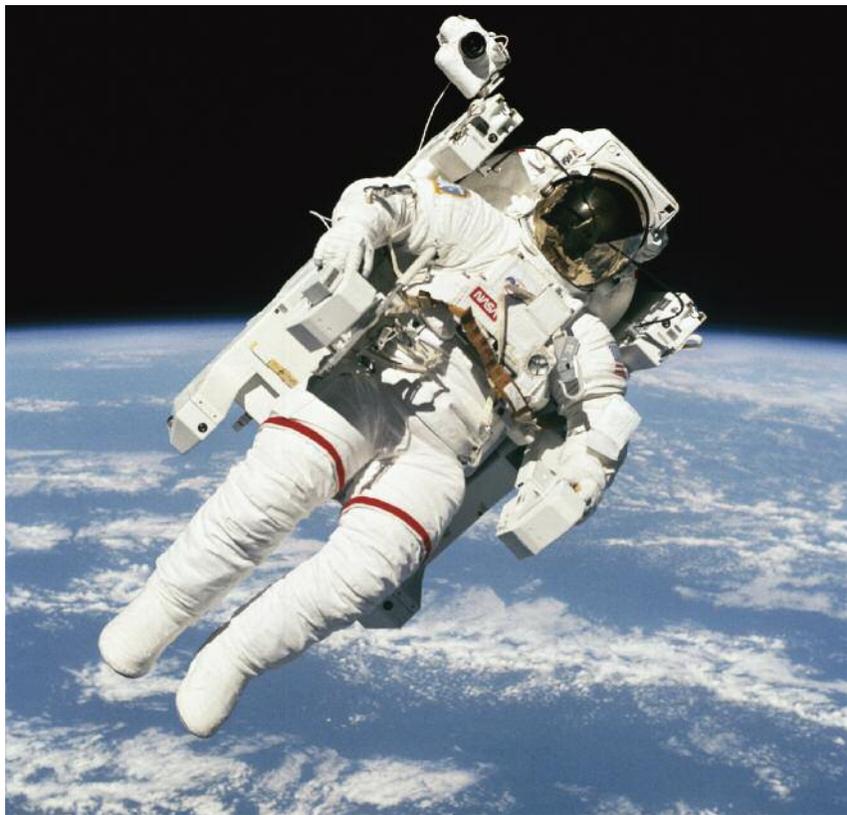
assembly and maintenance of the ISS, which required the most challenging series of EVAs to date.

The first shuttle EVAs were devoted to testing the tools and suit equipment that would be used in upcoming spacewalks. After suit/airlock problems scrubbed the first attempt, NASA conducted the first EVA since 1974 during Space Transportation System (STS)-6 on April 7, 1983. This EVA practiced some of the shuttle contingency tasks and exercised the suit and tools. The goal was to gain confidence and experience with the new EVA hardware. Then on STS-41B (1984), the second EVA flight tested some of the critical tools and techniques

that would be used on upcoming spacewalks to retrieve and repair satellites. One of the highlights was a test of the manned maneuvering unit, a jet pack designed to allow EVA crew members to fly untethered, retrieve satellites, and return with the satellite to the payload bay for servicing. The manned maneuvering unit allowed an EVA crew member to perform precise maneuvering around a target and dock to a payload in need of servicing.

Shuttle Robotic Arm

Another highlight of the STS-41B EVAs was the first demonstration of an EVA crew member performing tasks while positioned at the end of the



Astronaut Bruce McCandless on STS 41B (1984) in the nitrogen-propelled manned maneuvering unit, completing an extravehicular activity. McCandless is floating without tethers attaching him to the shuttle.



Shuttle Robotic Arm. This capability was a major step in streamlining EVAs to come as it allowed a crew member to be moved from one worksite to another quickly. This capability saved the effort required to swap safety tethers during translation and set up and adjust foot restraints—sort of like being able to roll a chair to move around an office rather than having to switch from chair to chair. It was also a first step in evaluating how an EVA crew member affected the hardware with which he or she interacted.

The concern with riding the Shuttle Robotic Arm was ensuring that the EVA crew member did not damage the robotic arm's shoulder joint by imparting forces and moments at the end of the 15-m (50-ft) boom that didn't have much more mass than the crew member. Another concern was the motion that the Shuttle Robotic Arm could experience under EVA loads—similar to how a diving board bends and flexes as a diver bounces on its end. Too much motion could make it too difficult to perform EVA tasks and too time consuming to wait until the motion damps out. Since the arm joints were designed to slip before damage could occur and crew members would be able to sense a joint slip, the belief was that the arm had adequate safeguards to preclude damage.

Allowing a crew member to work from the end of the arm required analysis of the arm's ability to withstand EVA crew member forces. Since both the Shuttle Robotic Arm and the crew member were dynamic systems, the analysis could be complicated; however, experts agreed that any dynamic EVA load case with a static Shuttle Robotic Arm would be enveloped by the case of applying brakes to the arm at its worst-case

runaway speed with a static EVA crew member on the end. After this analysis demonstrated that the Shuttle Robotic Arm would not be damaged, EVA crew members were permitted to work on it. Working from the Shuttle Robotic Arm became an important technique for performing EVAs.

Satellite Retrieval and Repair

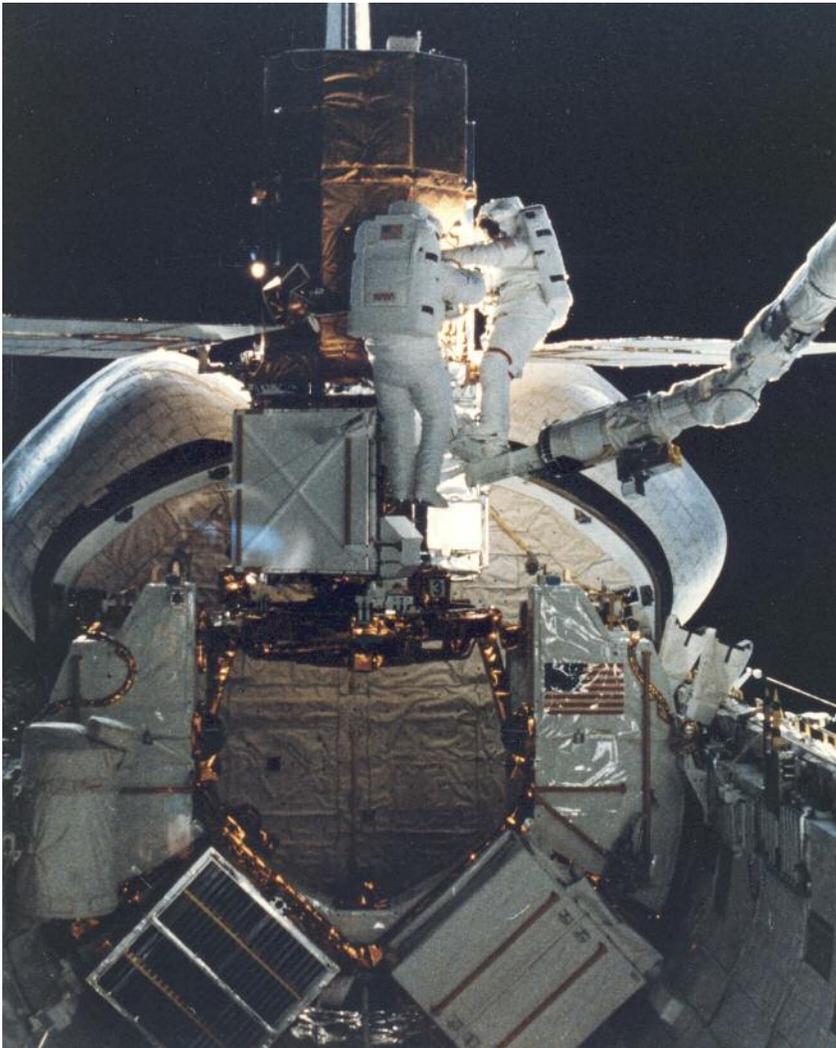
Once these demonstrations and tests of EVA capabilities were complete, the EVA community was ready to tackle satellite repairs. The first satellite to be repaired was SolarMax, on STS-41C (1984), 1 year after the first shuttle EVA. Shortly after STS-41B landed, NASA decided to add retrieval of Palapa B2 and Westar VI to the shuttle manifest, as the satellites had failed shortly after their deploy on that flight. While these early EVAs were ultimately successful, they did not go as originally planned.

NASA developed several new tools to assist in the retrieval. For SolarMax, the trunnion pin attachment device was built to attach to the manned maneuvering unit on one side and then mate to the SolarMax satellite on the other side to accommodate the towing of SolarMax back to the payload bay. Similarly, an apogee kick motor capture device (known as the "stinger") was built to attach to the manned maneuvering unit to mate with the Palapa B2 and Westar VI satellites. An a-frame was also provided to secure the Palapa B and Westar satellites in the payload bay. All was ready for the first operational EVAs; however, engineers, flight controllers, and managers would soon have their first of many experiences demonstrating the value of having a crew member in the loop.

When George Nelson flew the manned maneuvering unit to SolarMax during STS-41C, the trunnion pin attachment device jaws failed to close on the service module docking pins. After several attempts to mate, the action induced a slow spin and eventually an unpredictable tumble. SolarMax was stabilized by ground commands from Goddard Space Flight Center during the crew sleep period. The next day, Shuttle Robotic Arm operator Terry Hart grappled and berthed the satellite—a procedure that flight controllers felt was too risky preflight. EVA crew members executed a second EVA to complete the planned repairs.

The STS-51A (1984) Palapa B2/Westar VI retrieval mission was planned, trained, and executed within 10 months of the original satellite failures. In the wake of the problem retrieving SolarMax, flight planners decided to develop backup plans in case the crew had problems with the stinger or a-frame. Joseph Allen flew the manned maneuvering unit/stinger and mated it to the Palapa B2 satellite; however, Dale Gardner, working off the robotic arm, was unable to attach the a-frame device designed to assist in handling the satellite. The crew resorted to a backup plan, with Gardner grasping the satellite then slowly bringing it down and securing it for return to Earth. On a subsequent EVA, Gardner used the manned maneuvering unit and stinger to capture the Westar VI satellite, and the crew used the Shuttle Robotic Arm to maneuver it to the payload bay where the EVA crew members secured it.

Although the manned maneuvering unit was expected to be used extensively, the Shuttle Robotic Arm proved more



Astronauts George Nelson (right) and James van Hoften captured Solar Maximum Satellite in the aft end of the Challenger's cargo bay during STS-41C (1984). The purpose was to repair the satellite. They used the mobile foot restraint and the robotic arm for moving about the satellite.

efficient because it had fewer maintenance costs and less launch mass.

The next major EVA missions were STS-51D and STS-51I, both in 1985. STS-51D launched and deployed Syncom-IV/Leasat 3 satellite, which failed to activate after deployment. The STS-51D crew conducted the first unscheduled shuttle EVA. The goal

was to install a device on the Shuttle Robotic Arm that would be used to attempt to flip a switch to activate the satellite. Although the EVA was successful, the satellite did not activate and STS-51I was replanned to attempt to repair the satellite. STS-51I was executed within 4 months of STS-51D, and two successful EVAs repaired it.

These early EVA flights were significant because they established many of the techniques that would be used throughout the Space Shuttle Program. They also helped fulfill the promise that the shuttle was a viable option for on-orbit repair of satellites. EVA flight controllers, engineers, and astronauts proved their ability to respond to unexpected circumstances and still accomplish mission objectives. EVA team members learned many things that would drive the program and payload customers for the rest of the program. They learned that moving massive objects was not as difficult as expected, and that working from the Shuttle Robotic Arm was a stable way of positioning an EVA crew member. Over the next several years, EVA operations were essentially a further extension of the same processes and operations developed and demonstrated on these early flights.

During the early part of the Space Shuttle Program, EVA was considered to be a last resort because of inherent risk. As the reliability and benefits of EVA were better understood, however, engineers began to have more confidence in it. They accepted that EVA could be employed as a backup means, be used to make repairs, or provide a way to save design complexity. Engineers were able to take advantage of the emerging EVA capability in the design of shuttle payloads. Payload designers could now include manual EVA overrides on deployable systems such as antennas and solar arrays instead of adding costly automated overrides. Spacecraft subsystems such as batteries and scientific instruments were designed to be repaired or replaced by EVA. Hubble and the Compton Gamma Ray Observatory were two notable science



satellites that were able to use a significant number of EVA-serviceable components in their designs.

EVA flight controllers and engineers began looking ahead to approaching missions to build the ISS. To prepare for this, program managers approved a test program devoted to testing tools, techniques, and hardware design concepts for the ISS. In addition to direct feedback to the tool and station hardware designs, the EVA community gained valuable experience in planning, training, and conducting more frequent EVAs than in the early part of the program.

Hubble Repair

As NASA had proven the ability to execute EVAs and accomplish some remarkable tasks, demand for the EVA resource increased sharply on the agency. One of the most dramatic and demanding EVA flights began development shortly after the deployment of Hubble in April 1990. NASA's reputation was in jeopardy from the highly publicized Hubble failure, and the scientific community was sorely disappointed with the capability of the telescope. Hubble was designed with several servicing missions planned, but the first mission—to restore its optics to the expected performance—took on greater significance. EVA was the focal point in recovery efforts. The mission took nearly 3 years to plan, train, and develop the necessary replacement parts.

The Hubble repair effort required significant effort from most resources in the EVA community. Designers from Goddard Space Flight Center, Johnson Space Center, Marshall Space Flight

Three Spacewalkers Capture Satellite



Astronauts Rick Hieb on the starboard payload bay mounted foot restraint work station, Bruce Melnick with his back to the camera, and Tom Akers on the robotic arm mounted foot restraint work station—on the backside of the Intelsat during STS-49 (1992).

STS-49 significantly impacted planning for future EVAs. It was the most aggressive EVA flight planned, up to that point, with three EVAs scheduled. Engineers designed a bar with a grapple fixture to capture Intelsat and berth it in the payload bay. The data available on the satellite proved inadequate and it was modeled incorrectly for ground simulations. After two EVA attempts to attach the capture bar, flight controllers looked at other options.

The result was an unprecedented three-man EVA using space hardware to build a platform for the crew members, allowing them to position themselves in a triangle formation to capture the Intelsat by hand. This required an intense effort by ground controllers to verify that the airlock could fit three crew members, since it was only designed for two, and that there were sufficient resources to service all three. Additional analyses looked at whether there were sufficient handholds to grasp the satellite, that satellite temperatures would not exceed the glove temperature limits, and that structural margins were sufficient. Practice runs on the ground convinced ground operators that the operation was possible. The result was a successful capture and repair during the longest EVA in the shuttle era.



Center, and the European Space Agency delivered specialized tools and replacement parts for the repair. Approximately 150 new tools and replacement parts were required for this mission. Some of these tools and parts were the most complicated ones designed to date. Flight controllers concentrated on planning and training the unprecedented number of EVA tasks to be performed—a number that continued to grow until launch. What started as a three-EVA mission had grown to five by launch date. The EVA timeliners faced serious challenges in trying to accomplish so many tasks, as precious EVA resources were stretched to the limit.

New philosophies for managing EVA timelines developed in response to the growing task list. Until then, flight controllers included extra time in timelines to ensure all tasks would be completed, and crews were only trained in the tasks stated in those timelines. For Hubble, timelines included less flexibility and crews were trained on extra tasks to make sure they could get as much done as possible. With the next servicing mission years away, there was little to lose by training for extra tasks. To better ensure the success of the aggressive timelines, the crew logged more than twice the training time as on earlier flights.

When astronauts were sent to the Hubble to perform its first repair, engineers became concerned that the crew members would put unacceptable forces on the great observatory. Engineers used several training platforms to measure forces and moments from many different crew members to gain a representative set of both normal and contingency EVA

Fatigue—A Constant Concern During Extravehicular Activity

Why are extravehicular activities (EVAs) so fatiguing if nothing has any weight in microgravity?

Lack of suit flexibility and dexterity forces the wearer to exert more energy to perform tasks. With the EVA glove, the fingers are fixed in a neutral position. Any motion that changes the finger/hand position requires effort.

Lack of gravity removes leverage. Normally, torque used to turn a fastener is opposed by a counter-torque that is passively generated by the weight of the user. In weightlessness, a screwdriver user would spin aimlessly unless the user's arm and body were anchored to the worksite, or opposed the torque on the screwdriver with an equal muscular force in the opposite direction. Tool use during EVAs is accomplished by direct muscle opposition with the other arm, locking feet to the end of a robotic arm, or rigidly attaching the suit waist to the worksite. EVA tasks that require many hand/arm motions over several hours lead to significant forearm fatigue.

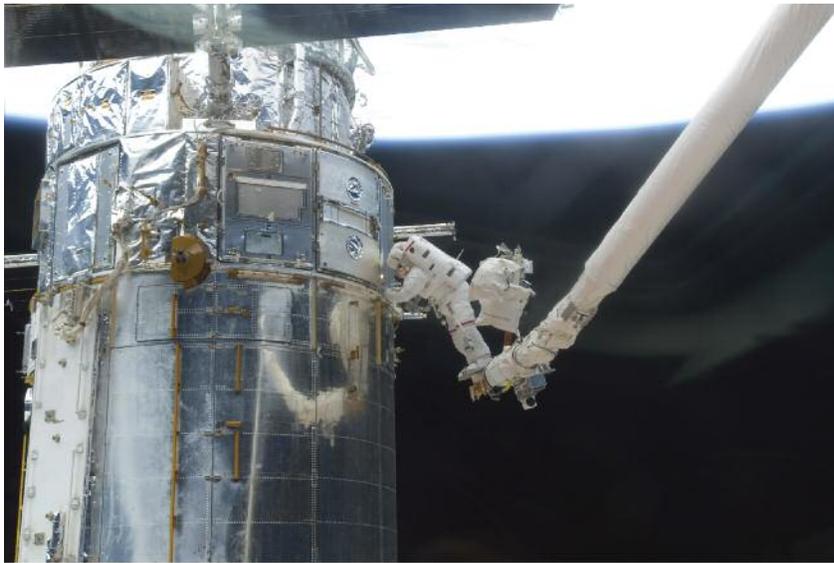
The most critical tasks—ingressing the airlock, shutting the hatch, and reconnecting the suit umbilical line—occur at the end of an EVA. Airlocks are cramped and tasks are difficult, especially when crew members are fatigued and overheated. Overheating occurs because the cooling system must be turned off before an astronaut can enter the airlock. The suit does not receive cooling until the airlock umbilical is connected. The helmet visor can fog over at this point, making ingress even more difficult.

Along with crew training, medical doctors and the mission control team monitor exertion level, heart rate, and oxygen usage. Communication between ground personnel and astronauts is essential in preventing fatigue from having disastrous consequences.

tasks. These cases were used to analyze Hubble for structural integrity and to sensitize EVA crew members to where and when they needed to be careful to avoid damage.

EVA operators also initiated three key processes that would prove very valuable both for Hubble and later for ISS. Operators and tool designers

requested that, during Hubble assembly, all tools be checked for fit against all Hubble components and replacement parts. They also required extensive photography of all Hubble components and catalogued the images for ready access to aid in real-time troubleshooting. Finally, engineers analyzed all the bolts that would be actuated during the repair



Astronaut John Grunsfeld, working from the end of the Shuttle Robotic Arm, installs replacement parts on the Hubble Space Telescope during the final repair mission, STS-125 (2009).

to provide predetermined responses to problems operating bolts—data like the maximum torque allowed across the entire thermal range. Providing these data and fit checks would become a standard process for all future EVA-serviceable hardware.

The first Hubble repair mission was hugely successful, restoring Hubble's functionality and NASA's reputation. The mission also flushed out many process changes that the EVA community would need to adapt as the shuttle prepared to undertake assembly of the ISS. What had been a near disaster for NASA when Hubble was deployed turned out to be a tremendous opportunity for engineers, flight controllers, and mission managers to exercise a station-like EVA mission prior to when such missions would become routine. This mission helped demonstrate NASA's ability to execute a complex mission while under tremendous pressure to restore a vital international resource.

Flight Training

Once NASA identified the tasks for a shuttle mission, the crew had to be trained to perform them. From past programs, EVA instructors knew that the most effective training for microgravity took place under water, where hardware and crew members could be made neutrally buoyant. The Weightless Environment Training Facility—a swimming pool that measured 23 m (75 ft) long, 15 m (50 ft) wide, and 8 m (25 ft) deep—was the primary location for EVA training early in the Space Shuttle Program. The Weightless Environment Training Facility contained a full-size mock-up of the shuttle payload bay with all EVA interfaces represented. In the same manner that scuba divers use buoyancy compensation vests and weights, crew members and their tools were configured to be neutrally buoyant through the use of air, foam inserts, and weights. This enabled them to float suspended at the worksite, thus simulating a weightless environment.

Crew members trained an average of 10 hours in the Weightless Environment Training Facility for every 1 hour of planned on-orbit EVA. For complicated flights, as with the first Hubble repair mission, the training ratio was increased. Later, EVA training moved to a new, larger, and more updated water tank—the Neutral Buoyancy Laboratory—to accommodate training on the ISS.

A few limitations to the neutral buoyancy training kept it from being a perfect zero-gravity simulation. The water drag made it less accurate for simulating the movement of large objects. And since they were still in a gravity environment, crew members had to maintain a “heads-up” orientation most of the time to avoid blood pooling in the head. So mock-ups had to be built and oriented to allow crew members to maintain this position.

The gravity environment of the water tank also contributed to shoulder injuries—a chronic issue, especially in the latter part of the program. Starting in the mid 1990s, several crew members experienced shoulder injuries during the course of their EVA training. This was due to a design change made at that time to the extravehicular mobility unit shoulder joint. The shoulder joint was optimized for mobility, but designers noticed wear in the fabric components of the original joint. To avoid the risk of a catastrophic suit depressurization, NASA replaced the joint with a scye bearing that was much less subject to wear but limited to rotation in a single plane, thus reducing the range of motion. The scye bearing had to be placed to provide good motion for work and allow the wearer to don the extravehicular mobility unit through the waist ring (like putting on a shirt),



Astronaut Dafydd Williams, STS-118, representing the Canadian Space Agency, is wearing a training version of the extravehicular mobility unit spacesuit while participating in an underwater simulation of extravehicular activity in the Neutral Buoyancy Laboratory near Johnson Space Center. Scuba-equipped divers are in the water to assist Williams in his rehearsal, intended to help prepare him for work on the exterior of the International Space Station. Observe Williams holding the Pistol Grip Tool in his left hand with his shoulder extended. This position causes shoulder pain during training in neutral buoyancy.

which placed the arms straight up alongside the head. Placement of the shoulder joint was critical to a good fit, but there were only a few sizes of upper torsos for all crew members. Some crew members had reasonably good fit with the new joint, but others suffered awkward placement of the ring, which exerted abnormal forces on the shoulders. This was more a problem during training, when stress on the shoulder joint was increased due to gravity.

On Earth, the upper arm is held fairly close to the body during work activities. The shoulder joint is least prone to injury in this position under gravity. In space, the natural position of the arms is quite different, with arms extended in front of the torso. Shoulders were not significantly stressed by EVA tasks performed in

microgravity. In ground training, however, it was difficult to make EVA tools and equipment completely neutrally buoyant, so astronauts often held heavy tools with their shoulders fully extended for long periods. Rotator cuff injuries, tendonitis, and other shoulder injuries occurred despite best efforts to prevent them. The problem was never fully resolved during the shuttle era, given the design limitations of the EVA suit and the intensity of training required for mission success.

The Precision Air Bearing Floor, also used for EVA training, is a 6-m (20-ft) by 9-m (30-ft), highly polished steel floor that works on the same principles as an air hockey table. Large mock-ups of flight hardware were attached to steel plates that had high-pressure air forced through tubes that ran along the bottom and sides. These formed a cushion under

the mock-up that allowed the mock-up to move easily in the horizontal plane, simulating zero-gravity mass handling. Despite the single plane limitation of the Precision Air Bearing Floor, when combined with neutral buoyancy training the two facilities provided comprehensive and valuable training of moving large objects.

Another training and engineering platform was the zero-gravity aircraft. This specially outfitted KC-135 (later replaced by a DC-9) aircraft was able to fly a parabolic trajectory that provided approximately 20 seconds of microgravity on the downward slope, similar to the brief periods experienced on a roller coaster. This platform was not limited by water drag as was the Weightless Environment Training Facility, or to single plane evaluations as was the Precision Air Bearing Floor; however, it was only effective for short-duration tasks. Therefore, the zero-gravity aircraft was only used for short events that required a high-fidelity platform.

Extravehicular Activity Tools

EVA tools and support equipment are the Rodney Dangerfield of spacewalks. When they work, they are virtually unnoticed; however, when they fail to live up to expectations, everyone knows. Looking at the cost of what appear to be simple tools, similar to what might be found at the local hardware store, one wonders why they cost so much and don't always work. The reality is that EVA tool engineers had a formidable task—to design tools that could operate, in vacuum, in temperatures both colder than the Arctic and as hot as an oven, and be operable by someone wearing the equivalent of several pairs of ski gloves,



in vacuum, while weightless. These factors combined to produce a set of competing constraints that was difficult to balance. When adding that the complete space environment cannot be simulated on the ground, the challenge for building specialized tools that perform in space became clear. Any discussion of tools invariably involves the reasons why they fail and the lessons learned from those failures.

EVA tools are identified from two sources: the required EVA tasks, and engineering judgment on what general tools might be useful for unplanned events. Many of the initial tools were fairly simple—tethers, foot restraints, sockets, and wrenches. There were also specialized tools devoted to closing and latching the payload bay doors. Many tools were commercial tools available to the public but that were modified for use in space. This was thought to be a cost savings since they were designed for many of the same functions. These tools proved to be adequate for many uses; however, detailed information was often unavailable for commercial tools and they did not generally hold up to the temperature extremes of space. Material impurities made them unpredictable at cold temperatures and lubricants became too runny at high temperatures, causing failures. Therefore, engineers moved toward custom tools made with high-grade materials that were reliable across the full temperature range.

Trunnion pin attachment device, a-frame, and capture bar problems on the early satellite repair flights were found to be primarily due to incorrect information on the satellite interfaces. Engineers determined that interfering objects weren't represented on satellite design drawings. After these events, engineers stepped up efforts

to better document EVA interfaces, but it is never possible to fully document the precise configuration of any individual spacecraft. Sometimes drawings include a range of options for components for which many units will be produced, and that will be manufactured over a long period of time. Designers must also have the flexibility to perform quick fixes to minor problems to maintain launch schedules. The balance between providing precise documentation and allowing design and processing flexibility will always be a judgment call and will, at times, result in problems.

Engineers modified tools as they learned about the tools' performance in space. White paint was originally used as a thermal coating to keep tools from getting too hot. Since tools bump against objects and the paint tends to chip, the paint did not hold up well under normal EVA operations. Engineers thus switched to an anodizing process (similar to electroplating) to make the tools more durable. Lubricants were also a problem. Oil-based lubricants would get too thick in cold temperatures and inhibit moving parts from operating. In warm environments, the lubricants would become too thin. Dry-film lubricants (primarily Braycote®, which acts like Teflon® on frying pans) became the choice for almost all EVA tools because they are not vulnerable to temperature changes in the space environment.

Pistol Grip Tool

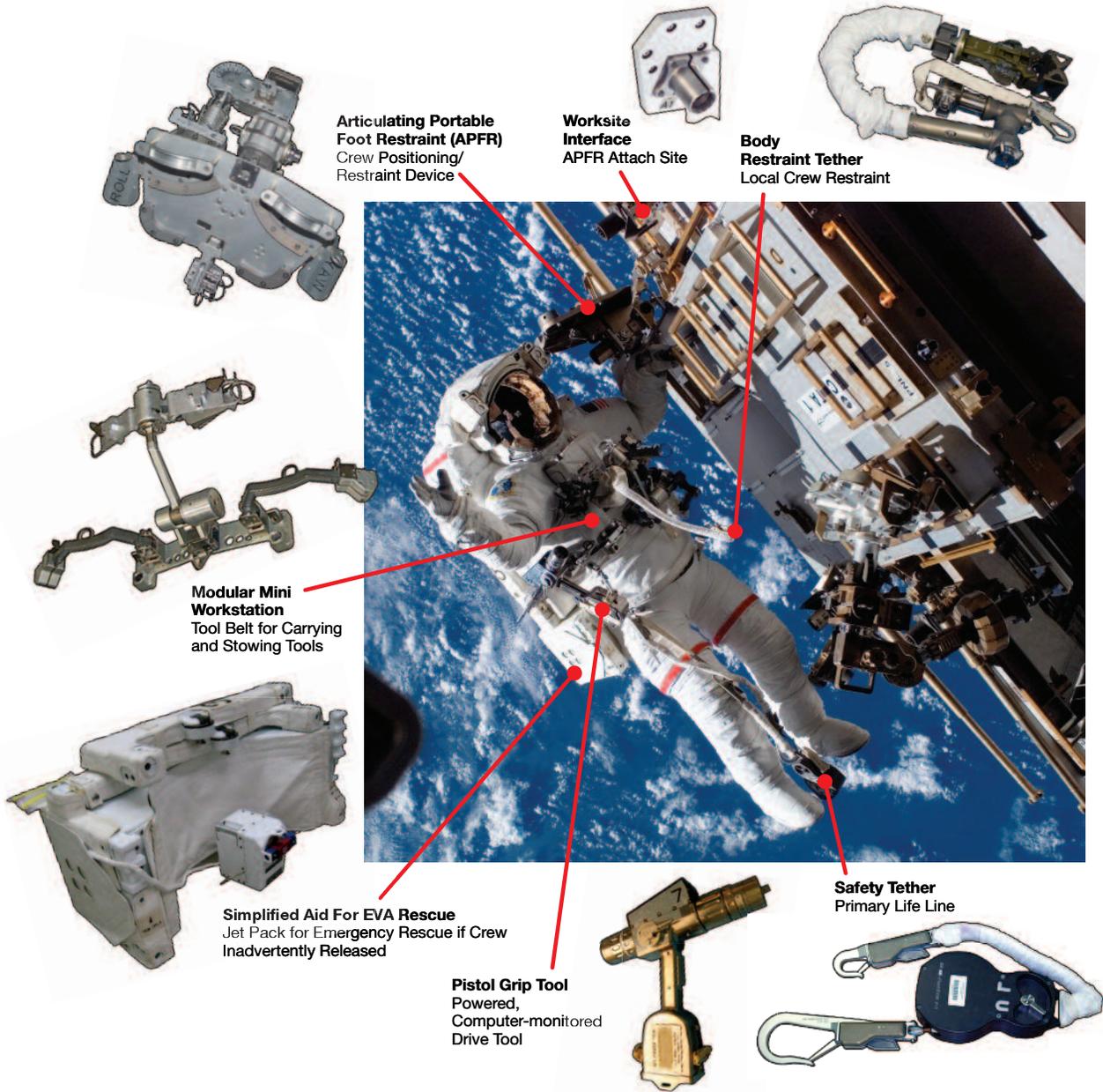
Some of the biggest problems with tools came from attempting to expand their use beyond the original purpose. Sometimes new uses were very similar to the original use, but the details were different—like trying to use a hacksaw

to perform surgery. The saw is designed for cutting, but the precision required is extremely different. An example is the computerized Pistol Grip Tool, which was developed to actuate bolts while providing fairly precise torque information. This battery-operated tool was similar to a powered screwdriver, but had some sophisticated features to allow flexibility in applying and measuring different levels of torque or angular rotation. The tool was designed for Hubble, and the accuracy was more than adequate for Hubble. When ISS required a similar tool, the program chose to purchase several units of the Hubble power tool rather than design a new tool specific to ISS requirements. The standards for certification and documentation were different for Hubble. ISS had to reanalyze bolts, provide for additional ground and on-orbit processing of the Pistol Grip Tool to meet ISS accuracy needs, and provide additional units on orbit to meet fault tolerance requirements and maintain calibration.

The use of the Pistol Grip Tool for ISS assembly also uncovered another shortcoming with regard to using a tool developed for a different spacecraft. The Pistol Grip Tool was advertised as having an accuracy of 10% around the selected torque setting. This accuracy was verified by setting the Pistol Grip Tool in a fixed test stand on the ground where it was held rigidly in place. This was a valid characterization when used on Hubble where EVA worksites were designed to be easily accessible and where the Pistol Grip Tool was used directly on the bolts. It was relatively easy for crew members to center the tool and hold it steady on any bolt. ISS worksites were not as elegant as Hubble worksites, however, since ISS is such a large vehicle and the Pistol Grip Tool



Extravehicular Activity Tools



Astronaut Rick Mastracchio, STS-118 (2007), is shown using several extravehicular activity (EVA) tools while working on construction and maintenance of the International Space Station during the shuttle mission's third planned EVA activity.



often had to be used with socket extensions and other attachments that had inaccuracies of their own. Crew members often had to hold the tool off to the side with several attachments, and the resulting side forces could cause the torque measured by the tool to be very different than the torque actually applied. Unfortunately, ISS bolts were designed and analyzed to the advertised torque accuracy for Hubble and they didn't account for this "man-in-the-loop" effect. The result was a long test program to characterize the accuracy of the Pistol Grip Tool when used in representative ISS worksites, followed by analysis of the ISS bolts to this new accuracy.

To focus only on tool problems, however, is a disservice. It's like winning the Super Bowl and only talking about the fumbles. While use of the Pistol Grip Tool caused some problems as NASA learned about its properties, it was still the most sophisticated tool ever designed for EVA. It provided a way to deliver a variety of torque settings and accurately measure the torque delivered. Without this tool, the assembly and maintenance of the ISS would not have been possible.

Other Tools

NASA made other advancements in tool development as well. Tools built for previous programs were generally simple tools required for collecting geology samples. While there weren't many groundbreaking discoveries in the tool development area, the advances in tool function, storage, and transport greatly improved EVA efficiency during the course of the program. The fact that Henry Ford

didn't invent the internal combustion engine doesn't mean he didn't make tremendous contributions to the automobile industry.

One area where tool engineers expanded EVA capabilities was in astronaut translation and worksite restraint. Improvements were made to the safety tether to include a more reliable winding device and locking crew hooks to prevent inadvertent release. Engineers developed portable foot restraints that could be moved from one location to another, like carrying a ladder from site to site. The foot restraints consisted of a boot plate to lock the crew member's feet in place and an adjustment knob to adjust the orientation of the plate for better positioning. The foot restraint had a probe to plug into a socket at the worksite. These foot restraints gave crew members the stability to work in an environment where unrestrained crew members would have otherwise been pushed away from the worksite whenever they exerted force.

The portable foot restraints were an excellent starting point, but they required a fair amount of time to move. They also became cumbersome when crew members had to work in many locations during a single EVA (as with the ISS). Engineers developed tools that could streamline the time to stabilize at a new location. The Body Restraint Tether is one of these tools. This tool consists of a stack of balls connected through its center by a cable with a clamp on one end to attach to a handrail and a bayonet probe on the other end to attach to the spacesuit. Similar to flexible shop lights, the Body Restraint Tether can be bent and twisted to the optimum position, then locked in that

position with a knob that tightens the cable. The Body Restraint Tether is a much quicker way for crew members to secure themselves for lower-force tasks.

Another area where tool designers made improvements was tool stowage and transport. Crew members had to string tools to their suits for transport until designers developed sophisticated tool bags and boxes that allowed crews to carry a large number of tools and use the tools efficiently at a worksite. The Modular Mini Workstation—the EVA tool belt—was developed to attach to the extravehicular mobility unit and has become invaluable to conducting spacewalks. Specific tools can be attached to the arms on the workstation, thereby allowing ready access to the most-used tools. Various sizes of tool caddies and bags also help to transport tools and EVA "trash" (e.g., launch restraints).

Space Shuttle Program tool designers expanded tool options to include computer-operated electronics and improved methods for crew restraint, tool transport, and stowage. While there were hiccups along the way, the EVA tools and crew aids performed admirably and expanded NASA's ability to perform more complicated and increasingly congested EVAs.

Extravehicular Activity During Construction of the International Space Station

From 1981 through 1996, the Space Shuttle Program accomplished 33 EVAs. From 1997 through 2010, the program managed 126 EVAs devoted primarily to ISS assembly and maintenance, with several Hubble



Space Telescope repair missions also included. Assembly and maintenance of the ISS presented a series of challenges for the program. EVA tools and suits had to be turned around quickly and flawlessly from one flight to the next. Crew training had to be streamlined since several flights would be training at the same time and tasks were interdependent from one flight to the next. Plans for one flight, based on previous flight results, could change drastically just months (or weeks) before launch. Sharing resources with the International Space Station Program was also new territory—the same tools, spacesuits, and crew members would serve both programs after the ISS airlock was installed.

Extravehicular Loads for Structural Requirements

The EVA loads development program, first started for the Hubble servicing missions, helped define the ISS structural design requirements. ISS was the first program to have extensive EVA performed on a range of structural interfaces. The load cases for Hubble repair had to protect the telescope for a short period of EVA operations and for a finite number of well-known EVA tasks.

ISS load cases had to have sufficient margin for tasks that were only partially defined at the time the requirements were fixed, to protect for hundreds of EVAs over the planned life of the ISS. The size of ISS was also a factor. An EVA task on one end of the truss structure could be much more damaging than the same task closer to the center (just like bouncing on the end of a diving board creates more

Medical Risks of Extravehicular Activity—Decompression Sickness

One risk spacewalkers share with scuba divers is decompression sickness, or “the bends.” “The bends” name came from painful contortions of 19th-century underwater caisson workers suffering from decompression sickness, which occurs when nitrogen dissolves in blood and tissues while under pressure, and then expands when pressure is lowered. Decompression sickness can occur when spacewalkers exit the pressurized spacecraft into vacuum in a spacesuit

Decompression sickness can be prevented if nitrogen tissue concentrations are lowered prior to reducing pressure. Breathing 100% oxygen causes nitrogen to migrate from tissues into the bloodstream and lungs, exiting the body with exhaling. The first shuttle-based extravehicular activities used a 4-hour in-suit oxygen prebreathe. This idle time was inefficient and resulted in too long a crew day. New solutions were needed.

One solution was to lower shuttle cabin pressure from its nominal pressure of 101.2 kPa (14.7 psi) to 70.3 kPa (10.2 psi) for at least 12 hours prior to the EVA. This reduced cabin pressure protocol was efficient and effective, with only 40 minutes prebreathe.

Shuttle EVA crew members working International Space Station (ISS) construction required a different approach. It is impossible to reduce large volume ISS pressure to 70.3 kPa (10.2 psi). To increase the rate of nitrogen release from tissues, crew members exercised before EVA while breathing 100% oxygen. This worked, but it added extra time to the packed EVA day and exhausted the crew. Planners used the reduced cabin pressure protocol by isolating EVA crew members in the ISS airlock the night before the EVA and lowering the pressure to 70.3 kPa (10.2 psi). This worked well for the remainder of ISS EVAs, with no cases of decompression sickness throughout the Space Shuttle Program.

stress at the base than bouncing on the base itself). EVA loads had to account for intentional tasks (e.g., driving bolts) and unintentional events (e.g., pushing away from a rotating structure to avoid collision). Engineers had to protect for a reasonable set of EVA scenarios without overly restricting the ISS design to protect against simultaneous

low-probability events. This required an iterative process that included working with ISS structures experts to zero in on the right requirements.

A considerable test program—using a range of EVA crew members executing a variety of tasks in different ground venues—characterized the forces and



moments that an EVA crew member could impart. The resulting cases were used throughout the programs to evaluate new tasks when the tasks were needed. While the work was done primarily for ISS, the loads that had been developed were used extensively in the post-Columbia EVA inspection and repair development.

Rescue From Inadvertent Release

NASA always provided for rescue of an accidentally released EVA crew member by maintaining enough fuel to fly to him or her. Once ISS assembly began, however, the Orbiter was docked during EVAs and would not have been able to detach and pursue an EVA crew member in time. The ISS Program required a self-rescue jet pack for use during ISS EVAs. The Simplified Aid for EVA Rescue was designed to meet this requirement. Based on the manned maneuvering unit design but greatly simplified, the Simplified Aid for EVA Rescue was a reliable, nitrogen-propelled backpack that provided limited capability for a crew member to stop and fly back to the station or Orbiter. It was successfully tested on two shuttle flights when shuttle rescue was still possible if something went wrong. Fortunately, the Simplified Aid for EVA Rescue never had to be employed for crew rescue.

Extravehicular Activity Suit Life Extension and Multiuse Certification for International Space Station Support

A significant advancement for the EVA suit was the development of a regenerable carbon dioxide removal system. Prior to the ISS, NASA used



Astronaut Douglas Wheelock, STS-120 (2007), uses virtual reality hardware in the Space Vehicle Mockup Facility at Johnson Space Center to rehearse some of his duties on the upcoming mission to the International Space Station.

single-use lithium hydroxide canisters for scrubbing carbon dioxide during an EVA. Multiple EVAs were routine during flights to the ISS. Providing a regenerative alternative using silver oxide produced significant savings in launch weight and volume. These canisters could be cleaned in the ISS airlock regenerator, thereby allowing the canisters to be left on orbit rather than processed on the ground and launched on the shuttle. This capability saved approximately 164 kg (361 pounds) up-mass per year.

Training Capability Enhancements

During the early shuttle missions, the Weightless Environment Training Facility and Precision Air Bearing Facility were sufficient for crew training. To prepare for space station assembly, however, virtually every mission would include training for

three to five EVAs—often with two EVA teams—with training for three to five flights in progress simultaneously.

To do this, NASA built the Neutral Buoyancy Laboratory to accommodate EVA training for both the Space Shuttle and ISS Programs. At 62 m (202 ft) long, 31 m (102 ft) wide, and 12 m (40 ft) deep, the Neutral Buoyancy Laboratory is more than twice the size of the previous facility, and it dramatically increased neutral buoyancy training capability. It also allowed two simultaneous simulations to be conducted using two separate control rooms to manage each individual event.

Trainers took advantage of other resources not originally designed for EVA training. The Virtual Reality Laboratory, which was designed primarily to assist in robotic operations,



became a regular EVA training venue. This lab helped crew members train in an environment that resembled the space environment, from a crew member's viewpoint, by using payload and vehicle engineering models working with computer software to display a view that changed as the crew member "moved" around the space station.

The Virtual Reality Laboratory also provided mass simulation capability by using a system of cables and pulleys controlled by a computer as well as special goggles to give the right visual cues to the crew member, thus allowing him or her to get a sense of moving a large object in a microgravity environment. Most of the models used in the Virtual Reality Laboratory were actually built for other engineering facilities, so the data were readily available and parameters could be changed relatively quickly to account for hardware or environment changes. This gave the lab a distinct advantage over other venues that could not accommodate changes as quickly.

In addition to the new training venues, changes in training philosophy were required to support ISS assembly. Typically, EVA crew training began at least 1 year prior to the scheduled launch. Therefore, crew members for four to five missions would have to train at the same time, and the tasks required were completely dependent on the previous flights' accomplishments. A hiccup in on-orbit operations could cascade to all subsequent flights, changing the tasks that were currently in training. In addition, on-orbit ISS failures often resulted in changes to the tasks, as repair of those components may have taken a higher priority.

To accommodate late changes, flight controllers concentrated on training individual tasks rather than timelines early in the training schedule. They also engaged in skills training—training the crew on general skills required to perform EVAs on the ISS rather than individual tasks. Flight controllers still developed timelines, but they held off training the timelines until closer to flight. Crews also trained on "get-ahead" tasks—those tasks that did not fit into the pre-mission timelines but that could be added if time became available. This flexibility provided time to allow for real-time difficulties.

Extravehicular Activity Participation in Return to Flight After Space Shuttle Columbia Accident

One other significant EVA accomplishment was the development of a repair capability for the Orbiter Thermal Protection System after the Space Shuttle Columbia accident in 2003. This posed a significant challenge for EVA for several reasons. The Thermal Protection System was a complex design that was resistant to high temperatures but was also delicate. It was located in areas under the fuselage that was inaccessible to EVA crew members. The materials used for repair were a challenge to work with, even in an Earth environment, since they did not adhere well to the damage. Finally, the repair had to be smooth since even very small rough edges or large surface deviations could cause turbulent airflow behind the repair, like rocks disrupting flow in a stream. Turbulent flow increased surface heating dramatically, with

potentially disastrous results. These challenges, along with the schedule pressure to resume building and resupplying the ISS, made Thermal Protection System repair a top priority for EVA for several years.

The process included using repair materials that engineers originally began developing at the beginning of the program that now had to be refined and certified for flight. Unique tools and equipment, crew procedures, and methods to ensure stabilizing the crew member at the worksite were required to apply the material. The tools mixed the two-part silicone rubber repair material but also kept it from hardening until it was dispensed in



Astronauts Robert Curbeam (foreground) and Rex Walheim (background) simulate tile repair, using materials and tools developed after the Space Shuttle Columbia accident, on board the zero-gravity training aircraft KC-135.



Astronaut Piers Sellers, STS-121 (2006), wearing a training version of the extravehicular mobility unit, participates in an extravehicular activity simulation while anchored on the end of the training version of the Shuttle Robotic Arm in the Space Vehicle Mockup Facility at Johnson Space Center (JSC). The arm has an attached 15-m (50-ft) boom used to reach underneath the Orbiter to access tiles. Lora Bailey (right), manager, JSC Engineering Tile Repair, assisted Sellers.

the damage area. The tools also maintained the materials within a fairly tight thermal range to keep them viable. Engineers were able to avoid the complexity of battery-powered heaters by selecting materials and coatings to passively control the material temperature. The reinforced carbon-carbon Thermal Protection System (used on the wing leading edge) repair required an additional set of tools and techniques with similar considerations regarding precision application of sensitive materials.

Getting a crew member to the worksite proved to be a unique challenge. NASA considered several options, including using the Simplified Aid for EVA

Rescue with restraint aids attached by adhesives. Repair developers determined, however, that the best option was to use the new robotic arm extension boom provided for Orbiter inspection. The main challenge to using the extension boom was proving that it was stable enough to conduct repairs, and that the forces the EVA crew member imparted on the boom would not damage the boom or the arm. These concerns were similar to those involved with putting a crew member on a robotic arm, but the “diving board” was twice as long. The EVA loads work performed earlier provided a foundation for the process by which EVA loads could be determined for this situation; however, the process

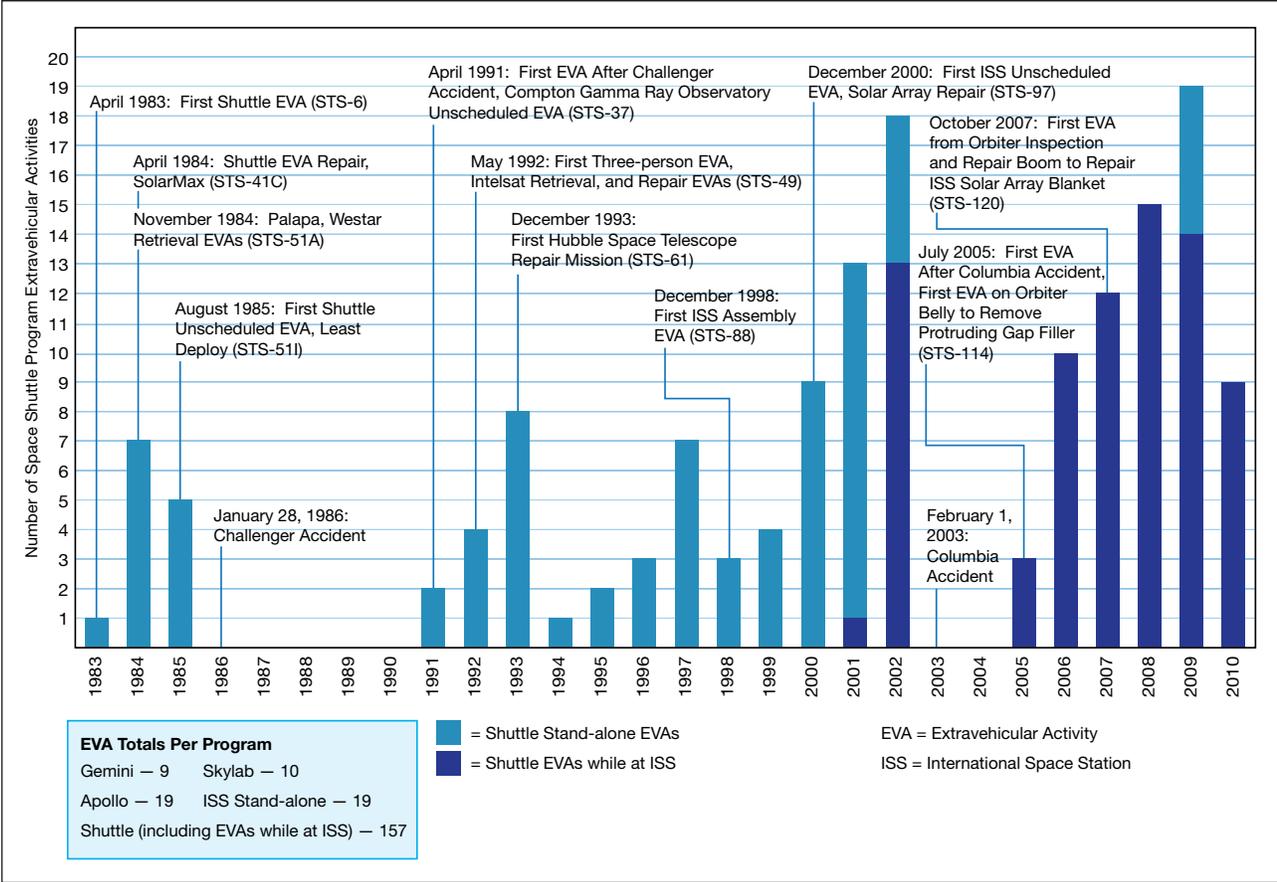
had to be modified since the work platform was much more flexible.

Previous investigations into EVA loads usually involved a crew member imparting loads into a fixed platform. When the loads were continuously applied to the boom/arm configuration, they resulted in a large (about 1.2 m [4 ft]) amount of sway as well as structural concerns for the arm and boom. Engineers knew that the boom/arm configuration was more like a diving board than a floor, meaning that the boom would slip away as force was applied, limiting the force a crew member could put into the system. Engineers developed a sophisticated boom/arm simulator and used it on the precision air bearing floor to measure EVA loads. These tests provided the data for analysis of the boom/arm motion. The work culminated in a flight test on STS-121 (2006), which demonstrated that the boom/arm was stable enough for repair and able to withstand reasonable EVA motions without damage.

Although the repair capability was never used, both the shuttle and the space station benefited from the repair development effort. Engineers made several minor repairs to the shuttle Thermal Protection System that would not have been possible without demonstrating that the EVA crew member could safely work near the fragile system. The boom was also used on the Space Station Robotic Arm to conduct a successful repair of a damaged station solar array wing that was not reachable any other way.



Major Extravehicular Activity Milestones



Summary

The legacy of EVA during the Space Shuttle Program consists of both the actual work that was done and the dramatic expansion of the EVA capability. EVA was used to successfully repair or restore significant national resources to their full capacity, such as Hubble, communications satellites, and the Orbiter, and to construct the ISS. EVA advanced from being a minor capability used sparingly to becoming

a significant part of almost every shuttle mission, with an increasing list of tasks that EVA crew members were able to perform. EVA tools and support equipment provided more capability than ever before, with battery-powered and computer-controlled tools being well understood and highly reliable.

Much was learned about what an EVA crew member needs to survive and work in a harsh environment

as well as how an EVA crew member affected his or her environment. This tremendous expansion in EVA capability will substantially benefit the future exploration of the solar system as engineers design vehicles and missions knowing that EVA crew members are able to do much more than they could at the beginning of the Space Shuttle Program.



Shuttle Builds the International Space Station

John Bacon

Melanie Saunders

Improvements to the Shuttle Facilitated Assembly of the International Space Station

Lee Norbraten

Financial Benefits of the Space Shuttle for the United States

Melanie Saunders

Psychological Support—Lessons from Shuttle-Mir to International Space Station

Albert Holland

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).

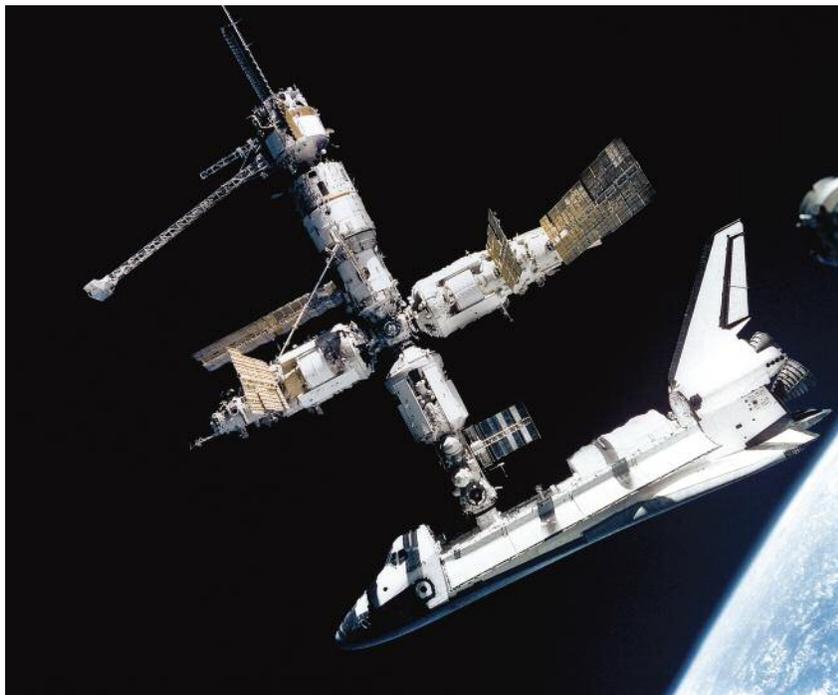
In April 1984, STS-41C deployed one of the most important and comprehensive test programs—the Long Duration Exposure Facility. STS-32 retrieved the facility in January 1990, giving critical evidence of the performance and degradation timeline of materials in the low-Earth environment. It was a treasure 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.

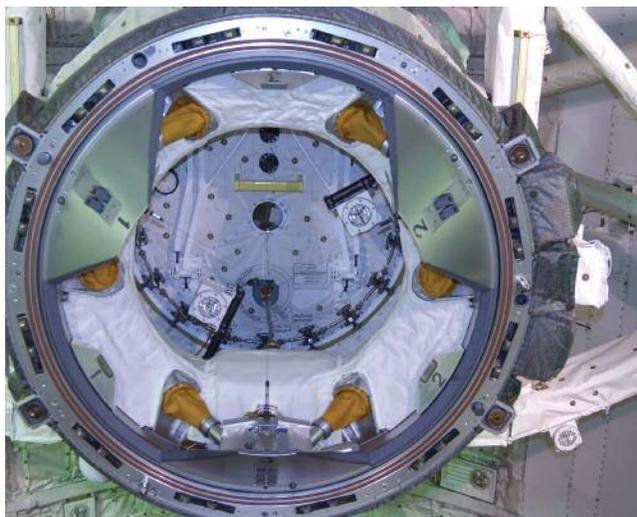
The Russians had a docking mechanism on their space station in a 51.6-degree orbit, awaiting a shuttle. That mechanism had a joint US-Russian design heritage. The Americans had a fleet of shuttles that needed to practice servicing missions to a space station in a 51.6-degree orbit. In a surprisingly 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



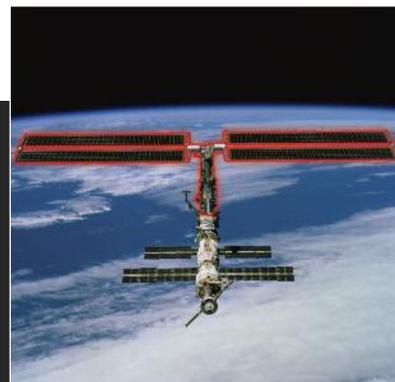
Discovery (STS-96) brought US-built Unity node, which attached to Russian-built Zarya.

1999



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

2000



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



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.

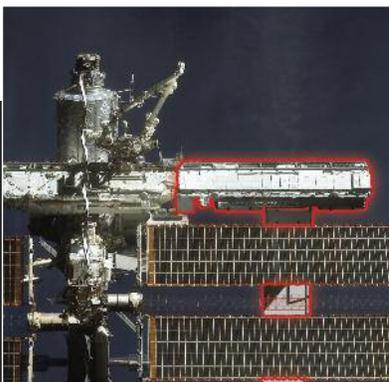
The mechanism must next damp out leftover motions in X, Y, and Z axes as well as damp rotational motions in pitch, yaw, and roll while bringing the two spacecraft into exact alignment. This step was a particular challenge for shuttle dockings. For the first time in space history, the docking mechanism 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.

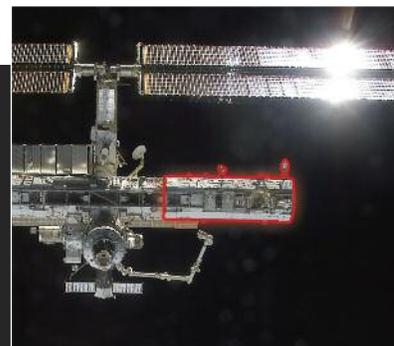
Next, the mechanism had to retract, pulling the two spacecraft close enough together that strong latches could engage. The strong latches clamped the two halves of the mechanism together with enough force to compress the seals. These latches held the halves together against the huge force of pressure 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

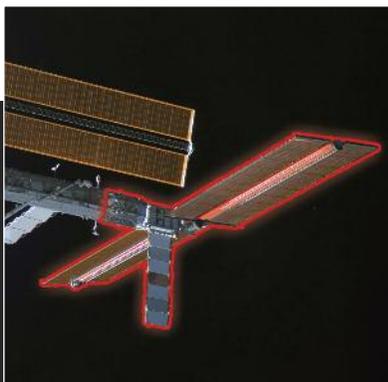
The assembly of the enormous ISS required that large structures were placed with high precision at great distance from the shuttle’s payload bay. As the Shuttle Robotic Arm



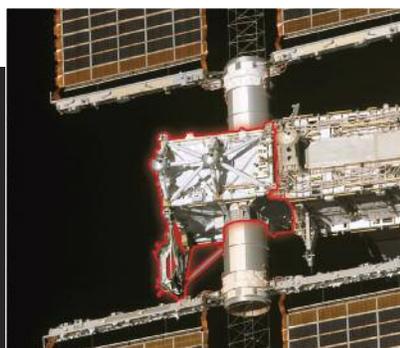
The Unity connecting module is being put into position to be mated to Endeavour's (STS-88 [1998]) docking system in the cargo bay. This mating was the first link in a long chain of events that led to the eventual deployment of the connected Unity and Zarya modules.

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.

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

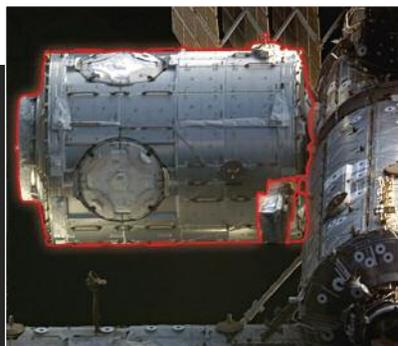
between the segments. The crew then attached major appendages and payloads with a smaller mechanism called a Common Attachment System.

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.

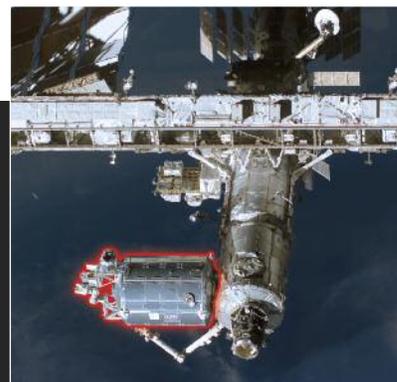
Meanwhile, the ISS design had to accommodate the shuttle. It needed to provide a zigzag tunnel mechanism (the Pressurized Mating Adapter) to optimize the clearance to remove payloads from the bay after the shuttle had docked. ISS needed to withstand the shuttle’s thruster plumes for heating, loads, contamination, 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



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).

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.

Further Improvements Facilitate Collaboration Between Shuttle and Station

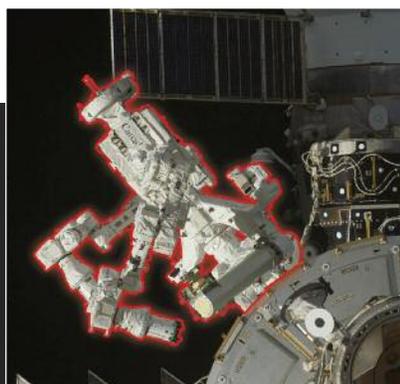
The ISS needed a tiny light source that could be seen at a distance of hundreds

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

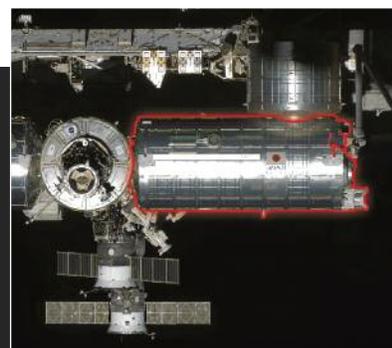
seeking vastly dimmer points of light. Thus, the shuttle's final rendezvous with the ISS involved taking a relative navigational "fix" on the ISS at night, when the ISS's small light bulb approximated the light from a star.



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



Endeavour (STS-123) also delivered Canadian-built Special Purpose Dexterous 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

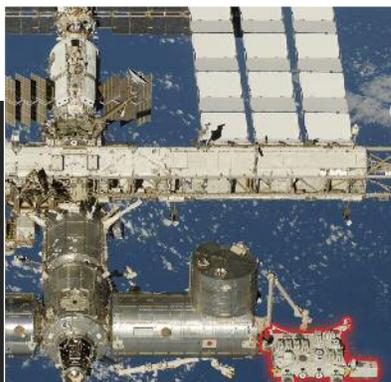
The shuttle was a workhorse that brought vast quantities of hardware and supplies to the International Space Station (ISS). Consumables and spare parts were a key part of that manifest, with whole shuttle missions dedicated to resupply. These missions were called “Utilization and Logistics Flights.” 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

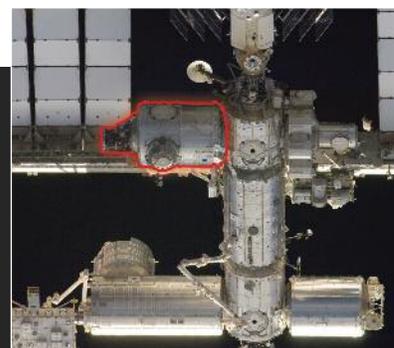
Perhaps the greatest shuttle contribution to ISS logistics was its unsurpassed capability to return key systems and components to Earth. Although most of the ISS worked perfectly from the start, the shuttle’s ability to bring components and systems back was essential in rapidly advancing NASA’s engineering



Discovery (STS-119) brought S6 truss segment.



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



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

2009

2010



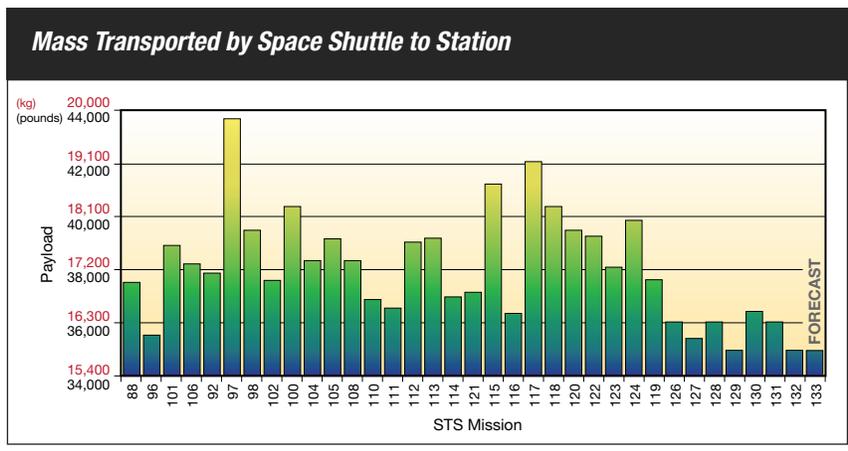
knowledge in many key areas. This allowed ground engineers to thoroughly diagnose, repair, and sometimes redesign the very heart of the ISS.

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.

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.

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.

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



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,

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.

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



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 m² (3,229 ft²) 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.



"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."

December 10th 1998
ACTIVATION OF THE INTERNATIONAL SPACE STATION BY THE CREW OF THE SPACE SHUTTLE "ENDEAVOUR" STS-88, 135 2A.
FROM SMALL BEGINNINGS, GREAT THINGS COME. TODAY WE INCREASED 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
Sergei Krikalev, PLT
Nancy Currie, MS1
John W. Williams, MS2
Vladimir Khukhrai, MS4



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

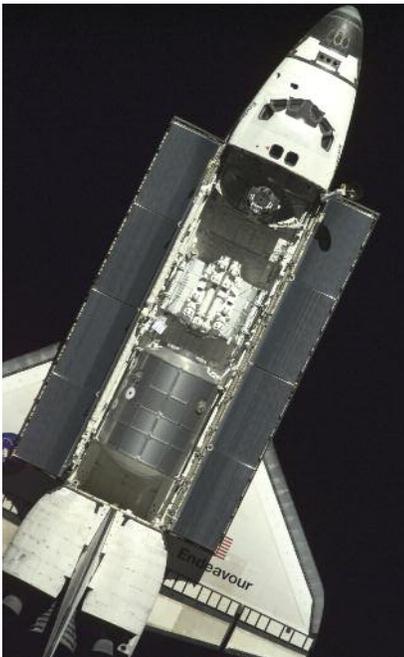
pulled tight enough to stretch the tent into a strong structure. The whole thing was in danger of collapsing, particularly if the shuttle fired jets to leave. Rocket plumes would certainly collapse the massive wings. If Endeavour left without tensioning the array, another shuttle might never be able 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

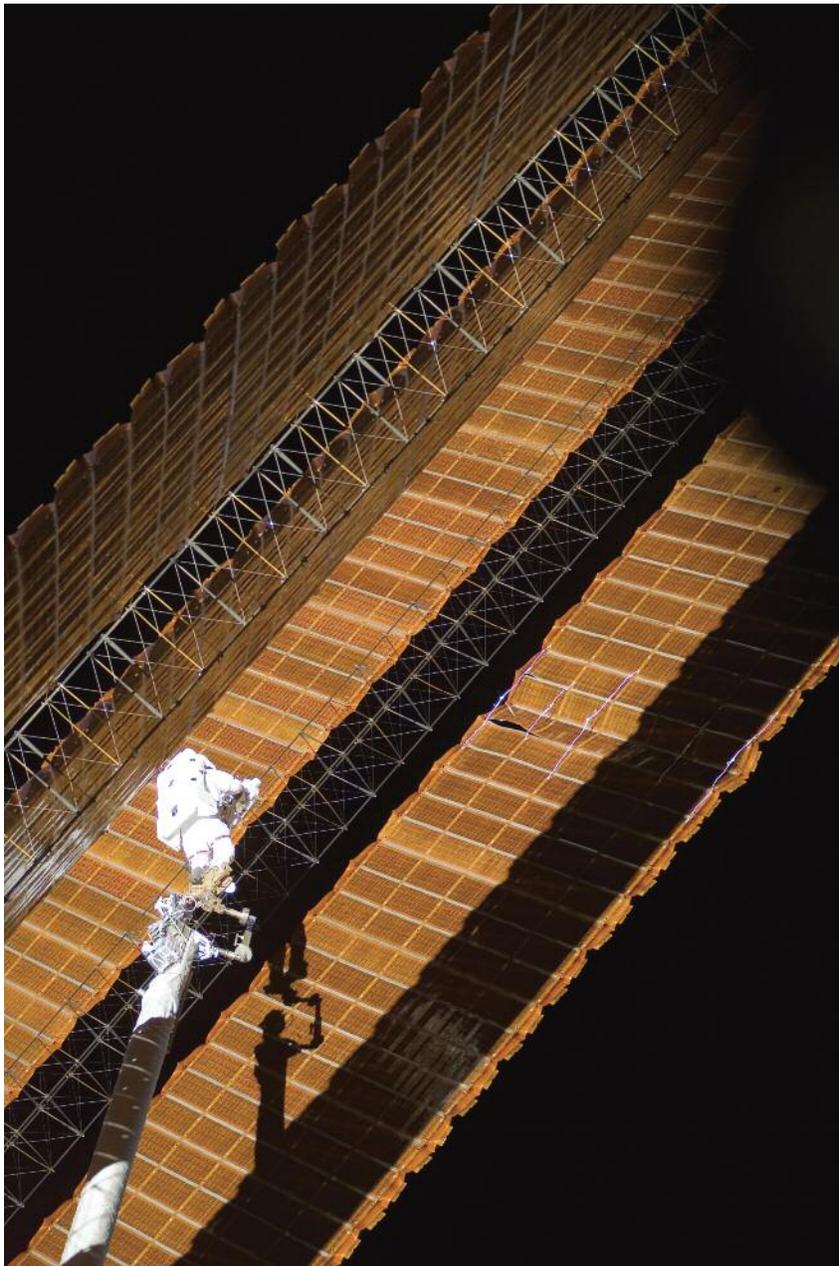
the stage in a “must succeed” EVA. During that EVA, the ISS would briefly be in an interim configuration where the shuttle could not dock to the ISS. On this flight, the ISS would finally achieve the full complement of solar arrays and reach its full width.

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 Whitton 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.

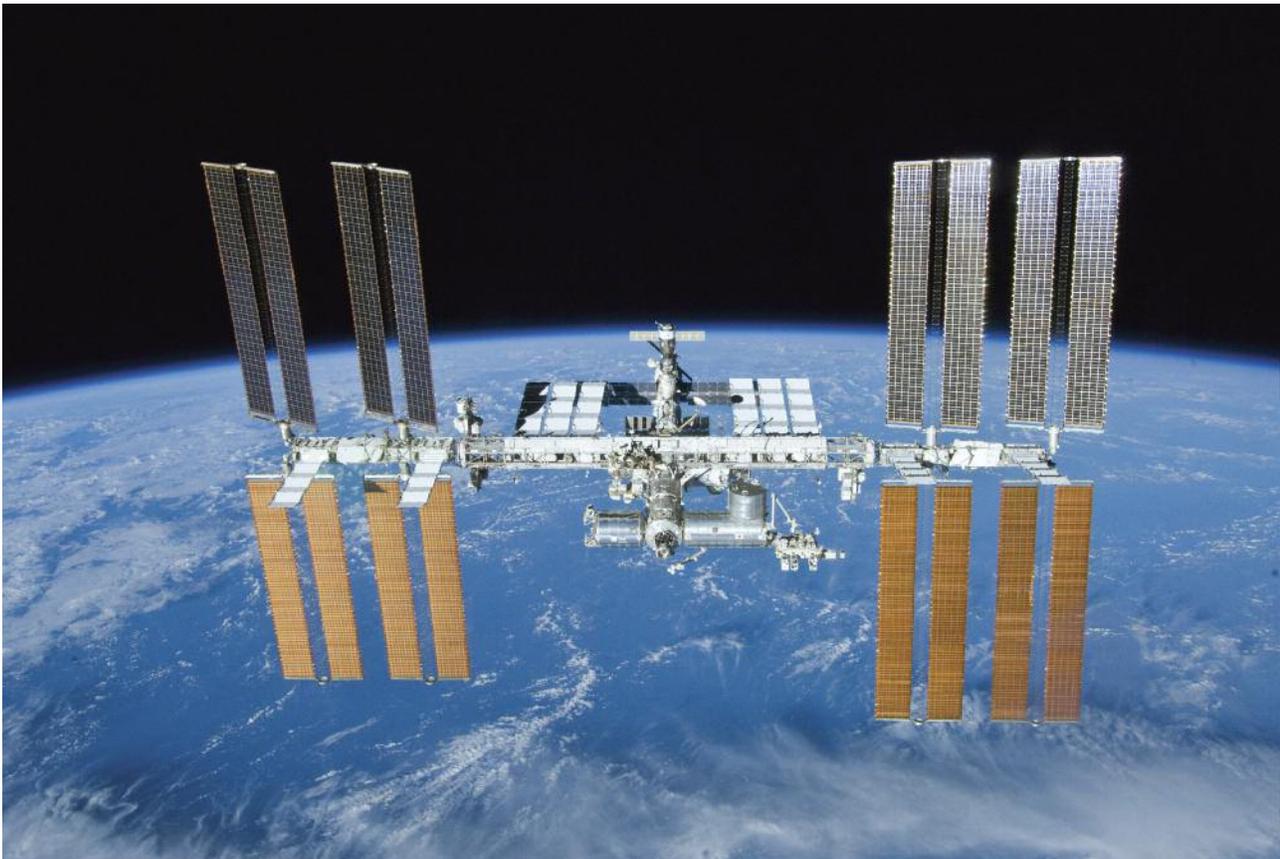


Image of the International Space Station, as photographed from STS-132 (2010), with all of the modules, trusses, and solar panels in place.

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.

