

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

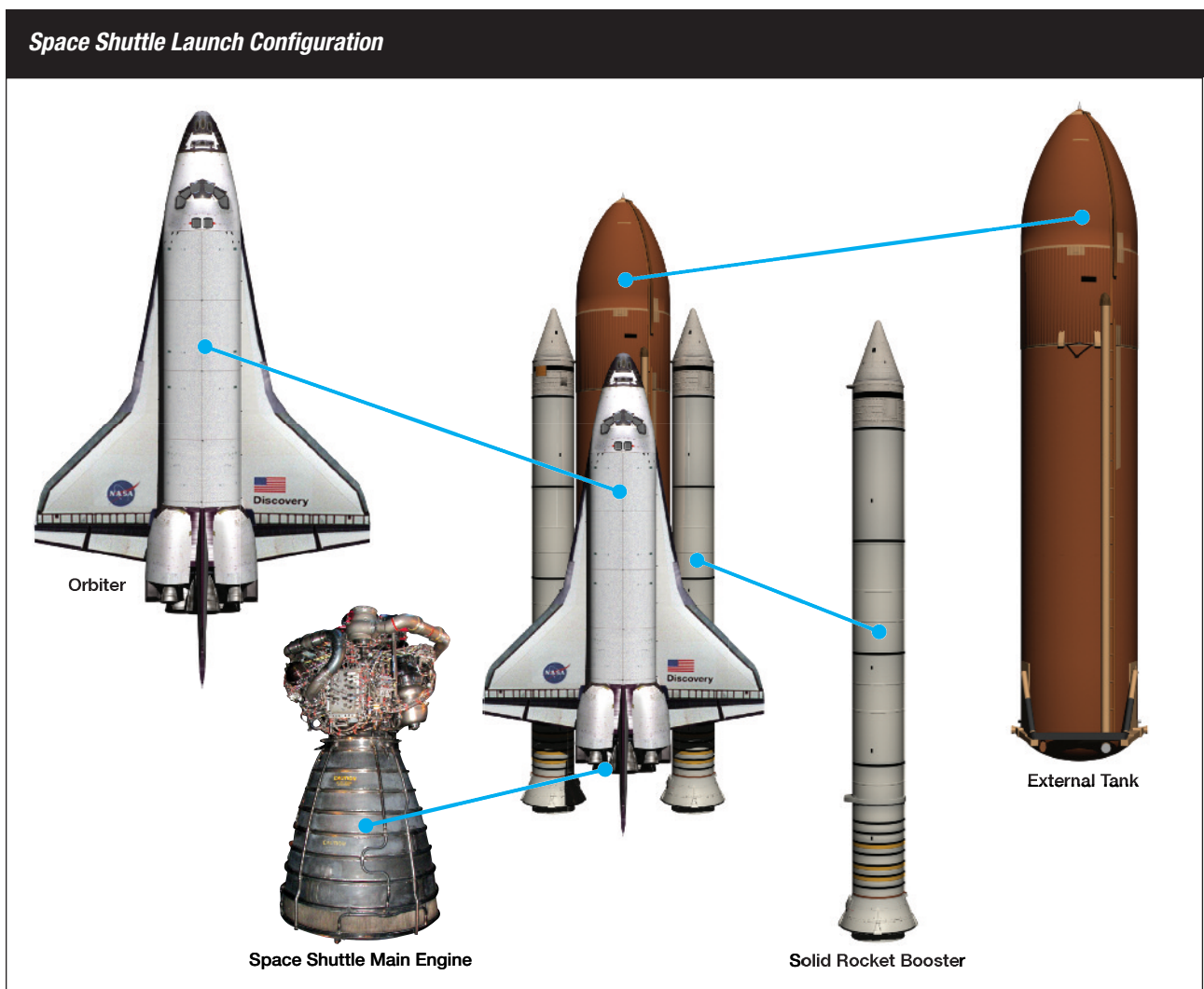
winged vehicle for cross-range capability for re-entry into Earth's atmosphere and the ability to land a heavyweight payload.

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.

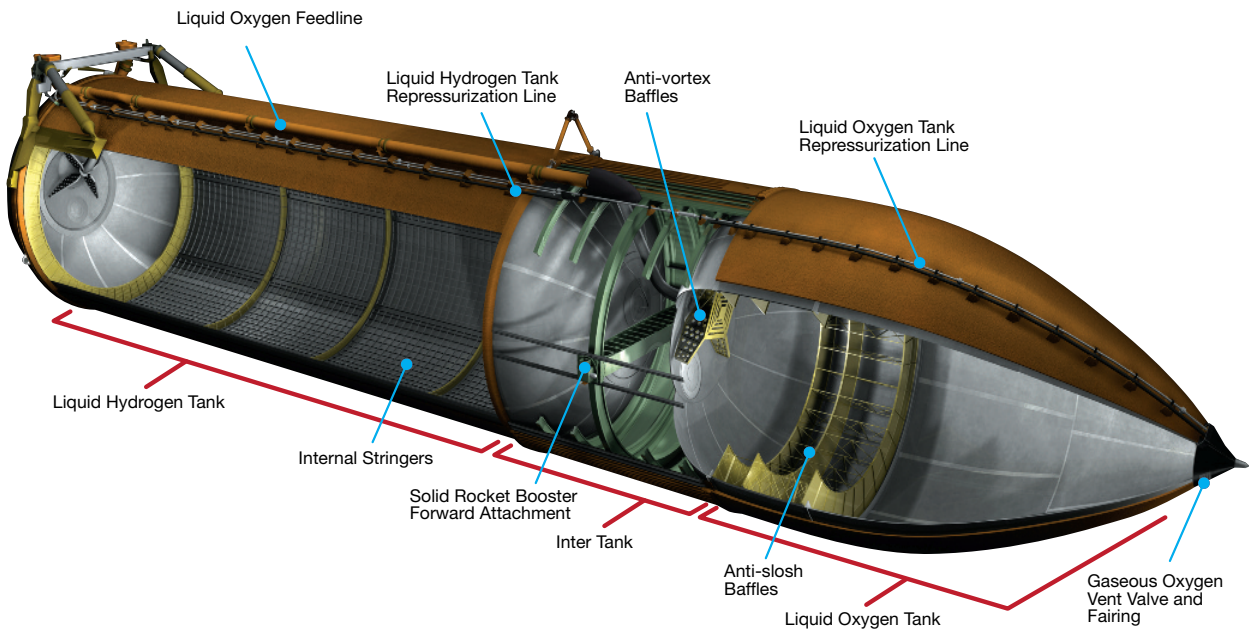
Solid Rocket Boosters

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.

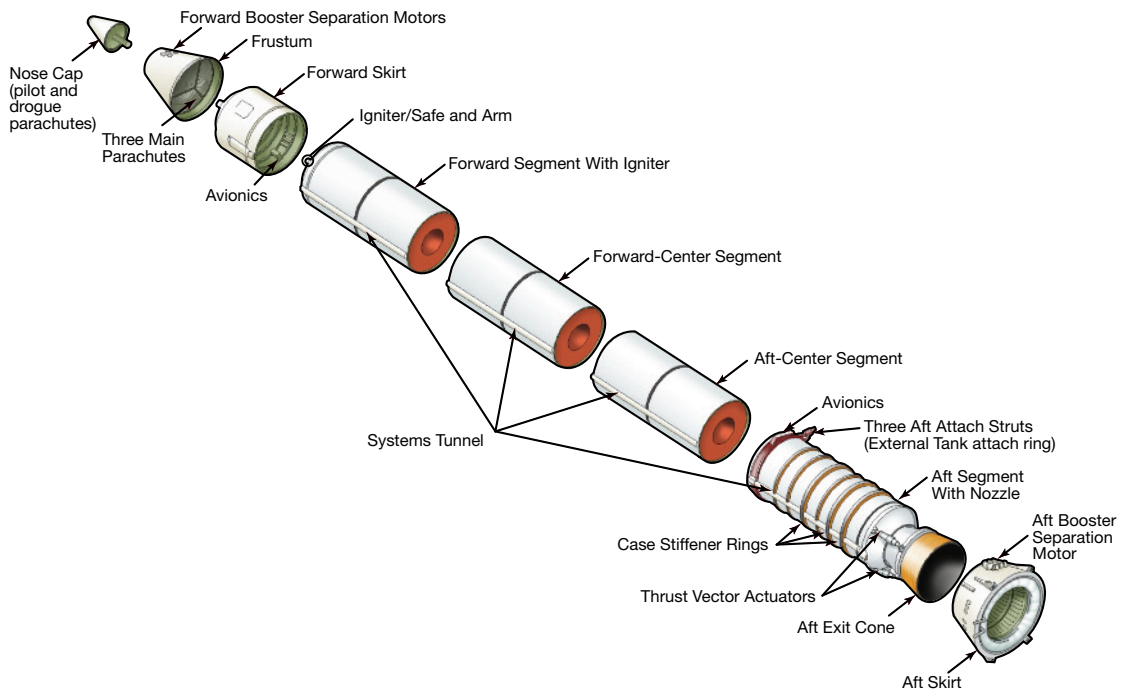
The SRB thrust vector control system enabled the nozzles to rotate, allowing the entire shuttle to maneuver to the required ascent trajectory during first stage. Two minutes after launch, the spent SRBs were jettisoned, having taken the vehicle to an altitude of about 45 km (28 miles). Not only were 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





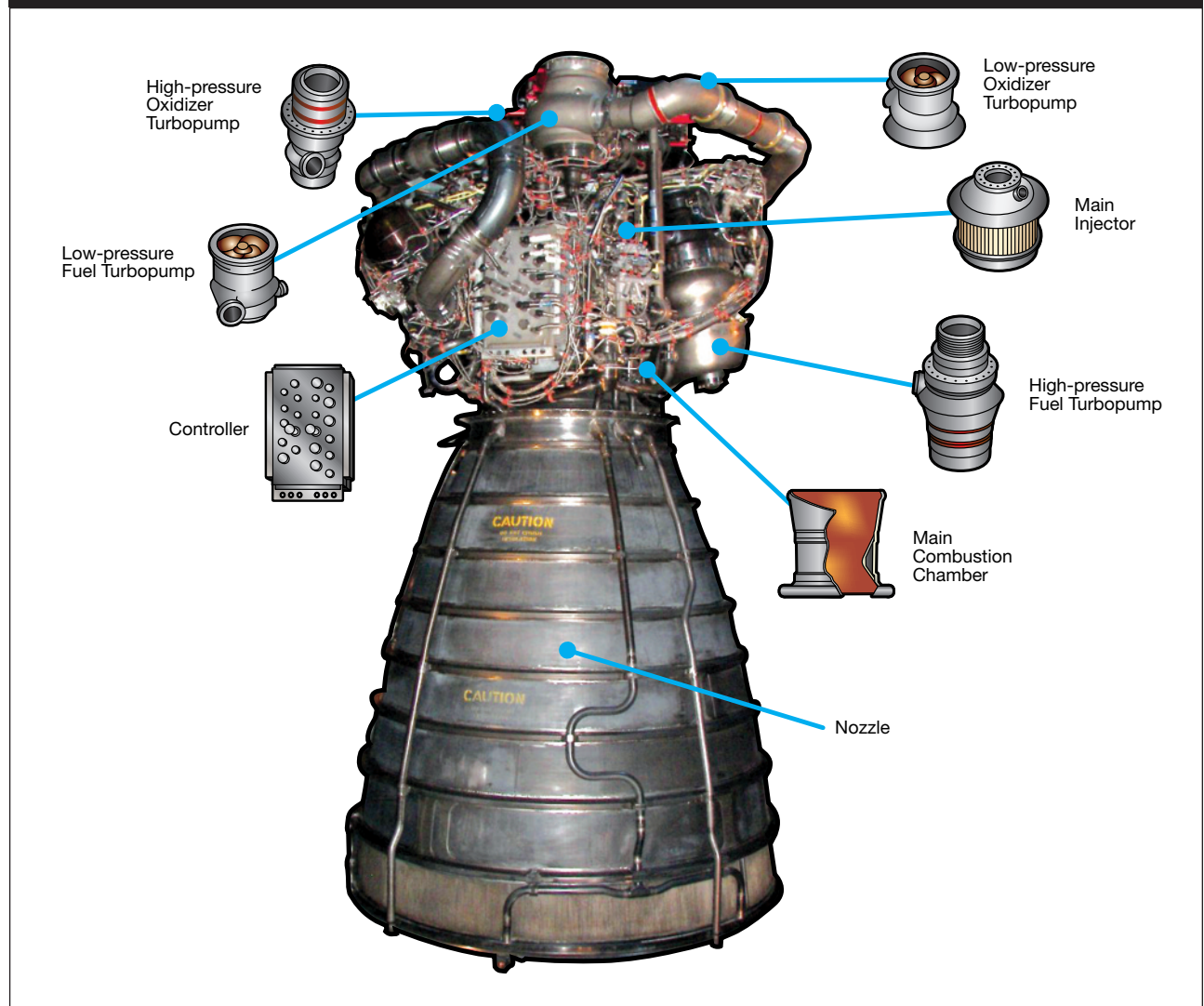
Space Shuttle Main Engines

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.

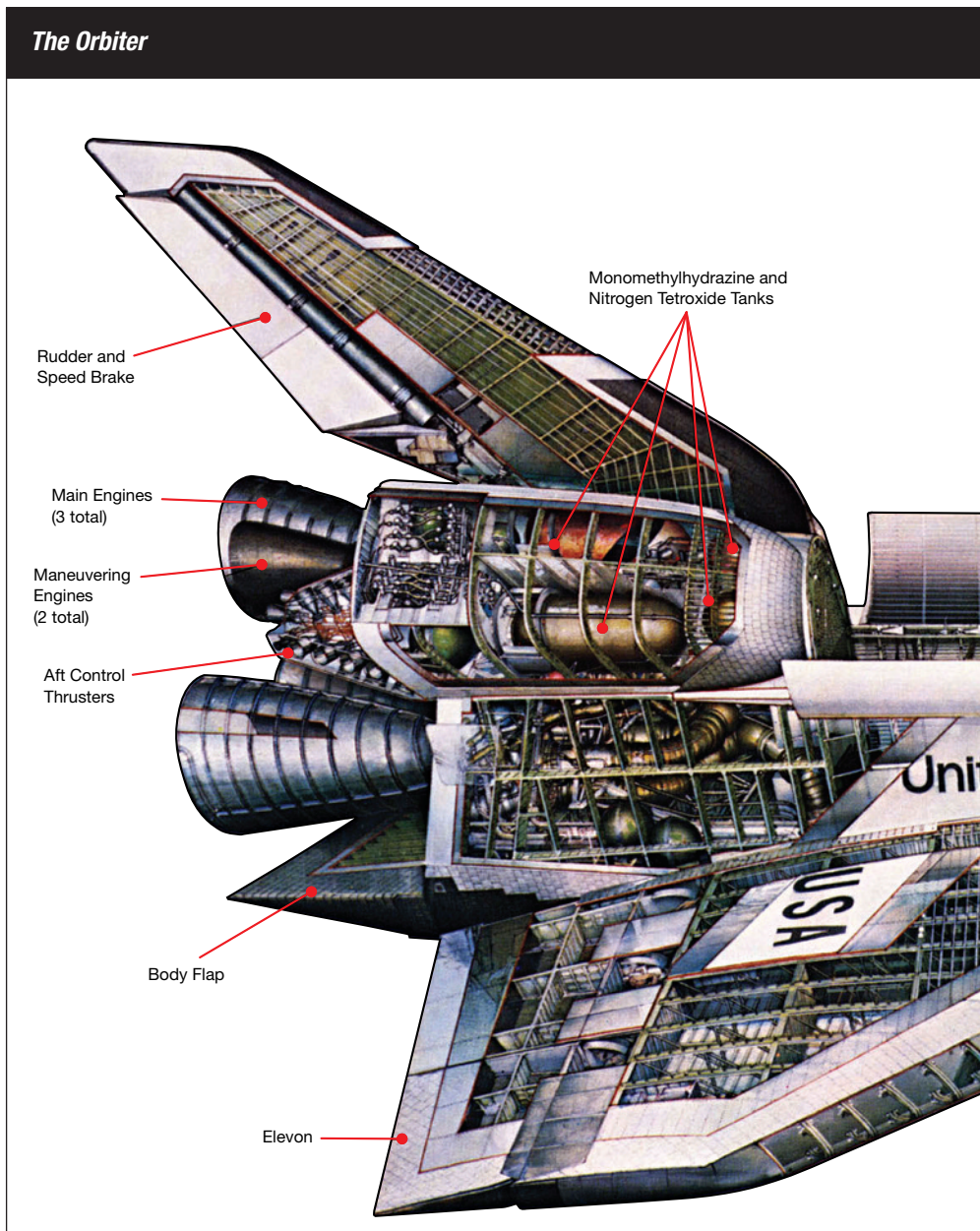
Space Shuttle Reusability

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.

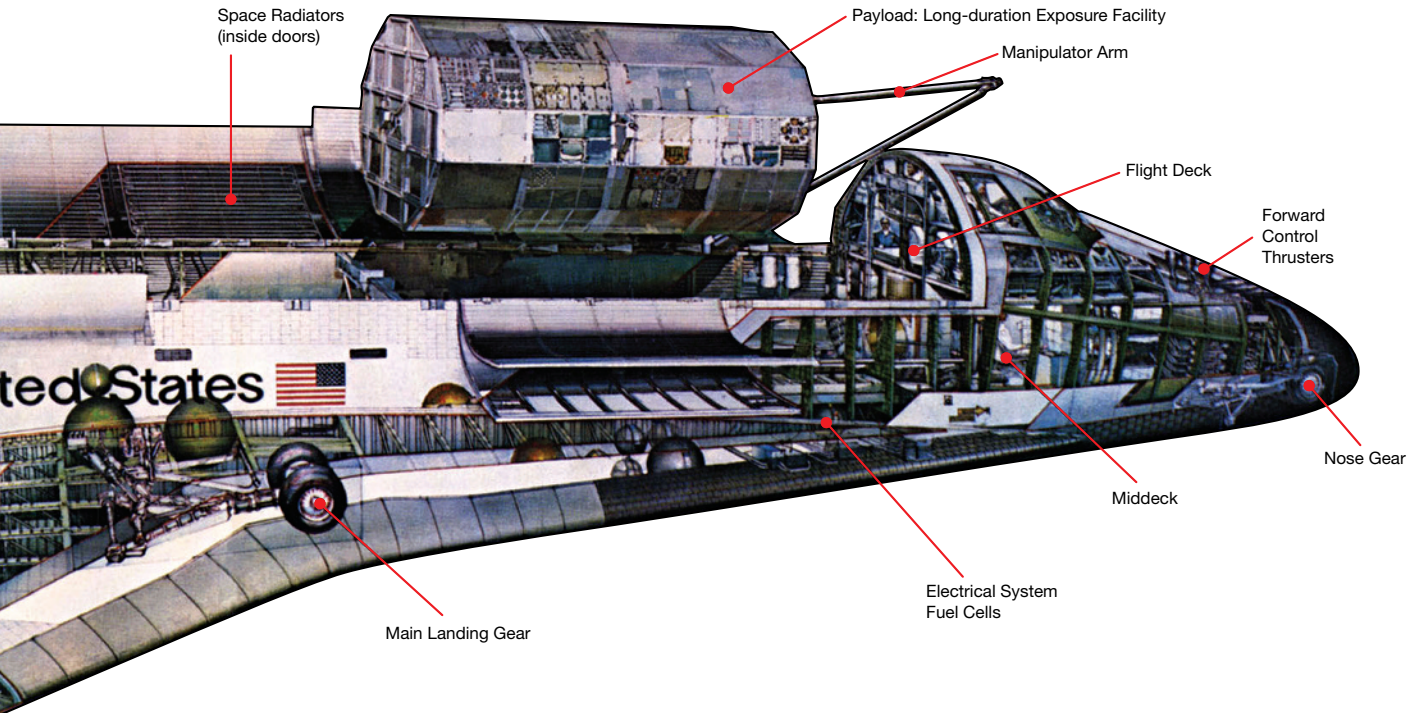
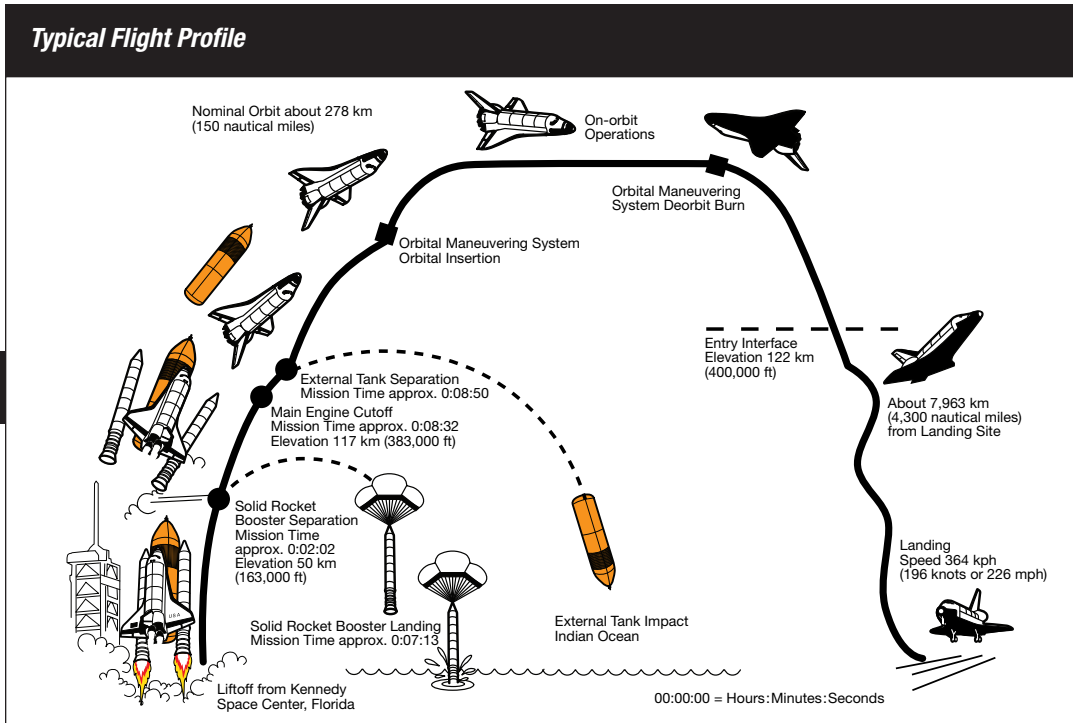
The Orbiter was the only fully reusable component of the shuttle system. Each Orbiter was designed and certified for 100 space missions and required about 5 months, once it landed, to service the different systems and configure the payload bay to support requirements for its next mission. NASA replaced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

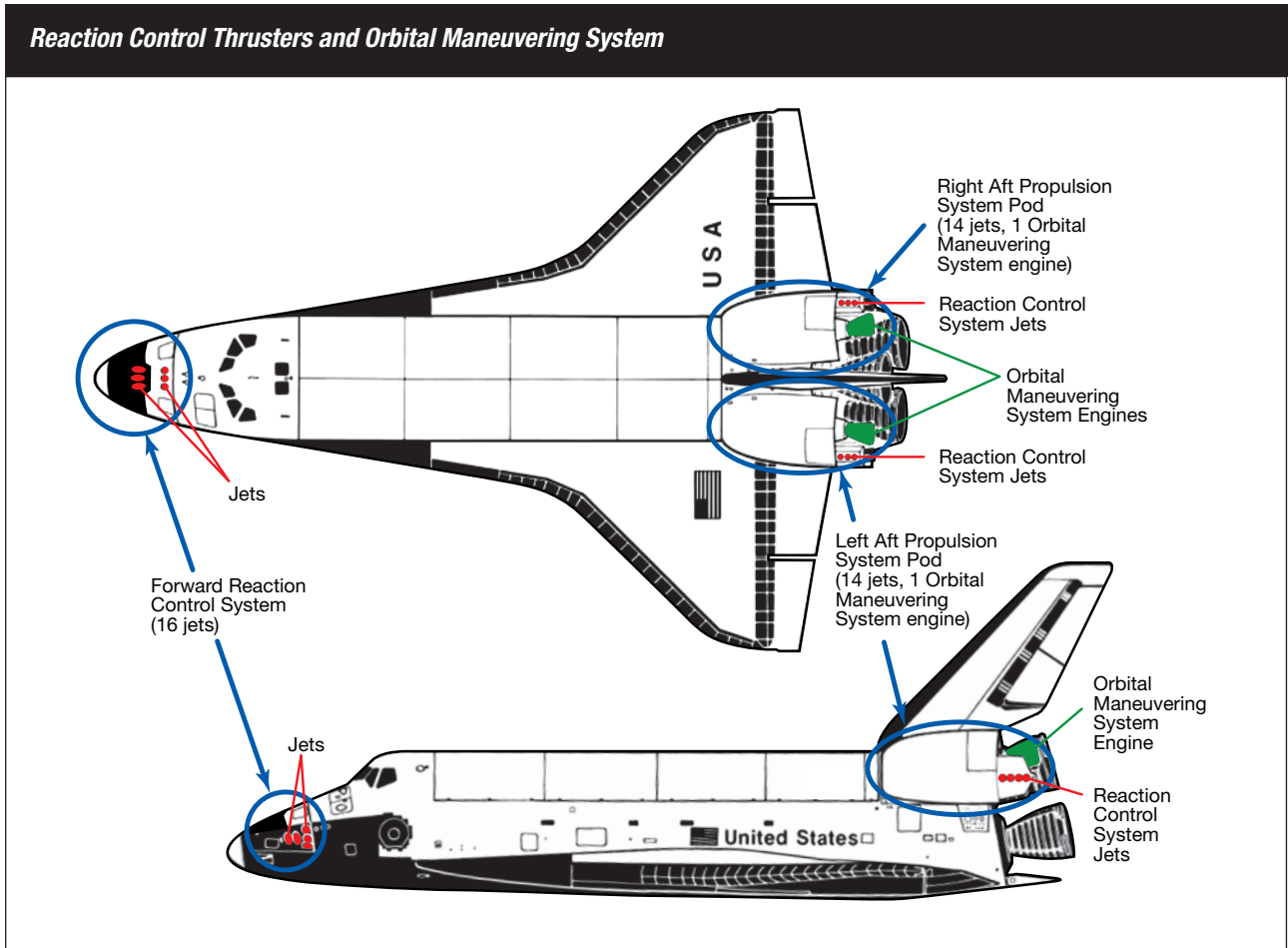
safe continuation of the mission. The loss of the second box still allowed the function to work properly with only two remaining boxes, which subsequently allowed for safe re-entry and landing of the Orbiter. Other critical functions were designed with only triple redundancy, which meant that fail-operational/fail-safe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



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.

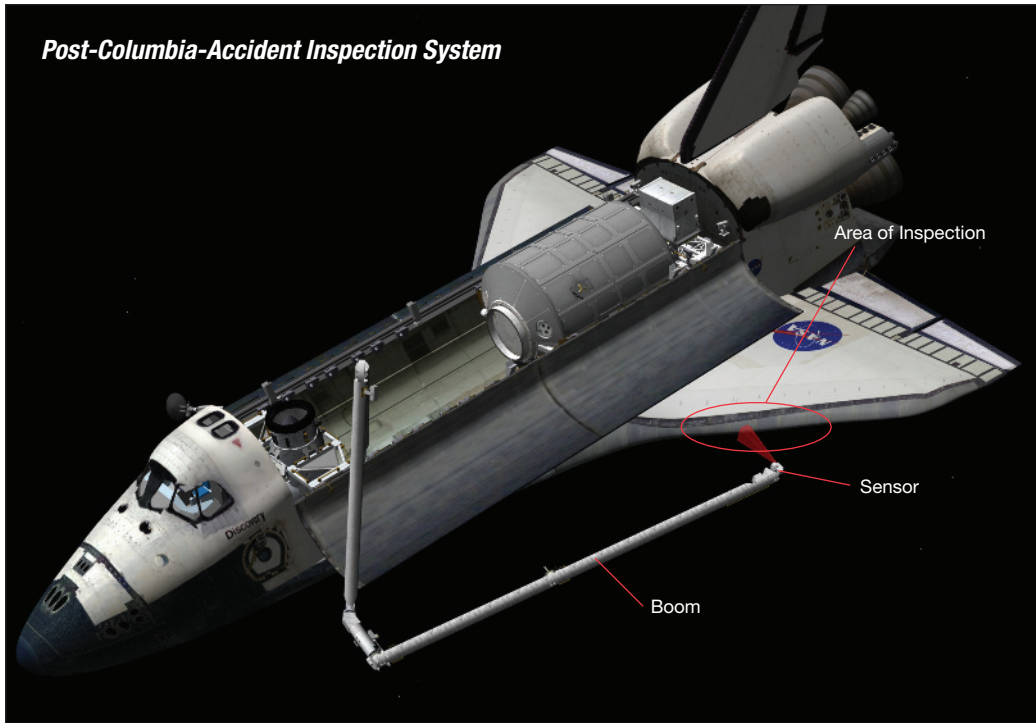
The first rendezvous missions targeted satellite objects less massive than the shuttle and grappled these objects with its robotic arm. During the proximity operations phase, the commander only had a docking camera view and accompanying radar information to guide the vehicle. Other astronauts aimed payload 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.

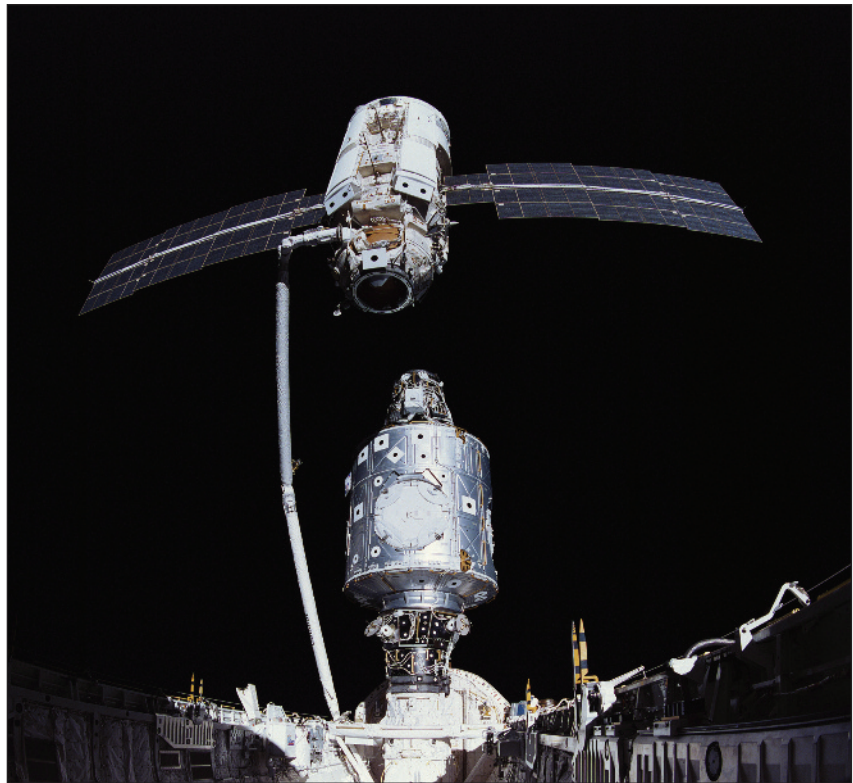


The Orbiter Boom Sensor System inspects the wing leading edge. This system was built for inspections after the Columbia accident (STS-107 [2003]).

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.



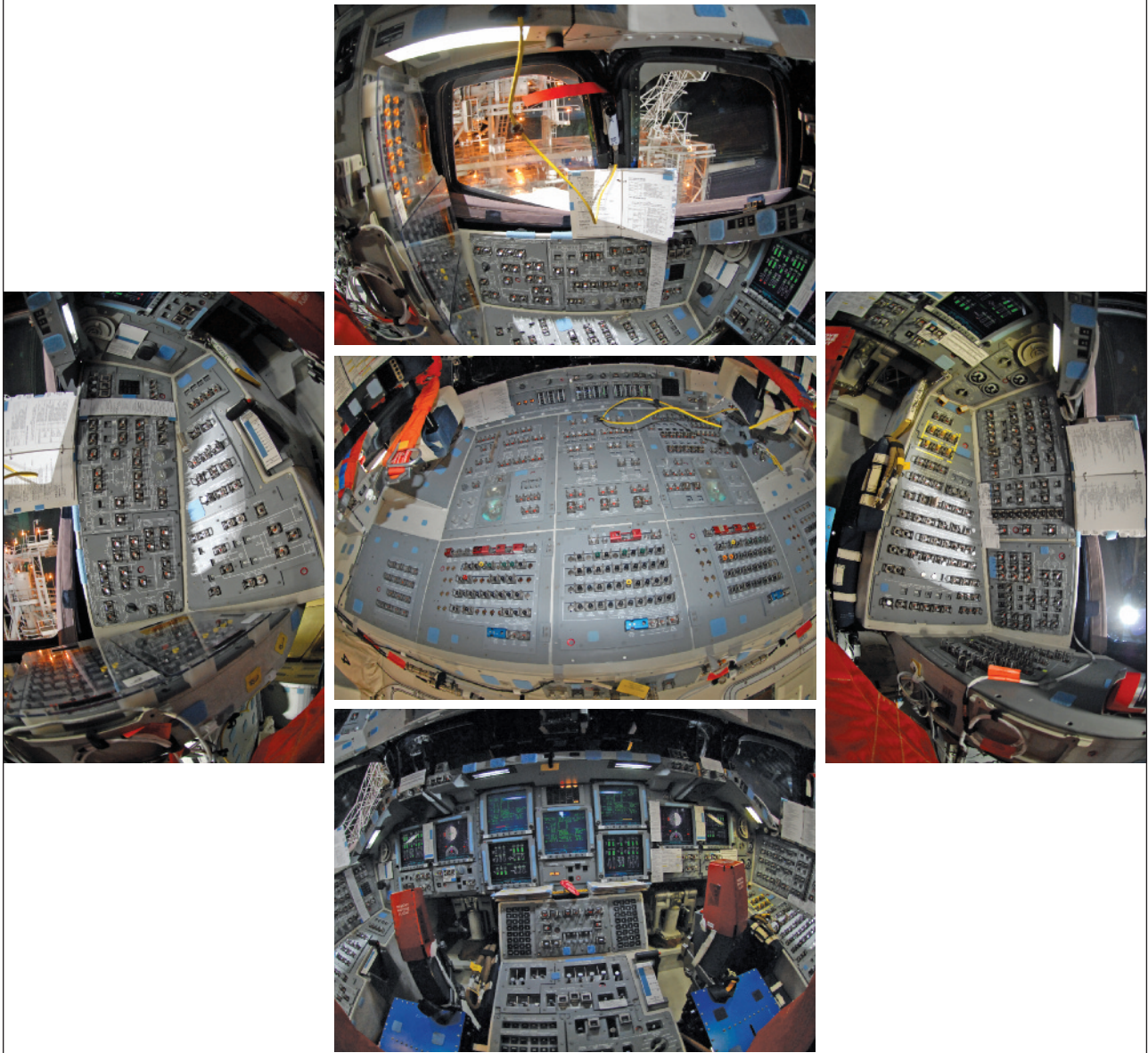
Crew Compartment Accommodation for Crew and Payloads

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.

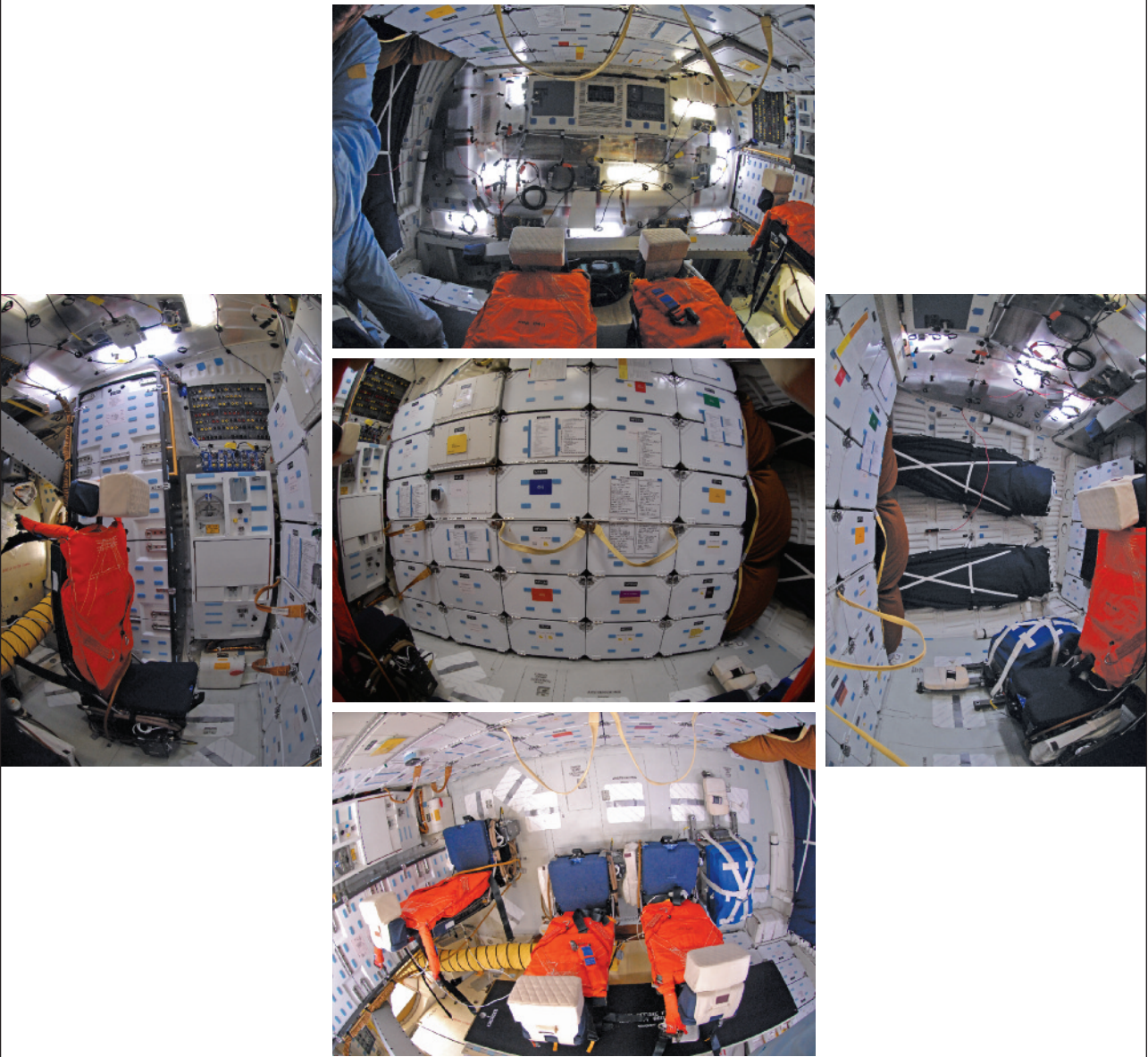


in the middeck area; it allowed up to three astronauts, wearing extravehicular mobility unit spacesuits, to perform an EVA in the vacuum of space. The standard practice was for only two crew members to perform an EVA.

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

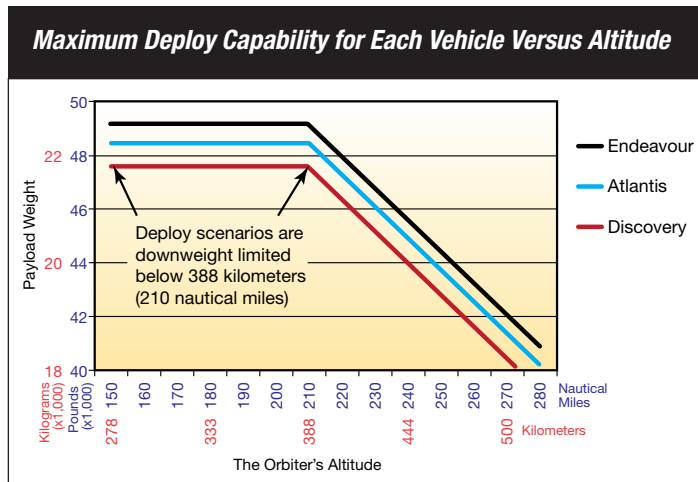
Throughout the history of the program, the versatile shuttle vehicle was configured and modified to accomplish a variety of missions, including: the deployment of Earth observation and communication satellites, interplanetary probes, and scientific observatories; satellite retrieval and repair; assembly; 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.

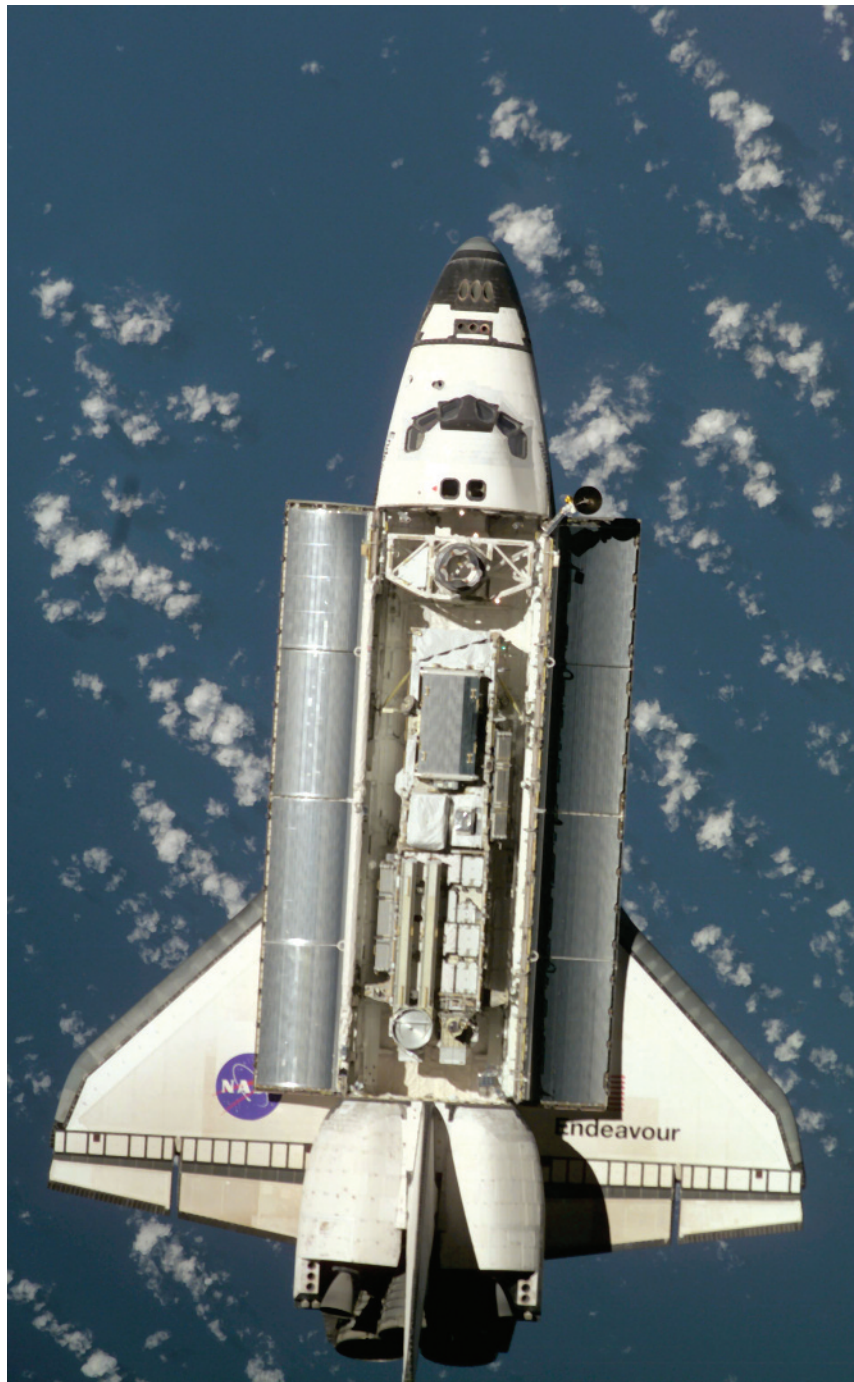


A Platform for Scientific Research

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).

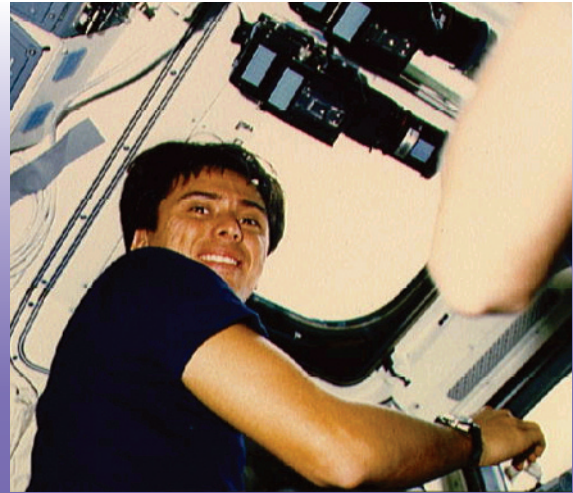


Franklin Chang-Díaz, PhD

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

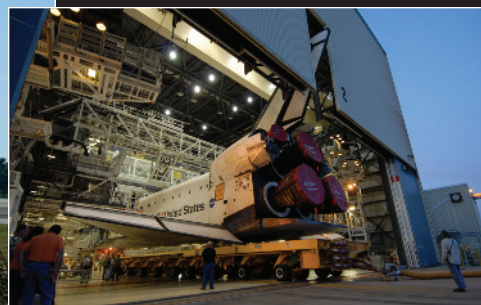
Similar to a conventional airport, the KSC shuttle landing facility used visual and electronic landing aids both on the ground and in the Orbiter to help direct the landing. Unlike conventional aircraft, the Orbiter had to land perfectly the first time since it lacked propulsion and landed in a high-speed 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