IB. Technical Development of the Space Transportation System

> *The Space Shuttle is the primary element of what once was to be an interrelated complex of a variety of spacecraft, called the Space Transportation System (STS). Even though most of the spacecraft once planned were never built, the title Space Transportation System has remained for what has mainly been a program to build the Space Shuttle.*[157]

The STS, commonly called the Space Shuttle (Figure No. A-26), was the first winged US spacecraft capable of launching crew vertically into orbit and landing horizontally upon return to Earth. The STS was comprised of four major elements: the reusable orbiter vehicle, which held the crew and payloads; three main engines, installed on the orbiter, which powered the orbiter into space; the large expendable ET, which held the propellants for the main engines; and a pair of reusable SRBs which provided initial ascent thrust for the vehicle. After the basic shuttle requirements were defined, each of the major elements experienced its own evolutionary path. Specific accomplishments and milestones in design, development, testing, production, and operations for the SSMEs, the ET, and the SRBs and SRMs, are contained in Parts III, IV, and V, respectively. Physical and functional descriptions for the major elements also are contained in these sections.

Phase C/D: Design, Development, Test, and Evaluation

By mid-1971, NASA was weighing the pros and cons of a phased approach to the development of the STS in which the orbiter vehicle would be developed first and initially tested with an interim expendable booster. While some preliminary booster design and development was conducted, full-scale hardware development of a reusable booster was started later.[158] NASA decided to sequence the development and testing of the system features. As a result, major contracts for each of the primary STS elements, including the orbiter vehicle, SSMEs, ET, SRMs, and SRBs were awarded separately.

<u>Propulsion Element DDT&E Contracts</u>

NASA awarded Phase C/D Design, Development, Test and Evaluation (DDT&E) contracts for the propulsion elements between April 1972 (SSME) and June 1974 (SRM); the contract for the ET was awarded in September 1973. The SRB was designed in-house by MSFC, and contracts for major SRB elements and systems, as well as assembly, were awarded during 1975 and 1976. The SSME was considered the "pacing component," and was developed in tandem with the orbiter.

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[157] Guilmartin and Mauer, "A Shuttle Chronology," i.
[158] "NASA studies a new approach to developing Space Shuttle system," *Roundup*, July 2, 1971, 1.

Three firms were invited to prepare proposals for the SSME contract: Aerojet General, United Aircraft Pratt & Whitney, and North American Rockwell's Rocketdyne Division. The RFP was issued on March 1, 1971. NASA awarded the SSME contract (NAS8-27980) to the Rocketdyne Division, Canoga Park, California (later, Pratt & Whitney Rocketdyne); the contract, initially valued at $205,766,000, was signed on August 16, 1972; this contract predated the orbiter contract award.[159] Assembly of the first prototype main engine, SSME 0001, was completed on March 24, 1975. (See Part III for further information regarding the SSME.)

Following the orbiter and the SSME, the ET was the third major procurement for the STS. The RFP for DDT&E of the ET was released on April 2, 1973, to four aerospace firms: Boeing, Chrysler, Martin Marietta, and McDonnell Douglas. Martin Marietta (later, Lockheed Martin Space Systems Company) of New Orleans, Louisiana, the successful proposer, was awarded the $152,565,000 contract (NAS8-30300) on September 1, 1973.[160] Production of the ETs was started in late 1975, and in June 1979, the first flight-ready ET was completed. (See Part IV for further information regarding the ET.)

On July 16, 1973, the RFP for design and development of the SRM was issued to Aeroject Solid Propulsion, Lockheed, Thiokol, and United Technologies. NASA selected the Thiokol Chemical Company of Promontory, Utah, on June 26, 1974. The DDT&E contract (NAS8-30490) was valued at $226,397,814.[161] (See Part V for further information regarding the SRM.)

While MSFC designed the SRB in-house, in 1975 and 1976, the center awarded contracts for the design, development, and testing of major SRB systems and subsystems, including the multiplexers/demultiplexers (July 1975), SRB separation motors (August 1975), thrust vector control servoactuators (August 1975), SRB structures (August 1975), integrated electronic assemblies (September 1975), pyrotechnic initiator controllers (September 1975), deceleration systems (parachutes) (July 1976), as well as signal conditioners, frequency division multiplexers, and location aid transmitters, among others. The last major contract award (NAS8-32000), for SRB assembly, checkout, launch operations, and refurbishment, was awarded to United Space Boosters, Inc. (USBI) of Sunnyvale, California, in December 1976. (See Part V for further information regarding the SRB.)

Orbiter and Integration Systems

The RFP for development of the orbiters and integration systems was released on March 17, 1972. "As a design objective," the RFP stated, "the Space Shuttle System should be capable of use for a minimum of 10 years, and each Orbiter Vehicle shall be capable of low cost refurbishment and maintenance for as many as 500 reuses."[162] Following the study of many

[159] Whalen and McKinley, "Chronology," 21.
[160] Whalen and McKinley, "Chronology," 26.
[161] Whalen and McKinley, "Chronology," 29.
[162] NASA MSC, Space Shuttle Program Request for Proposal No. 9-BC421-67-2-40P (Huntsville, AL: MSFC

candidate concepts, the Space Shuttle system configuration, the RFP noted, was selected on the basis of development and per-flight operating costs. The RFP covered the DDT&E, plus production phases, divided into increments. Increment 1, representing approximately the first two years of DDT&E, included a detailed development program plan for components, subsystems, orbiter vehicle major structural elements, and support equipment, sufficient for proceeding with detailed design and hardware development. The balance of the DDT&E effort, Increment 2, included the development and delivery of two orbiter vehicles. The Production phase, Increment 3, covered the manufacture, test, and delivery of three additional orbiter vehicles, as well as an upgrade/retrofit of the first two development orbiter vehicles to operational status.[163] The scope in the RFP specified that proposals from joint ventures would not be accepted.[164]

The NASA Source Evaluation Board solicited eight firms for the orbiter DDT&E procurement; twenty-nine other firms requested and received copies of the RFP. Of these, only four companies submitted proposals: Grumman Aerospace Corporation, the Space Systems Division of Lockheed Missiles and Space Company, McDonnell Douglas Corporation, and the Space Division of North American Rockwell. All four had participated in previous feasibility and preliminary design studies.[165] A total of 416 people representing seven NASA Centers, NASA Headquarters, and the Air Force participated in the evaluation of proposals.[166] As a result, North American Rockwell (now The Boeing Company) was selected in July 1972 for negotiations leading to a contract to begin development of the space shuttle system. Rockwell's greatest advantage, according to the selection board, was in the area of management. This firm was selected over the others because it "attained the highest score from a mission suitability standpoint, because its cost proposal was lowest and credible, and because its approaches to program performance gave high confidence . . . it will indeed produce the Shuttle at the lowest cost."[167]

The estimated cost of the contract was $2.6 billion over about six years, with the first increment, valued at $540 million, to cover the initial two years.[168] NASA issued a letter contract on August 9, 1972, authorizing North American Rockwell to proceed with the development of the orbiter. The letter provided Rockwell the authority to proceed while a definitive contract was being negotiated. NASA obligated $12,300,000 as the initial funding under the contract (NAS9-14000).[169] A supplemental agreement (Increment 2, NAS9-14000, Schedule A) that formally incorporated the construction of OV-101 (*Enterprise*) and OV-102 (*Columbia*) was signed in

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History Office, no date), IV-5.
[163] NASA Manned Spacecraft Center, Request for Proposal, 1-7 and 1-8.
[164] NASA Manned Spacecraft Center, Request for Proposal, 1-2.
[165] "Selection of Contractor for Space Shuttle Program," Sweetsir Collection, Box 67D.6, Folder 12, 9-72 (Florida: KSC Archives, September 18, 1972), 1-4.
[166] "Selection of Contractor," 3.
[167] "Selection of Contractor," 4.
[168] "NAR Selected for Shuttle Negotiations," *Marshall Star*, August 2, 1972: 2.
[169] "NASA and NR Ink Shuttle Pact," *Roundup*, August 18, 1972, 1.

October 1975.[170] The agreement represented work valued at approximately $1.8 billion and brought the estimated value of the orbiter contract to slightly over $2.7 billion.[171]

Following its selection as the prime contractor, Rockwell subcontracted a large percent of the work to about 240 subcontractors, suppliers, and vendors. Of these subcontracts, eighty-eight were in excess of $1 million, and nineteen had a value of $10 million or more.[172] Midway through 1975, some 34,000 workers in forty-seven states were employed in support of the SSP, working for NASA, the prime contractors, and the subcontractors. The buildup reached a peak of 47,000 during 1977.[173] Among the major subcontracts awarded by Rockwell were those to Grumman Aerospace Corporation in Bethpage, New York, for the design, fabrication, and testing of the orbiter wing, valued in excess of $40 million; to McDonnell Douglas, St. Louis, Missouri, for the orbital maneuvering system, valued at $50 million; to Republic Division of Fairchild Industries in Farmingdale, New York, for the vertical fin, valued at $13 million; and a $40 million contract for the mid-fuselage, awarded to the Convair Division of General Dynamics in San Diego, California.[174]

In January 1977, NASA issued a modification (Increment 3, NAS9-14000, Schedule B) to Rockwell's contract valued at $10,031,250. This agreement incorporated nine contract changes previously authorized by NASA "for configuration changes to the orbiter for the Approach and Landing Test, changes in definition of a quarter scale ground vibration test model and additional simulation efforts to cover support of Orbiter 102, the first Orbiter to be launched into space."[175] This supplement brought the estimated value of the Rockwell contract to $3.038 billion.

Increment 3, Production and Modification Contract NAS9-14000, Schedule B, issued in February 1979 and valued at $1.9 billion, governed the manufacture of OV-103 (*Discovery*) and OV-104 (*Atlantis*), the conversion of Structural Test Article (STA)-099 into the flight orbiter OV-099 (*Challenger*), as well as major modifications. The contract also called for modifications to OV-102 (*Columbia*), then under assembly.[176] Effective August 1, 1987, Rockwell completed contract negotiations to build OV-105 (*Endeavour*), the "replacement orbiter." The OV-105 contract (NAS9-17800), valued at $1.3 billion, specified a forty-five month work schedule, with orbiter delivery set on April 30, 1991. The last addition to the orbiter fleet would be assembled using existing structural spares, and incorporate all new technology, with the latest upgrades and modifications built in. A significant percentage of the work was to be performed by more than 100 subcontractors.[177]

[170] The Boeing Company, *Orbiter Vehicle Data Pack Document: Orbiter Vehicle Atlantis (OV-104), Volume I* (Huntington Beach, California: The Boeing Company, 2011), 20-26.
[171] "NASA Signs Pact for Two Orbiters," *Roundup*, October 10, 1975, 1.
[172] "First Shuttle Hardware Arrives," *X-Press*, March 28, 1975, 2.
[173] Heppenheimer, *Development of the Space Shuttle, 1972-1981*, 33.
[174] Heppenheimer, *Development of the Space Shuttle, 1972-1981*, 29.
[175] "NASA, Rockwell sign supplemental contract," *Roundup*, January 21, 1977, 1.
[176] "Contract Signed for Orbiters," *Marshall Star*, February 14, 1979, 2; Boeing, *OV-104, Volume I*, 20-26.
[177] "Rockwell secures contract to build replacement Orbiter," *Space News Roundup*, August 14, 1987, 1.

The contracts for orbiter development were followed by a series of Phase E Operations Support contracts, beginning with Increment 3, NAS9-14000, Schedule E. This Operations contract, which covered the period between 1981 and 1989, was succeeded by NAS9-18400 (1989-1994), NAS9-19000 Consolidated Contract (1994-1996), Space Flight Operations Contract (SFOC) NAS9-20000 (1996-2006), and Space Program Operations Contract (SPOC) NNJ06VA01C (2006-2015), and Transition and Retirement Contract NAS9-20000 (NNJ06VA01C; 2005-2015).[178]

The final SPOC, with United Space Alliance (USA), valued at $232.9 million, covered closeout contract modifications from October 1, 2011, through September 30, 2013.[179] It included the "safing" of the three extant orbiter vehicles for public display; ferry operations for *Discovery*, plus property and records disposition.

Test Articles and Orbiter Prototypes

Each NASA orbiter designation is composed of a prefix and a suffix separated by a dash. The prefix for operational orbiter vehicles is OV. The suffix is composed of two parts: the series and the vehicle number. The numbering is sequential, with the series beginning with a 0 for a non-flight ready orbiter and 1 for a flight-ready orbiter. OV-100 was never used, as it would read "Orbiter Vehicle Series 1 Vehicle 0." "STA" was used to designate a structural test article. As noted below, a few structural test articles were associated with OV numbers.

OV-095

The Shuttle Avionics Integration Laboratory (SAIL), located in Building 16 at JSC was also known as the Shuttle Test Station (STS) OFT (Orbital Flight Test) Test Article. Assigning this laboratory an orbiter vehicle number (STS OV-095) did not follow the OV naming protocol. Reportedly, the number was assigned by an IBM programmer to meet a SAIL software requirement. OV-095 has unofficially been referred to as a "bird without a skin." Rather than the SAIL facility proper, the "bird without a skin" more aptly describes the "Big Rig" located within the SAIL (Figure No. A-27). The "Big Rig" is a full-scale mockup of the orbiter minus the wings and landing gear, the latter of which is simulated. It contains all of the equipment and wiring (exposed), usually flight certified, found on the orbiter. The "Big Rig" was developed at JSC in 1974 to provide integration and verification of Space Shuttle hardware and software for flight. The "Big Rig" has numerous interfaces with external laboratories, including the Inertial Measurement Laboratory, the Electronic Systems Test Laboratory, the Software Production Facility, the Orbiter Data Record Center, the KSC Launch Processing System Checkout, Control,

[178] Boeing, *OV-104, Volume I*, 20-26.
[179] USA is a Limited Liability Company (LLC) equally owned by The Boeing Company and Lockheed Martin Corporation. It was formed in 1996 to consolidate more than thirty contracts supporting the SSP. "United Space Alliance," 2012, http://www.unitedspacealliance.com/about-USA.cfm.

and Monitor System, the Guidance Integration Test and Facility, the Payload Operations Control Center, and the Mission Control Center.[180]

STA-096 and STA-097

A Boeing Shuttle manager reported that STA-096 was an Environmental Control and Life Support System test article that was cancelled prior to delivery. However, the NASA History Office has no record of STA-096, and its current state and disposition are unknown. Similarly, while STA-097 is listed in NASA records as a Vibro Acoustic (Mid Fuselage) Test Article, the NASA History Office has no record of this structural test article.[181]

STA-098 (MPTA-098)

The Main Propulsion Test Article (MPTA), constructed by Rockwell, is named OV-098 in some NASA records. However, since it was a test article and does not fit the OV nomenclature for a non-flight ready orbiter, the reference to the MPTA as OV-098 appears to be incorrect and unofficial. It may have been reassigned as OV-098 when it was rebuilt into the Shuttle-C mockup during the 1990s.[182] The test article is more commonly referenced in documents as MPTA-098. The MPTA "consisted of an aft-fuselage, a truss arrangement which simulated the mid-fuselage, and a complete thrust structure including all main propulsion system plumbing and electrical systems."[183] It was mated with an ET (MPTA-ET) and three prototype SSMEs, and used between April 21, 1978, and the end of 1979, for propellant loading and static firing tests. It was last used on January 17, 1981, for static firing of flight nozzles. The MPTA is presently stored at NASA's SSC in Mississippi.

OV-098

There are many references to the *Pathfinder* Orbiter Weight Simulator as OV-098. While never formally numbered by NASA, the OV-098 designation was assigned unofficially and retroactively. The *Pathfinder* was designed and engineered by the Product Planning Branch, Fabrication Division of the Test Lab at MSFC, and assembled by the Mockup and Prototype Assembly Branch at MSFC in 1977. The nucleus of the structure was a scrapped Titan solid rocket motor case, with frames, collars, nose, tail structures, and wings added, and finished with aluminum sheeting for the outer skin. The simulator had roughly the same size, shape, weight, and center of gravity as an actual orbiter, and was used as a stand-in for *Enterprise* (OV-101).[184]

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[180] ACI and Weitze Research, *NASA-Wide Survey and Evaluation of Historic Facilities in the Context of the US Space Shuttle Program: Roll-Up Report* (survey report, NASA Headquarters, February 2008), 3-3, 3-4.
[181] ACI and Weitze Research, *Roll-Up Report*, 3-4.
[182] ACI and Weitze Research, *Roll-Up Report*, 3-4.
[183] Jenkins, *Space Shuttle*, 225.
[184] Amos Crisp, "Homemade Orbiter To Make Practice Runs at Marshall," *Marshall Star*, November 23, 1977, 4.

It was first used at MSFC in order to fit-check the roads and facilities that were used during the MVGVT program, and also employed to test the hoisting system for lifting *Enterprise* (Figure No. A-11). In April 1978, the *Pathfinder* was shipped by barge to KSC and was used, until early 1979, to check out the Mate-Demate Device (MDD), OPF, and VAB work platforms. Fit-checks were performed in the OPF-1 to ensure that the work platforms were positioned correctly and would not hit the orbiter when used.[185] In addition, the *Pathfinder* was used to train ground crew in post-landing procedures at the KSC Shuttle Landing Facility (SLF). Following these operations, in late 1979, *Pathfinder* was returned to MSFC for storage. Years later, it was modified by Teledyne-Brown Engineering to more closely replicate an orbiter.[186] Subsequent to its display at the Great Space Shuttle Exposition in Tokyo, Japan, between June 1983 and August 1984, it was transferred to NASM. It is currently on display at the US Space & Rocket Center in Huntsville, Alabama, where it is mounted on the MPTA-ET, along with a pair of inert SRBs (whose nose segments and aft skirts were removed in 1999 and replaced by a set of mockups).

STA-099

STA-099, a high-fidelity structural test article, was built by Rockwell under the Increment 1, NAS9-14000 contract. Structural assembly was started on November 21, 1975, and final assembly was completed on February 10, 1978. Subsequently, Rockwell delivered STA-099 to the Lockheed Company at Palmdale (Figure No. A-28), where the test article underwent a year-long test program, concluded on October 4, 1979. Testing took place in a specially-built 430-ton steel rig, known as a reaction frame. The rig contained 256 hydraulic jacks that operated, under the control of a computer, to distribute loads across 836 application points. STA-099 was subjected to various simulated stress levels that duplicated the launch, ascent, on-orbit, reentry, and landing phases of flight.[187] Three 1-million pound-force hydraulic cylinders were used to simulate the thrust from the SSMEs, and heating and cooling simulations were also conducted using gaseous nitrogen to simulate the cold of space and heating blankets to simulate ascent and reentry heating. Thermal loads were applied directly to the metal structure. “In a separate test, the fuselage was given loads that simulated the impact of the nose landing gear on a runway.”[188]

After testing was completed, STA-099 was returned to Rockwell on November 7, 1979, for conversion into OV-099 (*Challenger*).[189] The conversion process involved a major disassembly of the vehicle. The payload bay doors, elevons, body flap, vertical stabilizer, upper forward fuselage, and entire aft fuselage were removed and returned to their original vendors for modification.[190]

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[185] Jenkins, *Space Shuttle*, 215.
[186] Jenkins, *Space Shuttle*, 215.
[187] Jenkins, *Space Shuttle*, 241; “Third Orbiter Passes Tests,” *Marshall Star*, October 17, 1979,1 and 4.
[188] Heppenheimer, *Development of the Space Shuttle*, 252-256.
[189] The original plan was to prepare *Enterprise* (OV-101) for space, but conversion of STA-099 was more cost effective.
[190] Jenkins, *Space Shuttle*, 242.

OV-101

OV-101 was built by Rockwell under the NAS9-14000, Schedule A contract.[191] Structural assembly was started in June 1974 and completed in March 1976. Rollout from the Palmdale assembly facility was on September 17, 1976.[192] The first orbiter hardware to arrive in Palmdale was the mid-fuselage, shipped from the Convair plant in San Diego in March 1975.[193] Next were the orbiter wings, in May. Fabricated in Grumman's facilities on Long Island, New York, the wings were transported on a container ship through the Panama Canal to Long Beach, California, where Grumman trucked them overland to Palmdale.[194] Rockwell shipped the orbiter crew module, which fit inside the lower half of the forward fuselage, from Downey to Palmdale in December. Rockwell mated the orbiter's forward, mid, and aft fuselages with the spacecraft's wings and vertical tail by the end of 1975. Rockwell next moved its Apollo checkout equipment from Downey to Palmdale for adaptation to the shuttle orbiter.[195] In May 1976, a fiberglass nose cap was installed on OV-101 for use in the upcoming ALT program.

As a test article, OV-101 featured numerous substitute components as placeholders for the equipment found in vehicles built for actual space flight.[196] Late in the summer of 1976, Rockwell mounted three dummy SSMEs in the rearmost section of the orbiter (the "boattail); the simulated SSMEs were fabricated by Rockwell's Rocketdyne Division at Air Force Plant (AFP) 56 in Canoga Park, California.[197] In the weeks before rollout, Rockwell oversaw a horizontal ground vibration test at Palmdale to verify structural dynamics data for a full-sized orbiter. Tests in the early 1970s at Langley had used one-eighth-scale models to study the anticipated longitudinal oscillation frequencies, known as "pogo." A second round of model tests, at one-quarter scale, had been a joint effort of JSC and Rockwell in 1975.[198]

On January 31, 1977, OV-101 was moved overland from Palmdale to NASA's DFRC for use in the ALT Program, conducted between February and October 1977, as described in Part IA. Transport of the orbiter test vehicle, which weighed approximately 150,000 pounds, proceeded at about three miles per hour.[199] Following completion of the ALT test flights, OV-101 was used for vibration tests at the MSFC. Subsequently, it was moved to KSC where, between May through July 1979, NASA used OV-101 to verify the correct locations of maintenance platforms, and to check crew escape procedures.[200] Later that year, OV-101 was flown to California, and

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[191] The Boeing Company, *Orbiter Vehicle Data Pack Document: Orbiter Vehicle Discovery (OV-103), Volume II* (Huntington Beach, California: The Boeing Company, 2011), 5.
[192] "Space Shuttle Orbiter 101 Rollout Set for Next Week," *Marshall Star* , September 8, 1976, 1 and 4.
[193] "First Shuttle Hardware Arrives," *X-Press*, March 28, 1975, 2.
[194] "Orbiter Wings to Arrive in Palmdale Today," *X-Press*, May 23, 1975, 2.
[195] "First Shuttle Orbiter Under Assembly," *Marshall Star*, December 3, 1975, 4; Heppenheimer, *Development of the Space Shuttle, 1972-1981*, 98.
[196] "Orbiter Gets A Nose Cap," *Marshall Star*, May 19, 1976, 7.
[197] "Space Shuttle Orbiter 101 Rollout Set for Next Week," *Marshall Star*, September 8, 1976, 1 and 4.
[198] Heppenheimer, *Development of the Space Shuttle*, 100, 251-252.
[199] "Enterprise Will Begin First Trip Next Monday," *Marshall Star*, January 26, 1977, 1 and 4.
[200] Jenkins, *Space Shuttle*, 216.

moved overland to Palmdale, where selected parts, including most of the cockpit instrumentation and consoles, the control sticks, and most of the avionics, were removed and refurbished in October 1979, for use on later orbiters.

In October 1982, NASA DFRC conducted vibration tests on OV-101 in its shuttle hangar.[201] Later, in early 1984, during inflight refueling tests, the center attached samples of Felt Reusable Surface Insulation (FRSI) and Advanced Flexible Reusable Surface Insulation (AFRSI) tiles to further evaluate these thermal protection materials.[202] Also during the 1980s, OV-101 was ferried to France for the Paris Air Show (May and June 1983); was displayed at the World's Fair in New Orleans (1984); visited Germany, Italy, England, and Canada; was put on display at the KSC (September 1985); and was used in a series of flight verification vehicle tests at Vandenberg.

In November 1985, OV-101 was officially transferred (on loan) to NASM. After retirement to the Smithsonian, *Enterprise* continued to be used for various tests, and for the loan of its parts. In the aftermath of the *Challenger* accident, OV-101 was used in tests of the shuttle orbiter arresting system, and of crew bail-out concepts, both conducted at Dulles International Airport in Sterling, Virginia. During the 1990s, various parts were removed and subsequently reinstalled, including the main landing gear (borrowed in April 1990; partially reinstalled in June 1997); the door from the starboard wing (removed in July 1993; reinstalled in March 1994); the nose gear (removed in June 1997); the simulated TPS tiles from the right side of the forward fuselage, as well as a splice plate and the thermal control system blankets under it (removed April-May 1999); and eight samples of Kapton wiring (permanently removed in October 1999).[203] In June and July 2002, T-seals were borrowed for use in foam impact tests, and the next year, the left main landing gear door was removed for use in TPS tile tests at KSC. Subsequently, OV-101 was transferred to the Southwest Research Institute for impact testing.[204] Since 2003, following completion of the new exhibit space, *Enterprise* was placed on permanent display at the NASM's Steven F. Udvar-Hazy Center in Chantilly, Virginia.

The Orbiter Fleet

Between 1974 and 1991, all five operational orbiters of the Space Shuttle fleet were assembled in Building 150 at AFP 42, Site 1 North in Palmdale, California. The fifth operational orbiter, *Endeavour*, which replaced *Challenger*, was built with structural spares made by various contractors during construction of *Discovery* (OV-103) and *Atlantis* (OV-104). Upon completion, each orbiter was rolled out of the assembly hangar and, with one exception, was transported overland to Edwards AFB for delivery to KSC. The last orbiter added to the fleet,

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[201] "Enterprise Tests to Prevent Failures," *X-Press*, October 1, 1982, 2 and 4.
[202] "Inflight Refueling Tests for Shuttle Ferry Flights," *X-Press*, February 3, 1984, 3-4.
[203] Jenkins, *Space Shuttle*, 221.
[204] Jacques Van Oene, "First Space Shuttle Set for 'retirement'," *Spaceflight*, October 2003, 419-421.

Endeavour (OV-105), was ferry-flighted directly from Palmdale to the KSC in May 1991.[205] This operation was made possible by the Orbiter Lifting Frame (OLF) mate-demate device newly erected at Palmdale.

Approximately two million parts, as well as about 237 miles of wire, were used to build each orbiter. The orbiter build flow is summarized in Part II. The orbiter production line at Palmdale saw minimal activity between January 1986 and October 1988, following final assembly of *Atlantis* in April 1985, and was shut down after final assembly of *Endeavour* in 1990. However, beginning in the summer of 1991, Building 150 was reactivated to perform maintenance and modifications of the fleet vehicles. Selected milestone dates for each operational orbiter are provided in the following table.

Space Shuttle Program Orbiter Assembly[206]

Milestone	OV-099	OV-102	OV-103	OV-104	OV-105
Start structural assembly	Jan. 28, 1979	June 28, 1976	Aug. 27, 1979	March 30, 1980	Feb. 15, 1982
Complete final assembly	Oct. 23, 1981	April 23, 1978	Aug. 12, 1983	April 10, 1984	July 6, 1990
Palmdale rollout	June 30, 1982	March 8, 1979	Oct. 16, 1983	March 6, 1985	April 25, 1991
Overland transport: Palmdale to Edwards AFB	July 1, 1982	March 12, 1979	Nov. 5, 1983	April 3, 1985	n/a
Delivery to KSC	July 5, 1982	March 24, 1979	Nov. 9, 1983	April 9, 1985	May 7, 1991

A summary of the manufacturing history, modifications, and mission highlights for *Columbia* (OV-102), *Challenger* (OV-099), *Atlantis* (OV-104), and *Endeavour* (OV-105) follows. *Discovery* (OV-103), the "orbiter of record," is the focus of Part II.

Columbia (OV-102)

Columbia (OV-102) was the first orbiter built for operational use in the SSP. The spacecraft was named after both the first American-helmed sloop, captained by Robert Gray, to circumnavigate the globe, and the Apollo 11 command module. Assembly of *Columbia*'s crew module began on June 28, 1976. Aft fuselage assembly began on September 13, 1976, and the wings arrived on August 26, 1977. Final assembly started on November 7, 1977, and the body flap arrived on February 24, 1978. The payload bay door segments followed two months later. The FRCS pod

[205] OV-106 was the administrative name given to the set of structural components manufactured to replace those used in the construction of *Endeavour* (OV-105). However, the contract for these was cancelled shortly afterwards, and they were never completed.
[206] Jim Dumoulin, "Challenger (STA-099, OV-99), November 10, 1993, http://science.ksc.nasa.gov/shuttle/resources/orbiters/challenger.html; Dumoulin, "Columbia (OV-102)," February 1, 2003, http://science.ksc.nasa.gov/shuttle/resources/orbiters/columbia.html; Dumoulin, "Discovery (OV-103)," August 8, 2005, http://science.ksc.nasa.gov/shuttle/resources/orbiters/discovery.html; Dumoulin, "Atlantis (OV-104)," May 17, 2010, http://science.ksc.nasa.gov/shuttle/resources/orbiters/atlantis.html; Dumoulin, "Endeavour (OV-105)," October 12, 2005, http://science.ksc.nasa.gov/shuttle/resources/orbiters/endeavour.html.

was finished on September 11, and combined systems testing concluded on February 3, 1979. Airlock door installation ended February 16, and vehicle post-checkout completion followed on March 5. Three days later, following final inspection, *Columbia* rolled out from Building 150 (Figure No. A-29).[207] At 158,290 pounds (empty weight) at rollout, it was the heaviest of the orbiters.[208]

On March 10, *Columbia* was mated to the SCA to test the pair's aerodynamics in flight. However, the flight was halted when 4,800 dummy and 100 permanent TPS tiles broke off from *Columbia* before the SCA lifted off the ground. The tiles were properly adhered, and *Columbia*'s ferry flight began on March 20 and ended four days later at KSC. Once in the OPF, *Columbia*'s TPS installation was completed, and all orbiter systems were tested between December 16, 1979, and January 12, 1980. Before the orbiter's first liftoff, engineers at KSC practiced launch procedures. A flight readiness firing on February 20, 1981, resulted in changes to NASA's Space Shuttle countdown policies. Pre-flight preparations were not without misfortune, as two Rockwell technicians died of asphyxiation after a countdown rehearsal on March 19.[209]

Missions and Milestones

OV-102 flew twenty-eight missions between 1981 and early 2003. The launch of *Columbia* on April 12, 1981 (STS-1) marked the first time a Space Shuttle flew into Earth orbit. Noteworthy achievements and "firsts" for *Columbia* included the successful completion of the Orbital Test Flight Program (STS-1 through STS-4); the maiden flight for Spacelab (STS-9); the first ESA astronaut (Dr. Ulf Merbold) (STS-9); recovery of the Long Duration Exposure Facility (LDEF) satellite from orbit (STS-32); the first manned Spacelab mission dedicated to human medical research (STS-40); the first Japanese Space Agency astronaut and first Japanese woman (Chiaki Mukai) to fly in space (STS-65); and deployment of the Chandra X-ray Observatory (STS-93).[210]

Columbia's first flight, STS-1, was commanded by John Young, a four-time space traveler, and piloted by Robert Crippen, a Navy test pilot. The first launch attempt on April 10, 1981, was scrubbed because of a timing issue between the primary flight software and the backup software; a restart of the primary software solved the problem.[211] Two days later, *Columbia* lifted off from LC-39A at 7:00 a.m. The goal of the successful two-day flight was to test the orbiter's components before landing at Edwards AFB.

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[207]Chris Gebhardt, "Space Shuttle Columbia: A New Beginning and Vision," February 1, 2011, http://www.nasaspaceflight.com/2011/02/space-shuttle-columbia-a-new-beginning-and-vision.
[208] Jenkins, *Space Shuttle*, 242; Boeing, *OV-104, Volume I*, 230 and 231.
[209] Gebhardt, "A New Beginning."
[210] Kathy Hagood, "Columbia was the first Space Shuttle to launch," *Spaceport News*, July 25, 2003, 6-7; NASA KSC, "Space Shuttle Overview: Columbia (OV-102)," December 8, 2008, http://www.nasa.gov/centers/kennedy/shuttleoperations/orbiters/.columbia_info.html.
[211] Terry Keeler, personal communication with Whitney Maples, JSC, June 15, 2012.

Space Shuttle *Columbia*: Launch, Landing, and Mission Summary

SSP Flight No.	Mission No.	Orbiter/ Flight No.	Launch Date	Landing Date	Landing Site	Primary Mission/ Payload Type
1	STS-1	*Columbia* - 1	April 12, 1981	April 14, 1981	EAFB	Test flight
2	STS-2	*Columbia* - 2	November 12, 1981	November 14, 1981	EAFB	Test flight
3	STS-3	*Columbia* - 3	March 22, 1982	March 30, 1982	WSMR	Test flight
4	STS-4	*Columbia* - 4	June 27, 1982	July 4, 1982	EAFB	DoD
5	STS-5	*Columbia* - 5	November 11, 1982	November 16, 1982	EAFB	Satellite
9	STS-9	*Columbia* - 6	November 28, 1983	December 8, 1983	EAFB	Science
24	STS-61C	*Columbia* - 7	January 12, 1986	January 18, 1986	EAFB	Satellite
30	STS-28	*Columbia* - 8	August 8, 1989	August 13, 1989	EAFB	DoD
33	STS-32	*Columbia* - 9	January 9, 1990	January 20, 1990	EAFB	DoD
38	STS-35	*Columbia* - 10	December 2, 1990	December 10, 1990	EAFB	Science
41	STS-40	*Columbia* - 11	June 5, 1991	June 14, 1991	EAFB	Science
48	STS-50	*Columbia* - 12	June 25, 1992	July 9, 1992	KSC	Science
51	STS-52	*Columbia* - 13	October 22, 1992	November 1, 1992	KSC	Science
55	STS-55	*Columbia* - 14	April 26, 1993	May 6, 1993	EAFB	Science
58	STS-58	*Columbia* - 15	October 18, 1993	November 1, 1993	EAFB	Science
61	STS-62	*Columbia* - 16	March 4, 1994	March 18, 1994	KSC	Science
63	STS-65	*Columbia* - 17	July 8, 1994	July 23, 1994	KSC	Science
72	STS-73	*Columbia* - 18	October 20, 1995	November 5, 1995	KSC	Science
75	STS-75	*Columbia* - 19	February 22, 1996	March 9, 1996	KSC	Science
78	STS-78	*Columbia* - 20	June 20, 1996	July 7, 1996	KSC	Science
80	STS-80	*Columbia* - 21	November 19, 1996	December 7, 1996	KSC	Science
83	STS-83	*Columbia* - 22	April 4, 1997	April 8, 1997	KSC	Science
85	STS-94	*Columbia* - 23	July 1, 1997	July 17 , 1997	KSC	Science
88	STS-87	*Columbia* - 24	November 19, 1997	December 5, 1997	KSC	Science
90	STS-90	*Columbia* - 25	April 17, 1998	May 3, 1998	KSC	Science
95	STS-93	*Columbia* - 26	23 July 1999	July 27, 1999	KSC	Interplanetary probe or observatory
108	STS-109	*Columbia* - 27	March 1, 2002	March 12, 2002	KSC	Science
113	STS-107	*Columbia* - 28	January 16, 2003	Destroyed during descent		

The orbiter flew three more test flight missions in 1981 and 1982. *Columbia*'s second mission, STS-2 (November 1981), marked the first time a manned spacecraft returned to orbit. It was also the last time an orbiter flew with an ET painted white. The five-day test-flight was reduced in duration when a fuel cell malfunctioned. However, the crew still accomplished most of their goals. STS-3 (March 1982) was the first time in the SSP's history that a crew conducted onboard experiments. This mission was also distinguished as the shuttle's first and only landing at White Sands Missile Range in New Mexico. Also, a computer glitch in the autopilot caused the orbiter to speed up before touchdown, which resulted in the longest rollout distance in SSP history at 13,737'. STS-4 in June began with the first on-time launch. *Columbia*'s crew performed scientific experiments on this final test flight, and for the first time, the shuttle carried a classified Air Force payload.[212]

After completion of the four test flights of the SSP, *Columbia* flew three missions until the *Challenger* accident in 1986. Two communication satellites were deployed during STS-5 (November 1982), *Columbia*'s fifth mission. OV-102 next launched one year later, in November 1983, for STS-9. Due to a faulty nozzle on an SRB, OV-102 became the first orbiter in SSP history to roll back from the launch pad. STS-9 was dedicated to an array of scientific experiments. It was the first NASA-ESA joint mission, and the first to include an ESA astronaut on board. Upon completion of STS-9, *Columbia* underwent a one-and-one-half year major modification at Palmdale. OV-102 returned to flight in January 1986 for the STS-61-C mission. A satellite was deployed, the first observations of Haley's Comet were documented, and experiments were carried out.

Columbia's first flight after the *Challenger* accident was STS-28 in August 1989, which carried a DoD payload. In January 1990, *Columbia*'s crew deployed the LEASAT 3 satellite, and completed additional experiments as part of the manifest for STS-32. During this mission, the LDEF satellite was recovered from orbit. After multiple postponements and two rollbacks, *Columbia* flew for the tenth time in December of that year for STS-35. During the mission, OV-102's crew conducted astronomical studies using the ASTRO-1 observatory. Three female astronauts, Mission Specialists Tamara E. Jernigan, M. Rhea Seddon, and Millie Hughes-Fulford, flew together for the first time on STS-40 (June 1991). During STS-40, eighteen life science experiments were completed over nine days as part of the Spacelab program. Microgravity research was the primary focus of STS-50 in June 1992. At thirteen days, it was the longest duration SSP mission to date. Microgravity research was also carried out during STS-52 (November 1992), and a satellite also was deployed. A number of scientific experiments were completed as part of STS-55 (April 1993). In October 1993, STS-58, *Columbia*'s fifteenth mission, was a life science research mission devoted to the study of weightlessness on the human body. The next two missions, STS-62 (March 1994) and STS-65 (July 1994), focused on microgravity research.[213]

Following a major modification period which ended in April 1995, *Columbia* returned to service in October 1995 for STS-73, dedicated to Earth science research. *Columbia*'s crew for STS-75 (February 1996) also focused on investigating the Earth's physical processes. Despite the loss of a deployed satellite system, important microgravity experiments were completed during the

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[212] Judith A. Rumerman, with Chris Gamble and Gabriel Okolski, *U.S. Human Spaceflight, A Record of Achievement, 1961-2006* (Washington, DC: NASA History Office, 2007), 39-40.
[213] Gebhardt, "A New Beginning."

mission. For *Columbia*'s twentieth flight in June 1996, the crew for STS-78 studied the effects of long-duration spaceflight on the human body, an important step in preparation for construction of the ISS. During STS-80 (November to December 1996), two satellites were deployed and retrieved, and further microgravity research was conducted. Issues with *Columbia*'s airlock forced the cancellation of two planned spacewalks. At seventeen-and-one-half days, this was the longest mission in SSP history.[214]

Despite a problematic fuel cell, *Columbia* successfully reached orbit for STS-83 in April 1997. However, the faulty fuel cell resulted in the premature termination of the mission after just three days. In an unprecedented action, NASA remanifested the orbiter, crew, and objective for the failed STS-83 mission as STS-94. Launched in July 1997, STS-94, *Columbia's* twenty-third mission, focused on microgravity research, which also was the objective of the next OV-102 mission, STS-87 (November 1997). The STS-87 mission also deployed the SPARTAN-201 satellite (which failed to operate), and ISS construction methods were tested during the two extra vehicular activities (EVAs). *Columbia*'s twenty-fifth mission, STS-90, launched in April 1998, was a Neurolab mission dedicated to the effects of microgravity on the brain and nervous system. STS-90 marked the last and most complex of the twenty-five Spacelab missions. *Columbia* did not fly again until STS-93 in July 1999; this SSP mission was distinguished as the first to be commanded by a female astronaut, Eileen Collins. OV-102 experienced low-level engine cutoff during ascent. The Chandra X-ray Observatory was deployed during STS-93, and physical and biomedical experiments were completed.[215]

After a hiatus of two-and-one-half years, which included a seventeen month orbiter major modification (OMM), *Columbia* launched in March 2002 on its twenty-seventh mission. STS-109 included five EVAs to service the HST. *Columbia*'s crew installed a new advanced camera for surveys, new rigid solar arrays, a new power control unit, a new reaction wheel assembly, and a new cryocooler for the Near Infrared Camera and multi-object spectrometer.

STS-107, *Columbia's* final mission, was launched on January 16, 2003. Over the next fifteen days, the crew completed an assortment of life science and Earth science studies. At 8:15 a.m. on February 1, *Columbia* began to deorbit and reenter the atmosphere. The Mission Control Center lost contact with the orbiter forty-five minutes later.[216] *Columbia* was destroyed over eastern Texas during its descent, approximately sixteen minutes before landing.

Columbia continued to influence space flight after the accident; recommendations by the CAIB resulted in major modifications to *Discovery*, *Atlantis*, and *Endeavour*. In her twenty-two years of service, *Columbia* flew twenty-eight missions; traveled 121,696,993 miles; completed 4,808 orbits; spent 300 days in space; and carried 160 crewmembers. *Columbia* flew the first four test

[214] Rumerman, *U.S. Human Spaceflight*, 61.
[215] Rumerman, *U.S. Human Spaceflight*, 61-65.
[216] Chris Gebhardt, "Columbia (OV-102): A Pioneer to the End," February 2, 2011, http://www.nasaspaceflight.com/2011/02/columbia-ov-102-a-pioneer-to-the-end.

missions of the SSP, deployed eight satellites, completed a service mission to the HST, and was distinguished by seventeen missions dedicated to the advancement of microgravity study.[217]

Modifications

OV-102 underwent four periods of major modification between January 1984 and February 2001, totaling almost thirty-nine months. *Columbia* also was taken out of service at other times for the installation of new equipment, or for other changes.

Timetable of *Columbia's* (OV-102) Major Modification Periods

OMM Designation	Begin OMM	End OMM	Duration	Next Flight
AA	January 25, 1984	September 11, 1985	18 months	Flight 7; STS-61C
J1	August 15, 1991	February 7, 1992	5.7 months	Flight 12; STS-50
J2	October 13, 1994	April 10, 1995	6 months	Flight 18; STS-73
J3	September 26, 1999	February 23, 2001	17 months	Flight 27; STS-109

In July 1982, *Columbia* was upgraded for the first time after completion of STS-4, the fourth and final test flight. A payload sensor processor and payload data interleaver were installed in order to carry the PAM-D (Payload Assist Module-Delta) payload during STS-5. Additionally, *Columbia*'s ejection seats were deactivated, a specialist seat was installed on the flight deck, another seat was added to the port side of the middeck, the middeck was strengthened, and parts of the developmental flight instrumentation (DFI) pallet were removed.

Columbia underwent additional changes both before and after STS-9. The first phase began when the orbiter finished STS-5 in November 1982. Most of the 152 modifications were completed so *Columbia* could carry the pressurized Spacelab scientific module. The mid-fuselage was strengthened; crew sleep stations were installed; the landing gear and brakes were modified; the remainder of the DFI pallet was removed; structural and electrical components were implemented to accommodate the Spacelab; the TPS was improved; and more mission specialist and payload seats were added.

Columbia returned from STS-9 in December 1983, and on January 25, 1984, began her first major modification, designated "AA OMM;" this modification period lasted eighteen months, ending on September 11, 1985. AA OMM was a "demodification of the orbiter from a test/development to an operational configuration."[218] The 231 modifications included the removal of the ejection seats; installation of head-up displays; upgrade to a 5.4 loads database; the installation of the new 17" disconnect valves; addition of infrastructure for the global positioning system (GPS); more brake improvements; more TPS enhancements; addition of infrastructure for manned maneuvering units; and installation of the Orbiter Experiments

[217] Gebhardt, "A Pioneer to the End."
[218] CAIB, *Report, Volume II* (Washington, DC: US Government Printing Office, 2003), 415, http://history.nasa.gov/columbia/CAIB_reportindex.html.

Program, which studied the aerodynamic and thermodynamic qualities of the orbiter. The Shuttle Entry Air Data System, or SEADS, was installed in the nose cap, the Shuttle Infrared Leeside Temperature Sensing, or SILTS, was installed in a pod on the vertical stabilizer, and the Shuttle Upper Atmospheric Mass Spectrometer, or SUMS, was installed between the nose cap and nose wheel doors.[219]

In the aftermath of the *Challenger* accident, *Columbia* received a new crew escape system, thermal protection on the chin panel, new brakes, and redesigned 17" propellant disconnects between the orbiter and the ET.[220]

Following the completion of STS-40 in June 1991, *Columbia's* eleventh mission, the orbiter was transported to Palmdale in August 1991, for its second OMM, designated J1. Before the ferry flight, part of the SILTS was removed at KSC; the remainder was removed at Palmdale. Over a period of almost six months, between August 1991 and February 1992, seventy-eight modifications were made, including several significant system changes. Upgrades made *Columbia* the first extended duration orbiter (EDO), with the capacity to fly shuttle missions of up to sixteen days plus two days of contingency. The major changes included providing the capacity to carry extra hydrogen and oxygen tanks in the cargo bay for use in generating electricity and water; installing improved equipment for handling waste onboard and for scrubbing the air of exhaled carbon dioxide; and providing extra oxygen and nitrogen for breathing air. *Columbia* had five "cryo sets" of hydrogen and oxygen tanks. A "16-day cryo-pallet" designed by Rockwell and mounted at the rear of the payload bay had the capability of carrying an additional four sets.[221]

Other advancements included new carbon brakes, the installation of new flight control computers, thermal tile upgrades to reduce preparations required between flights, improvements to the nosewheel steering and brake controls, installation of a drag chute to slow and stabilize the spacecraft on landing, and installation of improved APUs used to power the hydraulics onboard.[222] Also, the orbiter was modified to meet the 6.0 loads database requirement.

In October 1994, *Columbia* began its third major modification period, J2. For six months, concluding in April 1995, eighty modifications and 143 deferred maintenance items were completed. These included upgrades to the main landing gear door thermal barrier, the tire pressure monitoring system, and radiator drive circuitry.[223] The corrosion prone wing-leading edge spar also received attention. In all, 488 visual and X-ray structural inspections were carried out.

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[219] Jenkins, *Space Shuttle*, 435-437.
[220] Jenkins, *Space Shuttle*, 282.
[221] Kyle Herring, "Extending Duration," *Space News Roundup*, June 1, 1990, 3.
[222] James Hartsfield, "Columbia passes 32-million-mile checkup," *Space News Roundup*, February 7, 1992, 1; Boeing, *Atlantis OV-104, Volume I*, 230.
[223] Boeing, *Atlantis OV-104, Volume I*, 230.

Columbia's final major modification period (J3) at Palmdale began in September 1999 and concluded in February 2001.[224] During this seventeen-month period, OV-102 received 133 modifications, most notably the upgrade to the Multifunction Electronic Display Subsystem (MEDS) glass cockpit.[225] More than 200 miles of wiring were inspected.[226] Unlike the other orbiters, *Columbia* retained its internal airlock, so it could continue to accommodate payloads requiring a 60' cargo bay capacity.[227]

Challenger (OV-099)

Challenger (OV-099) was the second orbiter built for operational use in the SSP. It was named after both *HMS Challenger*, a nineteenth century British Naval research vessel, and the Apollo 17 lunar module. Conversion from the test article STA-099 to the flight orbiter OV-099 was initiated in Palmdale in November 1979, and completed in October 1981.[228] During this time, the major components were returned to their manufacturers for modification, and the airframe was disassembled and rebuilt. *Challenger* rolled out on June 30, 1982, and was delivered to KSC in early July 1982. At 155,400 pounds, *Challenger* was 2,889 pounds lighter than predecessor *Columbia*, despite the presence of more equipment and a stronger structure.[229] In addition, the ejection-seat area, integral to *Columbia*, was retrofitted as cabin space.[230]

During its brief service, OV-099 was associated with a number of "firsts," including the first spacewalk of the SSP (STS-6); the deployment of the first satellite in the TDRS System (STS-6); the launch of the first female American astronaut, Sally Ride (STS-7); the first to launch and land at night and the first to carry an African-American astronaut, Guion S. Bluford (STS-8); the first shuttle landing at KSC (STS-41B); the first to host a crew that included two US female astronauts (STS-41G); and the first German-dedicated Spacelab mission (STS-61A). In addition, in January 1983, *Challenger* became the only orbiter to undergo two flight readiness firings before a debut launch. The second was necessitated after a leak was detected during the first firing.[231]

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[224] Jenkins, *Space Shuttle*, 437-438.
[225] *Columbia* was the second orbiter to get the MEDS upgrade.
[226] NASA, "Columbia to Begin Third Decade in Space with Feb. 28 Liftoff," *Kennedy News*, February 14, 2002, http://www.nasa.gov/centers/kennedy/news/releases/2002/release-20020214.html.
[227] NASA KSC, "Columbia Scheduled to Depart KSC for Major Modifications in Palmdale, CA," KSC Release No. 74-99 (Florida: Kennedy Space Center, September 23, 1999), http://www-pao.ksc.nasa.gov/kscpao/release/1999/74-99.htm.
[228] Boeing, *OV-104, Volume I*, 234.
[229] Jenkins, *Space Shuttle*, 240-242.
[230] "New Orbiter Challenger at NASA Dryden," *X-Press*, July 2, 1982, 2.
[231] NASA KSC, "Space Shuttle Overview: Challenger (OV-099)," August 6, 2008, http://www.nasa.gov/centers/kennedy/shuttleoperations/orbiters/challenger-info.html.

Space Shuttle *Challenger*: Launch, Landing, and Mission Summary

SSP Flight No.	Mission No.	Orbiter/ Flight No.	Launch Date	Landing Date	Landing Site	Primary Mission/ Payload Type
6	STS-6	*Challenger* - 1	April 4, 1983	April 9, 1983	EAFB	Satellite
7	STS-7	*Challenger* - 2	June 18, 1983	June 24, 1983	EAFB	Satellite
8	STS-8	*Challenger* - 3	August 30, 1983	September 5, 1983	EAFB	Satellite
10	STS-41B	*Challenger* - 4	February 3, 1984	February 11, 1984	KSC	Satellite
11	STS-41C	*Challenger* - 5	April 6, 1984	April 13, 1984	EAFB	Satellite
13	STS-41G	*Challenger* - 6	October 5, 1984	October 13, 1984	KSC	Interplanetary probe or observatory
17	STS-51B	*Challenger* - 7	April 29, 1985	May 6, 1985	EAFB	Science
19	STS-51F	*Challenger* - 8	July 29, 1985	August 6, 1985	EAFB	Science
22	STS-61A	*Challenger* - 9	October 30, 1985	November 6, 1985	EAFB	Science
25	STS-51L	*Challenger* - 10	January 28, 1986	Lost seventy-three seconds after launch		

The April 4, 1983, inaugural launch of *Challenger* was the sixth mission (STS-6) of the SSP (Figure No. A-30). During this mission, the first TDRS was deployed. Also, *Challenger* became the first orbiter to launch in the afternoon, take off from KSC's MLP-2, and use the new lightweight tank (LWT). STS-6 marked the first EVA in SSP history when two astronauts tested new spacesuits.[232]

During STS-7 (June 1983), two satellites were deployed, and scientific experiments on metal alloys were conducted. *Challenger* returned to space two months later for STS-8, the first night launch in SSP history. An Indian satellite was deployed, and the crew tested the orbiter's ability to withstand the cold of space. *Challenger*'s nighttime landing at Edwards AFB on September 5, 1983, was the first in SSP history. *Challenger*'s fourth flight, STS-41B, began on February 3, 1984. Two satellites were deployed and two crewmembers performed the first untethered EVA. Two months later, on STS-41C, *Challenger* deployed the LDEF. Despite some difficulty, the crew also retrieved, repaired, and redeployed the Solar Max satellite.[233]

STS-41G (October 1984) carried the first seven-member crew; it also was the first flight to include two female astronauts, Mission Specialists Sally Ride and Kathryn Sullivan. Sullivan was also the first American woman to walk in space. The Earth Radiation Budget Satellite was deployed during this mission. *Challenger* launched for the seventh time in April 1985 (STS-51B). The mission was dedicated to scientific experiments. Two monkeys and twenty-four

[232] Chris Gebhardt, "1983-1986: The Missions and History of Space Shuttle Challenger," January 28, 2011, http://www.nasaspaceflight.com/2011/01/1983-1986-missions-history-space-shuttle-challenger.htm.
[233] Rumerman, *U.S. Human Spaceflight*, 40-42.

rodents were aboard for the life sciences experiments, marking the first time astronauts flew with live mammals.[234] STS-61A (October 1985) also was dedicated to scientific experiments.[235]

Challenger's final mission, STS-51L, was originally scheduled to launch on January 22, 1986. However, a number of factors, including bad weather, slipped the launch date to January 28. Temperatures the night before were below freezing, and launch was delayed two hours to inspect for ice. When *Challenger* lifted off at 11:38 a.m., the ground temperature was 36 degrees Fahrenheit (F), the lowest for a launch in SSP history by fifteen degrees. Seventy-three seconds after liftoff, the vehicle was destroyed, claiming the lives of its seven-member crew. The cause of the accident was determined to be an O-ring failure in the right SRB; the cold weather was determined to be a contributing factor.

In three years of service, *Challenger* flew ten missions, traveled 23,661,290 miles, completed 995 orbits, spent sixty-two days in space, and carried sixty crewmembers.[236]

Atlantis (OV-104)

Atlantis (OV-104), the fourth orbiter built for operational use in the SSP, was named after the marine research vessel for the Woods Hole Oceanographic Institute in Massachusetts. It was the first US vessel to be used for oceanographic research, from 1930 to 1966. Assembly of the *Atlantis* crew module began on March 3, 1980. Aft fuselage assembly started on November 23, 1981, and the wings arrived on June 13, 1983. Final assembly started on December 2, 1983, and was completed on April 10, 1984. Upon rollout on March 6, 1985, *Atlantis* weighed 154,670 pounds, almost 7,000 pounds lighter than *Columbia*.[237] The decreased weight was largely attributable to the greater use of thermal protection blankets on the upper body instead of tiles.[238] *Atlantis* left Palmdale on April 3, 1985, and arrived at KSC on April 9, 1985.

Missions

Atlantis flew thirty-three missions in twenty-six years of service, from 1985 to 2011. The landing of OV-104 on July 21, 2011, brought the operational phase of the SSP to a close. *Atlantis* is associated with a number of "firsts," including the first landing at KSC since STS-51D in 1985 (STS-38, 1990); the first RTF spacewalk (STS-37, 1991); the first docking operation with *Mir*, as well as the first mission to land with a different crew than the one at launch (STS-71, 1995); the first joint US/Russian EVA (STS-86, 1997); and the first flight with the new MEDS glass cockpit (STS-101, 2000). Other accomplishments of *Atlantis* included deployment of the

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[234] Jenkins, *Space Shuttle*, 274.
[235] Gebhardt, "Space Shuttle Challenger."
[236] NASA, *Space Shuttle Era Facts*.
[237] Boeing, *OV-104, Volume I*, 240.
[238] Boeing, *OV-104, Volume I*, 240.

Magellan and Galileo planetary probes, as well as the Compton Gamma Ray Observatory.[239] STS-135 was the first mission since RTF-2 in 2005 during which there was no contingency shuttle on the pad. *Atlantis* support missions to the ISS delivered the US laboratory *Destiny* module, the Joint Airlock *Quest*, and several sections of the integrated truss structure.

Space Shuttle *Atlantis*: Launch, Landing, and Mission Summary

SSP Flight No.	Mission No.	Orbiter/ Flight No.	Launch Date	Landing Date	Landing Site	Primary Mission / Payload Type
21	STS-51J	*Atlantis* – 1	October 3, 1985	October 7, 1985	EAFB	DoD
23	STS-61B	*Atlantis* – 2	November 26, 1985	December 3, 1985	EAFB	Satellite
27	STS-27	*Atlantis* – 3	December 2, 1988	December 6, 1988	EAFB	DoD
29	STS-30	*Atlantis* – 4	May 4, 1989	May 8, 1989	EAFB	Interplanetary probe or observatory
31	STS-34	*Atlantis* – 5	October 18, 1989	October 23, 1989	EAFB	Interplanetary probe or observatory
34	STS-36	*Atlantis* – 6	February 28, 1990	March 4, 1990	EAFB	DoD
37	STS-38	*Atlantis* – 7	November 15, 1990	November 20, 1990	KSC	DoD
39	STS-37	*Atlantis* – 8	April 5, 1991	April 11, 1991	EAFB	Interplanetary probe or observatory
42	STS-43	*Atlantis* – 9	August 2, 1991	August 11, 1991	KSC	Satellite
44	STS-44	*Atlantis* – 10	November 24, 1991	December 1, 1991	EAFB	DoD
46	STS-45	*Atlantis* – 11	March 24, 1992	April 2, 1992	KSC	Science
49	STS-46	*Atlantis* – 12	July 31, 1992	August 8, 1992	KSC	Satellite
66	STS-66	*Atlantis* – 13	November 3, 1994	November 14, 1994	EAFB	Science
69	STS-71	*Atlantis* – 14	June 27, 1995	July 7, 1995	KSC	*Mir* support
73	STS-74	*Atlantis* – 15	November 12, 1995	November 20, 1995	KSC	*Mir* support
76	STS-76	*Atlantis* – 16	March 22, 1996	March 31, 1996	EAFB	*Mir* support
79	STS-79	*Atlantis* – 17	September 16, 1996	September 26, 1996	KSC	*Mir* support
81	STS-81	*Atlantis* – 18	January 12, 1997	January 22, 1997	KSC	*Mir* support
84	STS-84	*Atlantis* – 19	May 15 , 1997	May 24, 1997	KSC	*Mir* support
87	STS-86	*Atlantis* – 20	September 25, 1997	October 6, 1997	KSC	*Mir* support
98	STS-101	*Atlantis* – 21	May 19, 2000	May 29, 2000	KSC	ISS support
99	STS-106	*Atlantis* – 22	September 8, 2000	September 20, 2000	KSC	ISS support
102	STS-98	*Atlantis* – 23	February 7, 2001	February 20, 2001	EAFB	ISS support
105	STS-104	*Atlantis* – 24	July 12, 2001	July 24, 2001	KSC	ISS support
109	STS-110	*Atlantis* – 25	April 8, 2002	April 19, 2002	KSC	ISS support
111	STS-112	*Atlantis* – 26	October 7, 2002	October 18, 2002	KSC	ISS support

[239] NASA KSC, "Space Shuttle Overview: Atlantis (OV-104)," January 20, 2012, http://www.nasa.gov/centers/kennedy/shuttleoperations/orbiters/atlantis-info.html.

SSP Flight No.	Mission No.	Orbiter/ Flight No.	Launch Date	Landing Date	Landing Site	Primary Mission / Payload Type
116	STS-115	*Atlantis* – 27	September 9, 2006	September 21, 2006	KSC	ISS support
118	STS-117	*Atlantis* – 28	June 8, 2007	June 22, 2007	EAFB	ISS support
121	STS-122	*Atlantis* – 29	February 7, 2007	February 20, 2008	KSC	ISS support
126	STS-125	*Atlantis* – 30	May 11, 2009	May 24 , 2009	EAFB	Interplanetary probe or observatory
129	STS-129	*Atlantis* – 31	November 16, 2009	November 27, 2009	KSC	ISS support
132	STS-132	*Atlantis* – 32	May 14, 2010	May 26, 2010	KSC	ISS support
135	STS-135	*Atlantis* – 33	July 8, 2011	July 21, 2011	KSC	ISS support

Atlantis' first flight, STS-51J (October 1985), carried a classified DoD payload. STS-61B, OV-104's second flight, was launched on November 26, 1985 (Figure No. A-31). At fifty-four days after the previous mission, this marked the fastest turnaround time in SSP history. Three commercial satellites were deployed. *Atlantis* did not fly again for almost three years, in the aftermath of the *Challenger* accident. During liftoff of the STS-27 mission in December 1988, *Atlantis* sustained heavy damage when a piece of the SRB insulating material damaged a wing. When the shuttle returned, after deploying a DoD payload, it was discovered that 700 tiles were damaged and one was missing.

In 1989, *Atlantis* deployed both Magellan to map Venus and Galileo to study Jupiter. OV-104 flew two more classified DoD missions, STS-36 and STS-38, in 1990. During STS-37 in 1991, *Atlantis* deployed the Compton Gamma Ray Observatory, the second piece of the Great Observatories program. Also that year, OV-104 released a commercial satellite in August (STS-43), and a DoD satellite in November (STS-44) during its tenth flight.[240]

During STS-45 (May 1992), *Atlantis* carried the first Atmospheric Laboratory for Applications and Science, created by an international partnership. STS-46, flown that summer, also was an international scientific endeavor. During STS-66, launched in November 1994, the *Atlantis* crew conducted studies of the Sun and its effects on Earth.

From 1995 to 1997, *Atlantis* flew seven of the SSP's nine missions to *Mir*. In June 1995, *Atlantis* became the first orbiter to dock with *Mir* and exchange crew members during STS-71, the 100th US space flight in history. A docking module and two solar arrays were brought to the space station as part of the STS-74 mission (November 1995), *Atlantis*' fifteenth flight. STS-76 (March 1996) marked the first time astronauts completed an EVA at two docked spacecraft. During STS-79 (September 1996), the fourth *Mir* docking mission, *Atlantis* returned astronaut Shannon Lucid back to Earth after her record-setting 188 days in orbit aboard *Mir*. Three more missions to *Mir*

[240] Rumerman, *U.S. Human Spaceflight*, 49-50.

followed for *Atlantis* in 1997, STS-81, -84, and -86. OV-104's twentieth flight, STS-86 in late 1997, included the first joint astronaut-cosmonaut spacewalk.[241]

From 2000 to 2007, *Atlantis* flew nine missions to the ISS. These usually involved the transport of supplies to the space station, a crew exchange, and construction and maintenance work. After undergoing it's second orbiter maintenance down period (OMDP)-2 in the late 1990s, *Atlantis* became the first orbiter to fly with the new MEDS glass cockpit during STS-101. The Quest airlock was transported to the ISS and installed as part of STS-104 in July 2001. In April 2002, *Atlantis* carried the S0 section of the integrated truss structure to the station during STS-110, the orbiter's twenty-fifth flight. Another section of the integrated truss structure followed later that year. After the *Columbia* accident, *Atlantis* also was the first orbiter designated as the emergency rescue vehicle during *Discovery*'s RTF. In September 2006, OV-104 carried the P3/P4 truss and solar arrays in STS-115, the first mission dedicated to construction of the ISS since the *Columbia* accident. The S3/S4 truss segment and more arrays were delivered in June 2007. *Atlantis* conveyed the *Columbus* laboratory to the ISS in February 2008.

The spacecraft's thirtieth mission, STS-125 (May 2009) was dedicated to servicing the HST for the final time. It was also planned as *Atlantis*' final flight before an OMDP.[242] However, *Atlantis* went through two minor modification periods and ended up flying three more missions, all to the ISS. The goal of STS-129 in November 2009, was to deliver spare parts to the station before the end of the SSP; *Atlantis* transported the Russian Rassvet research module during STS-132 in May 2010.[243]

STS-135 (July 2011) was not only *Atlantis*' last mission, but the final flight of the SSP.[244] Commanded by Chris Ferguson and piloted by Doug Hurley, OV-104 launched July 8, 2011, with the *Raffaello* MPLM in the payload bay. Almost six tons of supplies and equipment were delivered, maintenance work was completed, experiments were performed, and a non-functioning cooling system pump module was removed from the ISS.[245] The final wheel stop of the SSP was at 5:57 a.m. on July 21, 2011. The final return of *Atlantis* was the twentieth landing in the dark. In twenty-six years of service, *Atlantis* flew thirty-three missions, traveled 125,935,769 miles, completed 4,848 orbits, spent 307 days in space, and carried 207 crewmembers.[246]

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[241] Rumerman, *U.S. Human Spaceflight*, 58-63.
[242] Gebhardt, "After a Storied 25 Years."
[243] Chris Gebhardt, "Reaching the End: Atlantis and the Fight Against Retirement," July 4, 2011, http://www.nasaspaceflight.com/2011/07/reaching-end-atlantis-fight-against-retirement.
[244] NASA, "STS-135: The Final Voyage," July 28, 2011, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts135/main/index.html .
[245] Jay Levine, "Final Flight," *Dryden X-Press*, September 2011, 22-24.
[246] NASA, "STS-135 Mission of Space Shuttle Atlantis by the Numbers," July 21, 2011, http://www.nasa.gov/topics/shuttle_station/features/135numbers.html.

Modifications

Atlantis completed two missions before the *Challenger* accident. Subsequently, she underwent a number of modifications prior to her first flight following the accident, including the installation of a crew escape system, the addition of thermal protection on the chin panel, new brakes, and the redesigned 17" propellant disconnects between the orbiter and the ET.[247]

The first major modifications at Palmdale (OMDP-1; J1) started on October 19, 1992, and were completed on May 27, 1994. During this nineteen month period, OV-104 received 331 modifications and 184 maintenance procedures. Modifications included the installation of a drag chute and improved APUs; an upgrade to the nose wheel steering system; the addition of EDO hardware; and preparations for the installation of the orbiter docking system (ODS) for missions to *Mir*.[248] OV-104 returned to KSC on May 29, 1994.

Atlantis departed KSC on November 11, 1997, to begin OMDP-2 (J2) at Palmdale.[249] Ninety-six modifications and eighty-seven maintenance procedures were completed.[250] The most notable was the first installation of the MEDS. Other modifications included the installation of the ODS for missions to the ISS and removal of the internal airlock. Among the weight-reduction measures implemented, the AFRSI was replaced with FRSI. *Atlantis* returned to KSC on September 27, 1998.[251]

In the aftermath of the *Columbia* accident, and in accordance with the recommendations by the CAIB, *Atlantis*, *Discovery* and *Endeavour* underwent a number of major modifications, as previously described, including the addition of the orbiter boom sensor system (OBSS). In all, *Atlantis* received approximately seventy-five modifications.[252]

Endeavour (OV-105)

Endeavour (OV-105) was the fifth and last orbiter built for operational use in the SSP. The name *Endeavour* was selected from entries proposed by US schoolchildren; it was the only shuttle name suggested by the public. The name honors two crafts: the Royal Navy vessel HMS *Endeavour,* commanded by Captain James Cook, which explored the South Pacific from 1768 to 1771, and the Apollo 15 command module that traveled to the Moon in 1971.[253]

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[247] Jenkins, *Space Shuttle*, 282.
[248] James Hartsfield, "Atlantis to get California refit after next flight," *Space News Roundup,* July 10, 1992, 1, 4.
[249] Jenkins, *Space Shuttle,* 438.
[250] ACI and Weitze Research, *Roll-Up Report*, 3-11.
[251] Jenkins, *Space Shuttle*, 438.
[252] Mike Leinbach, *NASA Direct*, August 22, 2006, http://www.nasa.gov/multimedia/podcasting/115_askmission_leinbach_transcript.html.
[253] Chris Gebhardt, "Space Shuttle Endeavour: A New Beginning (Part I)," April 21, 2011, http://www.nasaspaceflight.com/2011/04/space-shuttle-endeavour-a-new-beginning-part-i/.

According to JSC's Orbiter Projects Office Manager, Richard A. Colonna, OV-105 was "built essentially to the OV-104 *Atlantis* drawings."[254] It incorporated the many modifications, upgrades and technologies that had been added to the fleet, such as the improved version of the APUs that provided power to the shuttle's hydraulic system; upgraded inertial measurement units and tactical air navigation (TACAN) systems; upgraded avionics systems that included advanced general purpose computers (GPCs); as well as the new carbon brakes.[255]

In 1983, NASA ordered spare parts including aft fuselage, midfuselage, forward fuselage, vertical stabilizer, rudder, wings, elevons, and an body flap. Rockwell International received $1.3 billion to build a new orbiter from these already assembled major structural components on July 31, 1987, and was given authority by NASA to begin construction in August 1987.[256] Final assembly began on February 2, 1988, and work was completed on July 6, 1990.[257] Upon rollout on April 25, 1991, *Endeavour* weighed 155,050 pounds, the lightest of the orbiters by 110 pounds because of more efficient manufacturing (Figure No. A-32).[258] It is the only orbiter to have been ferried directly from Palmdale to the KSC, where it was delivered on May 7, 1991. *Endeavour* started its maiden flight, STS-49, with liftoff on May 7, 1992.

Missions

Endeavour is associated with a number of "firsts," including the first three-astronaut EVA, and the first mission to feature four EVAs (STS-49, 1992); the first operational use of a drag chute (STS-47, 1992); the first flight of the SPACEHAB[259] module (STS-57, 1993); the first HST servicing mission (STS-61, 1993); the first flight with toughened uni-piece fibrous insulation (TUFI) tiles (STS-59, 1994); and the first deployment and retrieval of two satellites on the same mission (STS-69, 1995).[260] In addition, *Endeavour* marked two milestones on STS-47 in 1992, as the first orbiter to fly a Japanese astronaut, Payload Specialist, Mamoru Mohri, as well as the first female African American astronaut, Mission Specialist, Mae C. Jemison. *Endeavour* delivered the *Unity* Node, the first US component of the ISS, on STS-88 (December 1998).

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[254] "OV 105 to incorporate latest advances," *Space News Roundup*, August 22, 1986, 1.
[255] Boeing, *Orbiter Vehicle Data Pack Document: Orbiter Vehicle Endeavour (OV-105), Volume I* (Huntington Beach, California: The Boeing Company, 2011), 245.
[256] Jenkins, *Space Shuttle*, 242-243; Kyle Herring, "Endeavour assembly advances," *Space News Roundup*, June 16, 1989, 3.
[257] Boeing, *OV-105, Volume II*, 13.
[258] Boeing, *OV-105, Volume I*, 244.
[259] The commercially-developed SPACEHAB is a pressurized laboratory designed to more than double the pressurized work space for crew-tended experiments. A total of twenty-two experiments were flown, covering materials and life sciences. The first SPACEHAB module flew in 1993 aboard STS-57. Steve Siceloff, "SPACEHAB Ready for Last Mission," July 16, 2007, http://www.nasa.gov/mission_pages/shutt;e/behindscenes/lastspacehab.html; "Space Shuttle Mission Archives, STS-57," March 31, 2010, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-57.html.
[260] NASA KSC, "Space Shuttle Overview: Endeavour (OV-105)," December 8, 2008, http://www.nasa.gov/centers/kennedy/shuttleoperations/orbiters/endeavour-info.html.

Space Shuttle *Endeavour*: Launch, Landing and Mission Summary

SSP Flight No.	Mission No.	Orbiter/ Flight No.	Launch Date	Landing Date	Landing Site	Primary Mission/ Payload Type
47	STS-49	*Endeavour* - 1	May 7, 1992	May 16, 1992	EAFB	Satellite
50	STS-47	*Endeavour* - 2	September 12, 1992	September 20, 1992	KSC	Science
53	STS-54	*Endeavour* - 3	January 13, 1993	January 19, 1993	KSC	Satellite
56	STS-57	*Endeavour* - 4	June 21, 1993	July 1, 1993	KSC	Science
59	STS-61	*Endeavour* - 5	December 2, 1993	December 13, 1993	KSC	Interplanetary probe or observatory
62	STS-59	*Endeavour* - 6	April 9, 1994	April 20, 1994	EAFB	Science
65	STS-68	*Endeavour* - 7	September 30, 1994	October 11, 1994	EAFB	Science
68	STS-67	*Endeavour* - 8	March 2, 1995	March 18, 1995	EAFB	Science
71	STS-69	*Endeavour* - 9	September 7, 1995	September 18, 1995	KSC	Science
74	STS-72	*Endeavour* - 10	January 10, 1996	January 20, 1996	KSC	Satellite
77	STS-77	*Endeavour* - 11	May 19, 1996	May 29, 1996	KSC	Satellite
89	STS-89	*Endeavour* - 12	January 22, 1998	January 31, 1998	KSC	*Mir* support
93	STS-88	*Endeavour* - 13	December 4, 1998	December 15, 1998	KSC	ISS support
97	STS-99	*Endeavour* - 14	February 11, 2000	February 22, 2000	KSC	Science
101	STS-97	*Endeavour* - 15	November 30, 2000	December 11, 2000	KSC	ISS support
104	STS-100	*Endeavour* - 16	April 19, 2001	May 1, 2001	EAFB	ISS support
107	STS-108	*Endeavour* - 17	December 5, 2001	December 17, 2001	KSC	ISS support
110	STS-111	*Endeavour* - 18	June 5, 2002	June 19, 2002	EAFB	ISS support
112	STS-113	*Endeavour* - 19	November 23, 2002	December 7, 2002	KSC	ISS support
119	STS-118	*Endeavour* - 20	August 8, 2007	August 21, 2007	KSC	ISS support
122	STS-123	*Endeavour* - 21	March 11, 2008	March 26, 2008	KSC	ISS support
124	STS-126	*Endeavour* - 22	November 14, 2008	November 20, 2008	EAFB	ISS support
127	STS-127	*Endeavour* - 23	July 15, 2009	July 31, 2009	KSC	ISS support
130	STS-130	*Endeavour* - 24	February 8, 2010	February 21, 2010	KSC	ISS support
134	STS-134	*Endeavour* - 25	May 16, 2011	June 1, 2011	KSC	ISS support

Endeavour launched for the first time on May 7, 1992 (STS-49), exactly one year after arriving at KSC. It was the only orbiter in the fleet to launch its inaugural flight from LC 39B; the other four shuttles made their first liftoffs from LC 39A. The purpose of STS-49 was to retrieve, repair, and relaunch the Intelsat VI satellite. Retrieval proved to be difficult, and required both three attempts and three astronauts, the only tri-astronaut spacewalk in SSP history. The four EVAs totaled twenty-five hours and twenty-seven minutes, the longest duration spacewalks for a mission. OV-105’s landing on May 16 marked the first time a shuttle landed with the new drag chute (Figure No. A-33). At eight days, twenty-one hours, seventeen minutes, and thirty-eight seconds, it was the longest inaugural flight.[261]

Forty-four materials and life science experiments were conducted during STS-47 in September 1992. *Endeavour* deployed a satellite during STS-54 in January 1993, and experiments were conducted on X-ray radiation and microgravity. Also that year, more experiments were completed as part of STS-57, and the malfunctioning EURECA (European Retrievable Carrier) dark matter experiment was retrieved from orbit.[262]

In December 1993, *Endeavour* flew the critical first service mission to the HST. STS-61 included a record five EVAs as the crew installed a modification to overcome a manufacturing flaw that caused the HST to produce blurry images. In 1994, the study of Earth was the focus of *Endeavour*'s sixth and seventh missions. In March 1995, STS-67 was OV-105's longest mission, at sixteen days. Later in 1995 during STS-69, astronauts aboard *Endeavour* conducted studies on the Sun, among other experiments. The orbiter flew for the tenth time in January 1996 for STS-72. During STS-72 (January 1996), a Japanese satellite was retrieved, experiments were performed, and practice ISS construction spacewalks were accomplished. *Endeavour* carried the SPACEHAB module and its associated experiments into space in May of that year (STS-77). In January 1998, *Endeavour* flew her only mission to *Mir*. OV-105 returned after 7,000 pounds of supplies and experiments were unloaded, an EVA was completed, and two crew members exchanged spacecraft.[263]

In December 1998, *Endeavour* flew the first construction mission to the ISS. For STS-88, the crew connected the US-built *Unity* module to the Russian *Zarya* module. In February 2000, *Endeavour* collected 1 trillion measurements of Earth during STS-97, a mission that resulted in more detailed topographic maps of the planet.

After the mapping mission, the remaining missions flown by OV-105 were exclusively to support the ISS. These missions usually involved the conveyance of supplies to the station, maintenance work, and a crew exchange before returning to Earth. In late 2000, *Endeavour* flew her fifteenth mission, STS-97, which delivered the P6 integrated truss; it contained the ISS's first set of power-generating solar arrays. In April 2001, *Endeavour* transported tons of equipment to the ISS, including a robot arm used for assembly. In December of that year, the orbiter flew STS-108, the first SSP mission after the September 11, 2001, attacks. Amid the heightened security, the launch time was not released until twenty-four hours before the scheduled liftoff. In addition to supplies, *Endeavour* carried items commemorating the attacks, including an American flag found at Ground Zero in New York City. In addition, three crew members were exchanged. STS-111 (June 2002) was another ISS supply, maintenance, and crew exchange mission. *Endeavour*

[261] NASA, "STS-49," March 31, 2010, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/srchives/sts-49.html.
[262] Rumerman, *U.S. Human Spaceflight*, 52-53.
[263] Chris Gebhardt, "Space Shuttle Endeavour: A New Beginning (Part 1)."

hauled the 27,506-pound P1 truss to the ISS during STS-113 in November 2002. The flight marked the last time a Russian cosmonaut flew aboard a shuttle, and the landing was delayed a record three times because of weather. STS-113 was *Endeavour*'s last flight for nearly five years.

After the *Columbia* accident, *Endeavour* underwent modifications before returning to flight for STS-118 in August 2007, the orbiter's twentieth mission. Originally scheduled to be flown by *Columbia*, the mission carried supplies and the S5 truss to the ISS. The crew included NASA's first Educator Astronaut, mission Specialist, Barbara R. Morgan.[264] For the first time, a shuttle's TPS was closely examined in space after cameras on the OBSS noticed a potential problem; it turned out to be minor tile damage. The mission also marked the first use of the three-string GPS. In a March 2008 night launch, *Endeavour* carried *Kibo*, a Japanese experiments module, to the ISS during STS-123. The orbiter spent a record eleven days, twenty hours, and thirty-six minutes docked to the station. *Endeavour* left the OBSS at the station so it could be used by *Discovery* during the next mission—the only example of this occurrence. Equipment was conveyed to the ISS during STS-126 (November 2008) in preparation for the expansion of the crew from three people to six. Upon reentry into the atmosphere, *Endeavour* landed at the temporary, shorter runway at Edwards AFB, the only orbiter to touch down there. The crew of STS-127, tasked with completing installation of the *Kibo* component, conducted a record-tying five spacewalks. Thirteen people were aboard the ISS during this mission, which was the most people together in space at once. *Endeavour* transported the Node-3, used to connect other modules, and a cupola with seven windows as part of STS-130 in February 2010.[265]

OV-105 launched for the last time on May 16, 2011. STS-134 received more attention than usual because the launch was attended by US Representative Gabrielle Giffords, the wife of mission Commander Mark Kelly and survivor of an assassination attempt earlier that year.[266] The payload contained the Alpha Magnetic Spectrometer-02, a physics experiment module used to study the universe. The $2 billion spectrometer was connected to the ISS. At the completion of her sixteen-day journey, *Endeavour* landed for the last time on June 1, 2011, at KSC. OV-105 was the second orbiter to be retired.[267] In nineteen years of service, *Endeavour* flew twenty-five missions, traveled 122,883,151 miles, completed 4,671 orbits, spent 299 days in space, and carried 173 crewmembers.[268]

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[264] On July 19, 1985, Morgan was selected as the backup candidate for the NASA Teacher in Space Program, and trained with Christa McAuliffe and the *Challenger* crew. NASA JSC, "Biographical Data, Barbara Radding Morgan," July 2010, http://www.jsc.nasa.gov/Bios/htmlbios/morgan.html.
[265] Chris Gebhardt, "OV-105 Endeavour: A Long-Standing Dream Realized," April 2011, http://www.nasaspaceflight.com/2011/04/ov-105-endeavour-a-long-standing-dream-realized.
[266] "Wounded Rep. Giffords Undergoes Brain Surgery With Husband in Space," May 18, 2011, http://www.space.com/11705-gabrielle-giffords-brain-surgery.html.
[267] NASA, "STS-134 Mission Information," June 9, 2011, http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts134/main/index.html.
[268] NASA KSC, *Space Shuttle Era Facts*.

Modifications

In 1996-1997, *Endeavour* underwent her first OMDP after completion of STS-72 in May 1996; OMDP-1 was partially conducted at Palmdale and partially at KSC. Sixty-three modifications were made at Palmdale, thirty-three at KSC, and ten were shared between the two facilities. The orbiter left KSC for Palmdale on July 30, 1996, and returned on March 27, 1997. The most notable improvement was the installation of an external airlock and ODS. In addition, the AFRSI blankets on the midfuselage, aft fuselage, payload bay doors, and upper wings were replaced by the thinner and lighter FRSI blankets. Also, doublers were added to several wing spars to eliminate load restrictions.

Beginning in December 2003, *Endeavour* underwent an almost two-year OMDP-2 at KSC. One hundred and twenty-four modifications were made, including safety measures and the new MEDS "glass cockpit."[269] In addition, the first station-to-shuttle power transfer system (SSPTS) was installed, as was the 3-string GPS. About 2,000 tiles were replaced, and seventy-two tiles were added to the wing leading edges and main and landing gear doors. Furthermore, approximately 2,000 TPS blankets were replaced or repaired.[270]

IC. Orbiter Thermal Protection System Development and Testing

Introduction

A variety of TPS materials were used to protect the orbiter vehicle, mostly from the extreme heat of reentry. Among the materials applied externally to the structural skin of the orbiter were reinforced carbon-carbon (RCC), high temperature reusable surface insulation (HRSI), fibrous refractory composite insulation (FRCI), low-temperature reusable surface insulation (LRSI), advanced flexible reusable surface insulation (AFRSI), and felt reusable surface insulation (FRSI), as well as strain isolator pads (SIPs) and gap fillers. In general, the type and placement of TPS materials on the orbiter was related to temperature. A description of the TPS materials which characterized the "end-state" orbiters *Discovery*, *Atlantis*, and *Endeavour* is provided in Part IIB.

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[269] Boeing, *OV-105, Volume II*, 65; "NASA's Space Shuttle Endeavour Comes to Life," NASA News Release, October 6, 2005,
http://www.nasa.gov/home/hqnews/2005/oct/HQ_05336_Endeavour_comes_to_life.html.

[270] Laura Herridge, "STS-118 crew members proud of modified Endeavour," *Spaceport News*, August 10, 2007, 1 and 4.