Part I. HISTORICAL CONTEXT

IA. Space Shuttle Program and the International Space Station

A "new era for the US Space Program" began on February 13, 1969, when President Richard Nixon established the Space Task Group (STG). The purpose of this committee was to conduct a study to recommend a future course for the US Space Program. The STG presented three alternative long-range space plans. All included an Earth–orbiting space station, a space shuttle, and a manned Mars expedition.[1] Three years later, on January 5, 1972, the Space Shuttle Program (SSP) was initiated in a speech delivered by President Nixon. During this address, Nixon outlined the end of the Apollo era and the future of a reusable space flight vehicle providing "routine access to space." By commencing work at this time, Nixon added, "we can have the Shuttle in manned flight by 1978 and operational a short time after that."[2] Ultimately, NASA's Space Transportation System (STS), as announced by President Nixon in 1972, was one shaped by the economic realities and politics of its time.

Early Visions and Concepts

The idea of a reusable space vehicle can be traced back to 1929 when Austrian aeronautical pioneer Dr. Eugen Sänger conceptualized the development of a two-stage spacecraft capable of launching into low-Earth orbit through the use of a large aircraft booster and returning to Earth.[3] While never built, Sänger's concept vehicle, the Silverbird, served as inspiration for future work.

Shortly after World War II, the Dornberger Project, carried out by Bell Aircraft Company, developed a two-stage piggy-back orbiter/booster concept.[4] In the 1950s, rocket scientist Dr. Wernher von Braun contributed to the concept of large reusable boosters. In a series of articles that appeared in *Colliers* magazine in 1952, he proposed a fully reusable space shuttle, along with a space station, as part of a manned mission to Mars.

The conceptual origins of NASA's space shuttle began in the mid-1950s, when the Department of Defense (DoD) began to explore the feasibility of a reusable launch vehicle in space. The primary use of the vehicle was for military operations including piloted reconnaissance, anti-

[1] NASA Headquarters, *Report of the Space Task Group* (Washington, DC: NASA History Office, 1969), http://www.hq.nasa.gov/office/pao/History/taskgrp.html.
[2] Marcus Lindroos, "President Nixon's 1972 Announcement on the Space Shuttle" (Washington, DC: NASA History Office), April 14, 2000, http://history.nasa.gov/stsnixon.htm.
[3] Dennis R. Jenkins, *Space Shuttle: The History of the National Space Transportation System, The First 100 Missions* (Cape Canaveral, FL: Specialty Press, 2001); Ray A. Williamson, "Developing the Space Shuttle," in *Exploring the Unknown: Selected Documents in the History of the US Civil Space Program, Volume IV: Accessing Space,* ed. John M. Logsdon (Washington, DC: US Printing Office, 1999), 161.
[4] David Baker, "Evolution of the Space Shuttle Part 1," *Spaceflight* 15, (June 1973): 202.

satellite interception, and weapons delivery. Various concepts were explored, and in November 1958, NASA joined with the US Air Force (USAF) on the X-20 Dynamic Soaring (Dyna-Soar) project. This concept envisioned a "delta-winged glider that would take one pilot to orbit, carry out a mission, and glide back to a runway landing," boosted into orbit atop a Titan II or III missile (Figure No. A-1). However, given limited available funds and the competing priorities of other programs, the Dyna-Soar program was cancelled in December 1963.[5]

After Secretary of Defense Robert McNamara announced cancellation of the Dyna-Soar program on December 10, 1963**,** conceptual planning of a reusable space shuttle began to "solidify."[6] By the mid-1960s, NASA and the DoD were considering a spacecraft capable of carrying payloads of 20,000 pounds or more into orbit and returning them to Earth. In 1964, NASA's Manned Spacecraft Center (MSC; renamed Lyndon B. Johnson Space Center [JSC] in 1973) issued a Request for Proposal (RFP) for the study of both lifting and ballistic vehicles as logistic support craft for space stations. While the ballistic vehicle concept proved to be a dead end, MSC selected the McDonnell Douglas Astronautics Company as the contractor for the lifting systems study. These unpowered aerodynamic maneuvering vehicles, designed for a horizontal land landing, offered more operations flexibility, notably in the cross-range capability.[7]

In the wake of the cancellation of the Dyna-Soar program, the USAF began the "umbrella" START (Spacecraft Technology and Advanced Reentry Tests) Program, formed to coordinate the range of Air Force efforts dealing with lifting reentry research and development. By January 1965, START encompassed both the PRIME (Precision Recovery Including Maneuvering Entry) and ASSET (Aerothermodyamic/Elastic Structural Systems Environmental Tests) studies, later considered to be critically important to the development of the shuttle.[8] Six launches of ASSET were conducted between September 1963 and March 1965. The test firings over the Atlantic Test Range used Thor and Thor-Delta boosters. ASSET subjected a wide range of structural and thermal protection materials to "an intensely realistic test environment."[9]

PRIME was devoted to the design, development, and testing of lifting body shapes suitable for orbital reentry. The genesis for the PRIME program was the emergent lifting body design by the Martin Company of Baltimore, Maryland, a Division of the Martin Marietta Company. Since late 1960, the Air Force had Martin under contract for developing a full-scale flight-testing program

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[5] Williamson, "Developing the Space Shuttle," 162.
[6] John F. Guilmartin, Jr. and John Walker Mauer, "A Shuttle Chronology 1964---1973 Abstract Concepts to Letter Contracts," December 1988, Sweetsir Collection, Box 45E.3N1, Folder 90-16, Kennedy Space Center Archives, Florida, I-4 and I-5.
[7] Guilmartin and Mauer, "A Shuttle Chronology," I-1, I-5, and I-21. According to the DoD, cross-range capability, or the ability to move laterally during entry, was desirable so that landings could be made at locations some distance to the side of the normal entry path. In the 1960s, a major undertaking of NASA's Flight Research Center (now, Dryden Flight Research Center [DFRC]) was the study of rocket-powered lifting body vehicles, including the M2-F2, M2-F3, and HL-10.
[8] Guilmartin and Mauer, "A Shuttle Chronology," I-10, I-19, and I-28.
[9] Guilmartin and Mauer, "A Shuttle Chronology," I-10.

of a lifting reentry vehicle. Following the results of wind-tunnel tests on a variety of designs, Martin selected the SV-5 configuration, a high-volume lifting body designed by Hans Multhopp, an aerodynamicist working for Martin. The SV-5 design was refined into the SV-5D, a 34", 890-pound aluminum vehicle with an ablative heat shield.[10] The Air Force purchased four of these vehicles, which they designated the X-23A, and tested three, between December 1966 and mid-April 1967, as part of the PRIME project.[11] The tests, made over the Western Test Range (Pacific Ocean), launched from Vandenberg Air Force Base (AFB). The PRIME vehicles "achieved the first aerodynamic maneuvering reentries ever;" the third vehicle attained significant cross-range (about 2329 feet) by aerodynamic maneuvering; collectively, the nine ASSET and PRIME tests "provided a wealth of the aerothermodynamic data on which the shuttle designs were based."[12]

George Mueller, the head of the Office of Manned Space Flight (OMSF) at NASA Headquarters, believed that following Apollo, a large space station, supported by low-cost, reliable launch vehicles, was the next logical program for NASA.[13] Testifying before the Senate Space Committee on February 28, 1968, he stressed the importance of a new approach to space logistics. Later that year, in an August speech before the British Interplanetary Society, Mueller stated:

> *Essential to the continuous operation of the space shuttle will be the capability to resupply expendables as well as to change and/or augment crews and laboratory equipment . . . Our studies show that using today's hardware, the resupply cost for a year equals the original cost of the space station. . . Therefore, there is a real requirement for an efficient earth-to-orbit transportation system - an economical space shuttle . . . The shuttle ideally would be able to operate in a mode similar to that of large commercial air transports and be compatible with the environment at major airports.* [14]

According to R. Dale Reed in *Wingless Flight: The Lifting Body Story*, lifting bodies remained major contenders for the Shuttle configuration until 1969, when two events steered the design towards winged vehicles. First, the newly invented lightweight silicone tile, developed by Lockheed, could offer thermal protection for a winged vehicle with the addition of only minimum weight. Secondly, the mandate by Congress that the shuttle design satisfy Air Force as well as NASA requirements, including a large payload compartment, made winged vehicles more attractive as a shuttle candidate.[15] In actuality, the Air Force requirements for cross-range

[10] R. Dale Reed, with Darlene Lister, *Wingless Flight: The Lifting Body Story* (Washington, DC: NASA History Series, 1997), http://history.nasa.gov/SP-4220/ch7.htm.
[11] Reed, *Wingless Flight.*
[12] Guilmartin and Mauer, "A Shuttle Chronology," I-10.
[13] Jenkins, *Space Shuttle*, 77.
[14] Jenkins, *Space Shuttle*, 78.
[15] Reed, *Wingless Flight.*

capability and large payload space defined the potential shuttle configuration, as discussed below.

The definition of the Space Shuttle took shape largely between 1969 and early 1972. Feasibility and concept studies (Phase A) were succeeded by definition studies (Phase B), conducted by both NASA and industry contractors. For the contractors, these studies were carried out in an environment of changing baseline requirements. Many candidate concepts were offered, which evaluated the relative merits of straight versus delta wings; internal versus external propellant tanks; manned versus unmanned boosters; liquid versus solid propellant boosters; and sequential burn versus parallel burn solid rocket motors, among others.

Phase A: Shuttle Feasibility and Concept Studies

> *Not many people realize the impact that the Air Force requirements had on Shuttle. The 1,500-mile cross-range was something that they really wanted for the orbiter coming back in. They also wanted a larger payload bay, and some of the payload requirements were driven by them. The cross-range had a lot of impact on the configuration of the orbiter.*[16]

On May 10, 1968, NASA's MSC and the Marshall Space Flight Center (MSFC) in Huntsville, Alabama, jointly completed the scope of work (SOW) for the Integral Launch and Reentry Vehicle (ILRV) study. The contract would cover a six-month examination of several configuration concepts and operational approaches to a versatile round-trip transportation system. The SOW, based largely on work done at MSFC, demonstrated NASA's decision to pursue the goal of developing a space logistics capability; affirmed the worthiness of reusability as a means of reducing the cost of space travel; and clarified NASA's performance requirements for such a vehicle.[17]

The ILRV RFP was issued on October 30, 1968. In their shuttle chronology, Guilmartin and Mauer note that the issuance of this RFP marked the formal beginning of space shuttle design study: "the retroactive re-labeling of the ILRV study effort as Phase A of the shuttle program is clear evidence of this development."[18] The ILRV RFP was heavily influenced by three early designs developed by NASA and Air Force-supported defense contractors: the Lockheed Missile and Space Company's STAR (Space Transport and Recovery) Clipper (Star Clipper); the Convair Triamese; and the MSC in-house straight-wing shuttle design.

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[16] James B. Odom, interview by Rebecca Wright, *NASA STS Recordation Oral History Project*, July 20, 2010, 2. http://www.jsc.nasa.gov/history/oral_histories/STS-R/OdomJB/OdomJB_7-20-10.htm. Mr. Odom served on the Source Selection Board for the Space Shuttle orbiter.
[17] Guilmartin and Mauer, "A Shuttle Chronology," II-2.
[18] Guilmartin and Mauer, "A Shuttle Chronology," I-4.

Lockheed's one-and-one-half-stage[19] Star Clipper combined a deep delta lifting body orbiter with high performance liquid oxygen (LO2)/liquid hydrogen (LH2) engines fed by a jettisonable external tank. It represented the first major concept that moved part of the propellant storage to an external tank. The Convair Triamese design (Figure No. A-2) featured three externally identical elements, including two outer boosters and a central orbiter element. The payload bays of the booster elements were fitted with fuel tanks, but otherwise shared the same design as the orbital element. Each of the elements had its own primary booster engines and switchblade wings. After reentry, the two boosters returned to the launch site as conventional aircraft. The orbital element continued to orbit with its engines fed by its own internal propellant supply.[20]

The MSC in-house design was developed under the direction of Dr. Maxime A. Faget, Director of Development and Engineering. It featured a two stage, fully reusable vehicle based on a straight, fixed wing orbiter with a larger booster mated piggyback style (Figure No. A-3).[21] Faget believed that the lifting body design was not practical for the space shuttle because of the dangerously high landing speed, and other reasons. He preferred that each stage of the space shuttle be designed as a winged airplane, which would only "fly" during the landing approach. Hence, the straight wing, he concluded, was the most suitable wing design.[22] The Air Force, which preferred the delta-shaped (triangular) wing, based on its experience with supersonic fighter planes and bombers, criticized Faget's straight wing as too simple. From the Air Force perspective, the delta wing better met their needs because of its superior cross-range capability.[23] However, this wing design would require more thermal protection due to the longer reentry period, resulting in a heavier and costlier shuttle.

On January 31, 1969, NASA awarded four six-month contracts for parallel design concept studies of a low-cost, space shuttle system, to McDonnell Douglas Astronautics Company (Contract No. NAS9-9204), managed by Langley Research Center (Langley); North American Rockwell Corporation (Contract No. NAS9-9205), managed by MSC; Lockheed Missile and Space Company (Contract No. NAS9-9206), managed by MSFC; and General Dynamics Corporation/Convair (Contract No. NAS9-9207), managed by MSFC.[24] The ILRV studies began with consideration of a broad range of concepts, including expendable stages and ballistic and semi-ballistic spacecraft. McDonnell Douglas, for example, originally studied a baseline design in detail, plus several alternate systems, corresponding to alternate payloads (size and weight).

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[19] One-and-one-half-stage design refers to any element of primary boost propulsion system which drops off a stage before the stage itself is expended. For example, the stage which drops off could be one with strap-on solid boosters, or a jettisonable external tank, or both. Guilmartin and Mauer, "A Shuttle Chronology," I-15.
[20] "Triamese," *Encyclopedia Astronautica*, http://www.astronautix.com/lvs/triamese.htm.
[21] Guilmartin and Mauer, "A Shuttle Chronology," I-12.
[22] T.A. Heppenheimer, *History of the Space Shuttle*, vol. 1, *The Space Shuttle Decision: NASA's Search for a Reusable Space Vehicle* (Washington, DC: Smithsonian Institution Press, 2002), 207-209.
[23] Heppenheimer, *The Space Shuttle Decision*, 210, 213.
[24] Linda Neuman Ezell, *NASA Historical Databook Volume III Programs and Projects 1969-1978* (Washington, DC: NASA History Office, 1988), 121-124, table 2-57, http://history.nasa.gov/SP-4012/vol3/sp4012v3.htm; Jenkins, *Space Shuttle*, 79; Williamson, "Developing the Space Shuttle," 164.

Then, beginning in February 1969, the company examined a reusable spacecraft launched by expendable boosters, as well as a stage-and-one-half concept.

The first two months of the ILRV study convinced NASA that a fully reusable, two-stage vehicle was the preferred shuttle configuration. Consequently, at the end of March 1969, the contractors were directed to study a fully reusable shuttle. Two months later, NASA, in conjunction with the Air Force, decided to raise the payload requirement to 50,000 pounds with a volume of 10,000 cubic feet or more (that is, the internal volume of a 15' x 60' cylindrical payload bay). This represented a fundamental change in the definition of payload.[25]

A few months after initiation of the ILRV contractor studies, on April 21, 1969, George Mueller selected LeRoy E. Day to head the MSC's Space Shuttle Task Group (SSTG). The immediate purpose of the SSTG was to provide material for a report on the space shuttle to President Nixon's STG. The SSTG held its first meeting on April 24. Mueller stressed the relationship between the Shuttle and space station, and emphasized that the provision of logistic support to the space station was the prime justification for the Space Shuttle.[26]

On June 12, 1969, the SSTG released a five-volume report, which identified five criteria as the "space shuttle baseline vehicle requirements." These requirements, developed in cooperation with the DoD, included a 50,000-pound payload, a crew of two, a 10,000-cubic foot internal payload volume (15' x 60'), a 270-nautical mile orbit at 55-degree orbital inclination, and a seven day mission duration. As a result of this new development, on June 20, 1969, NASA redirected the contractors' Phase A studies. North American Rockwell, originally tasked with examining an expendable booster, was now directed to study Faget's straight-wing concept. McDonnell Douglas, originally focused on the stage-and-one-half design, switched to a two-stage, fully reusable configuration featuring orbiter designs derived from the HL-10 lifting body vehicle (Figure No. A-4); thirteen configurations were studied.[27] Lockheed continued their studies of the Star Clipper and its own version of the Triamese designs, while General Dynamics examined variants of the Triamese concept and a fully reusable concept with two elements. Each of the four contractors received a supplementary payment of $150,000 for the study extension. McDonnell Douglas received an additional $225,000 to cover an in-depth study of the two-stage fully reusable concept.[28]

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[25] Guilmartin and Mauer, "A Shuttle Chronology," II-5.
[26] Guilmartin and Mauer, "A Shuttle Chronology," II-31.
[27] The HL-10, a NASA design, was one of five vehicles used in DFRC's Lifting Body Research Program. It was flown thirty-seven times, and logged the highest altitude and fastest speed in the program. The other four wingless lifting body vehicles in the program were the M2-F2, the M2-F3, the X-24A, and the X-24B. NASA DFRC, *HL-10 Lifting Body*, Fact Sheets (California: Dryden Flight Research Center, 2009). http://www.nasa.gov/centers/dryden/news/FactSheets/FS-010-DFRC.html.
[28] Heppenheimer, *The Space Shuttle Decision*, 218.

After the decision to drop the partially reusable designs was made at a meeting of shuttle managers on August 6, NASA would consider only fully reusable concepts. As summarized by Heppenheimer:

> *Partially-reusable designs had represented an effort to meet economic goals by seeking a shuttle that would cost less to develop than a fully-reusable system, even while imposing higher costs per flight. This approach had held promise prior to the spring of 1969, when the shuttle had been considered largely as a means of providing space station logistics. Now its intended uses were broadening to include launches of automated spacecraft which meant it might fly more often. The low cost per flight of a fully-reusable now made it more attractive, and encouraged NASA to accept its higher development cost.*[29]

The ILRV contractors submitted their final Phase A study reports in December 1969.[30] In the executive summary to their three-volume report, McDonnell Douglas stated that the objective of study was "to provide verification of the feasibility and effectiveness of the MSC in-house studies and provide design improvements, to increase the depth of engineering analyses and to define a development approach."[31] The McDonnell Douglas study emphasized a two stage to orbit reusable spacecraft system. The upper stage orbiter was a 107' HL-10 configuration, modified slightly in the base area to accommodate the two booster engines. The launch propellant tanks were integral with the primary body structure. The carrier was a 195' clipped delta configuration with ten launch engines identical to those of the orbiter. A dual lobed cylindrical launch propellant tank formed the primary body structure. A 15 percent thick delta wing was incorporated, which contained the landing gear, air-breathing engines, and propellant.[32]

NASA also received a report from the Martin Marietta Corporation on December 1. This study, unfunded by NASA, used the ILRV study guidelines and was coordinated with the SSTG. The study featured the Spacemaster vehicle, a two-stage, fully reusable vehicle featuring a twin-fuselage catamaran booster and delta-winged orbiter situated between the booster fuselages.[33]

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[29] Heppenheimer, *The Space Shuttle Decision*, 218-219.

[30] North American Rockwell Space Division, *Study of Integral Launch and Reentry Vehicle System, Final Report,* Volume I, Summary Report – Second Phase, December 1969, Sweetsir Collection, Accession No. N70-31832, Kennedy Space Center Archives, Florida; Lockheed Missiles & Space Company, *Final Report Integral Launch and Reentry Vehicle*, LMSC-A959837, December 22, 1969, Sweetsir Collection, Accession No. X70-13624, Kennedy Space Center Archives, Florida; McDonnell Douglas Corporation, *A Two-Stage Fixed Wing Space Transportation System, Final Report*, Volume I Condensed Summary, December 15, 1969, i, Sweetsir Collection, Accession No. N70-31597, Kennedy Space Center Archives, Florida.

[31] McDonnell Douglas Corporation, *A Two-Stage System*, i.

[32] McDonnell Douglas Astronautics Company, *Integral Launch and Reentry Vehicle System*, Executive Summary, Contract NAS9-9204, Report No. MDC E0049, November 1969, Sweetsir Collection, Kennedy Space Center Archives, Florida.

[33] Martin Marietta Corporation, Denver Division, *Spacemaster A Two-Stage Fully Reusable Space Transportation System. Phase A Final Report*, M-69-36, December 1969, Sweetsir Collection, Accession No. N70-74750, Kennedy

On December 10, 1969, a joint NASA-DoD Space Shuttle Task Group submitted a "Summary Report of Recoverable versus Expendable Booster Space Shuttle Studies," in which the group recommended a fully reusable system.[34] Thus, at the completion of Phase A studies, NASA's plan was to develop a STS based on a fully reusable two-stage shuttle. Both the booster and orbiter stages would be rocket-powered, burning hydrogen and oxygen carried in internal fuel tanks. "After launch, the booster would fly back to the launch site for a horizontal landing and be refurbished for the next flight. The orbital stage would proceed to orbit and, upon completing its mission, return to Earth and land horizontally. The projected development cost for this configuration was $5.2 billion."[35] Dr. Faget presented this shuttle configuration concept to a meeting of the American Institute of Aeronautics and Astronautics in California in late 1969.

Phase B: Shuttle Definition Studies

The Phase A studies had demonstrated the "technical feasibility and the economic benefits of the space shuttle."[36] As a next step, prior to the submittal of final Phase A study reports, NASA initiated a Phase B definition program which included the preliminary design of a fully reusable two-stage space shuttle vehicle. A joint Air Force and NASA Design Criteria Review identified evaluation criteria and established baseline systems characteristics for Phase B space shuttle development in October 1969. At this time, the shuttle requirements included a payload capacity of 25,000 pounds, a 240 nautical mile, 55-degree orbit, and a 200 to 1,500 nautical mile cross-range capability. Both straight winged and delta winged designs were to be studied.[37]

The SOW for Phase B space shuttle definition studies, released by the OMSF in October 1969, defined the preliminary design and planning effort. It also included all system elements for the space shuttle configuration, and the identification of "all appropriate interfaces between the booster and the orbiter such that separate phase C contracts could be let if desired."[38] Two months later, NASA established the Phase B Source Evaluation Board.[39]

NASA issued the RFP for Phase B definition studies on February 18, 1970, with proposals due on March 30. Following the evaluation of proposals, on May 12, 1970, NASA selected two firms

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Space Center Archives, Florida.
[34] Ezell, *Databook Volume III*, 121-124, table 2-57.
[35] US House, Committee on Science and Technology, Subcommittee on Space Science and Applications, *United States Civilian Space Programs, 1958-1978* (Washington, DC: US Government Printing Office, 1981), 451.
[36] L.E. Day, "The Space Shuttle A New Approach to Space transportation," paper presented at the XXIst International Astronautical Congress, Constance, German Federal Republic, October 9, 1970, 5, Marshall Space Flight Center History Office, Alabama.
[37] US House, *United States Civilian Space Programs*, 452.
[38] NASA Office of Manned Space Flight, *Statement of Work, Space Shuttle System Program Definition (Phase B)* (Huntsville, AL: MSFC History Office, October 1969), 2.
[39] Jessie E. Whalen and Sarah L. McKinley, "Chronology: MSFC Space Shuttle Program, Development, Assembly, and Testing Major Events (1969-April 1981)," (Huntsville, AL: George C. Marshall Space Flight Center, Management Operations Office, December 1988), 3.
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19910005807_1991005807.pdf.

for negotiation leading to eleven-month, $8 million fixed-price contracts for parallel studies.[40] NASA awarded Phase B contracts to McDonnell Douglas (teamed with Martin Marietta; Contract No. NAS9-26016) and to North American Rockwell (teamed with General Dynamics; Contract No. NAS8-10960).[41] MSFC was to manage the McDonnell Douglas contract, and MSC was to oversee the North American Rockwell work. Each contractor was tasked with studying two designs in parallel: one for an orbiter with a cross-range of 200 nautical miles, and the other for a cross-range of 1500 nautical miles.[42] In a presentation before the International Astronautical Congress in October 1970, Leroy E. Day reported that the Phase B studies, scheduled to be completed by June 1971, "will provide data which will define the program in terms of vehicle design, the cost and schedule of such a program and identify critical technology requirements."[43]

The booster portion of the shuttle initially developed by North American Rockwell was a manned, powered, fly-back vehicle. Propulsion systems for the baseline design included twelve main engines, twenty-two altitude control thrusters, and four thrust air-breathing engines. The flight deck was designed to hold a two-man flight crew.[44] Both McDonnell Douglas and North American Rockwell proposed a fully reusable orbiter carrying all propellant tankage within the fuselage. The designs, however, differed in regard to the thermal protection system. McDonnell Douglas favored hot structures "with insulation to protect the underlying framework and temperature-resistant metal panels facing the heat of reentry."[45] North American Rockwell proposed using thermally protective tiles applied directly to the titanium skin of the airframe, with the exception of the upper wing surfaces, upper fuselage, nose, wing leading edges, and vertical fin.[46]

In January 1971, NASA rewrote the shuttle specifications to include a delta-winged orbiter with a 1,500 nautical mile cross-range capability and the ability to put a 65,000-pound payload into a 100 nautical mile due east orbit, 40,000 pounds into polar orbit, and 25,000 pounds into a 277 nautical mile, 55-degree orbit. The estimated development cost for this configuration was about $9.9 billion. In the face of budget cutbacks, NASA was uncertain whether this configuration could move forward. In March 1971, NASA instructed McDonnell Douglas and North American Rockwell to develop variants of their configurations to include external, expendable LH2 tanks.[47] NASA began the study of alternate booster concepts "to achieve a less expensive design for the shuttle."[48] Mid-1971 marked the beginning of change to "the entire approach," as the "economics of annual funding rates would play a key role in designing the final configuration."[49]

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[40] Whalen and McKinley, "Chronology," 5.
[41] Baker, "Evolution of the Space Shuttle Part 1," 203.
[42] Heppenheimer, *The Space Shuttle Decision*, 224.
[43] L.E. Day, "The Space Shuttle," 21.
[44] Baker, "Evolution of the Space Shuttle Part 1," 209-210.
[45] Heppenheimer, *The Space Shuttle Decision*, 333.
[46] Heppenheimer, *The Space Shuttle Decision*, 335.
[47] Heppenheimer, *The Space Shuttle Decision*, 338.
[48] US House, *United States Civilian Space Programs*, 452.
[49] David Baker, "Evolution of the Space Shuttle, North American Rockwell – Part 2." *Spaceflight* 15, (July 1973):

Both North American Rockwell and McDonnell Douglas released their Space Shuttle Phase B Final Reports in June 1971. However, the following month, NASA awarded four-month contract extensions, from July 1 to October 30, 1971, to each contractor. A second extension added four additional months, through February 1972, with the option for a further extension to April 30, 1972. McDonnell Douglas examined external hydrogen and oxygen tankage for the orbiter, interim expendable boosters, various system concepts, and a "relaxation of specific requirements," including reduced payload weights associated with the interim expendable boosters. The most significant changes were those associated with accommodating low-cost recoverable and reusable booster concepts.[50] The booster concepts of both McDonnell Douglas and North American Rockwell proposed large and heavy vehicles, each with twelve space shuttle main engines and either ten turbojets or twelve jet engines, respectively, for flyback to the launch site.[51]

In addition, "Phase A Extension" contracts were awarded to Grumman/Boeing and to Lockheed Missiles and Space Company to study a phased approach to shuttle design and the use of liquid or solid propellant boosters for interim capability.[52] NASA also provided extensions to these parallel Phase A study contracts. While the Phase A and Phase B studies initially proceeded independently of each other, after time these efforts began to overlap, particularly in regard to the external orbiter fuel tankage. When the shuttle specifications were rewritten in January 1971, as described previously, NASA directed that both Phase A and Phase B studies use the same performance criteria.

Alternate Concept Studies

Shortly after North American Rockwell and McDonnell Douglas started the Phase B studies, on June 15, 1970, NASA selected Grumman (teamed with Boeing; Contract No. NAS9-11160), Lockheed (Contract No. NAS8-26362), and Chrysler (Contract No. NAS8-26241) to conduct eleven-month feasibility studies ("Extended Phase A" studies) on alternate shuttle design concepts. The objective of these studies was to answer the basic question of whether there was a lower cost shuttle option than the two-stage fully reusable system. The alternate concept studies proceeded concurrently with both shuttle Phase A and Phase B studies, and generally served to influence design concepts and philosophies.[53]

The examination of alternative concepts focused on a partially reusable configuration with propellant carried in expendable tanks. The shift from a fully reusable to partially reusable configuration reflected NASA's pragmatism in the face of funding obstacles. While NASA's intended goal for the STS was to provide a low cost capability "for delivering payloads of men,

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[50] McDonnell Douglas Corporation, *Phase B System Study Extension Final Report*, 1-2.
[51] Heppenheimer, *The Space Shuttle Decision*, 346.
[52] David Baker, "A Chronology of the Space Shuttle." *Spaceflight* 15, (June 1973): 214.
[53] US House, *United States Civilian Space Programs*, 452.

equipment, supplies, and other spacecraft to and from space," the ultimate goal was to develop a permanent manned space station.[54] However, to secure program approval, NASA had to meet its commitment to the US Government Office of Management and Budget (OMB) to make access to space more economical. One key strategy was getting support from the DoD.[55] Among the Air Force requirements for the shuttle were that it was powerful enough to accommodate large payloads such as classified satellites, and the ability to fly often and on short notice.[56] Ultimately, in an effort to overcome congressional opposition to the shuttle program, and to reduce costs in the face of continued federal budget cuts, NASA chose a partially rather than a fully reusable shuttle design, with the support of the Air Force.

Grumman/Boeing was awarded a $4 million contract to evaluate a stage-and-one-half shuttle with expendable propellant tanks, a reusable orbiter with expendable booster, and a reusable booster and solid propellant auxiliary boosters. This contract was managed by MSC. Lockheed received a $1 million contract to study an expendable tank orbiter, and Chrysler was awarded a $750,000 contract to study a single-stage reusable orbiter. Both of these contracts were managed by MSFC.

The study of alternate space shuttle concepts initiated by Grumman/Boeing started with twenty-nine configurations in three general concept categories, which included:

- stage-and-one-half with and without thrust augmentation (e.g., strap-on solid rocket motors; cryogenic or hypergolic strap-on propulsion packages);
- expendable booster with reusable orbiter; and
- two-stage reusable orbiter and booster systems with several approaches.

During the five-month study, all but four of the initial twenty-nine configurations were eliminated. The four that remained were studied and evaluated in detail. These included:

- a stage-and-one-half orbiter with solid rocket thrust augmentation;
- a two-stage solid rocket expendable booster; and
- a two-stage fully reusable system, both with and without a phased development option (which involved several years of low flight rate operation using a modified S-1C booster).

The study results through December 15, 1970, were presented in a mid-term report, dated December 31, 1970. In this document, the Grumman/Boeing team concluded that the two-stage fully reusable system (reusable orbiter/booster concept) without phased development offered the

[54] Jenkins, *Space Shuttle*, 99.
[55] Jenkins, *Space Shuttle*, 99.
[56] David M. Harland, *The Story of the Space Shuttle* (Chichester, UK: Praxis Publishing, 2004), 5.

lowest cost per flight operation, the lowest total program cost, and the fewest operational restrictions.[57]

In parallel with these studies, in the fall of 1970, Grumman investigated other possible design concepts. The most promising approach used expendable external tanks; this concept was presented to MSC in November 1970.[58] Subsequently, NASA directed the Grumman/Boeing team to conduct parallel studies of reusable two stage configurations employing internally and externally mounted orbiter hydrogen tanks; these studies were conducted as the second phase of the alternate concepts study, performed under Contract Change Modification 5C to Contract NAS9-11160. Following review by NASA in March and April 1971, the Grumman/Boeing team was authorized to study a three-engine, external hydrogen tank orbiter in conjunction with the heat sink booster, referred to as the H-33 configuration.[59]

Grumman released their *Alternate Space Shuttle Concepts Study Final Report* on July 6, 1971. Subsequently, under the four-month extension to its Alternate Space Shuttle Concepts Study, between July and November 1971, the Grumman/Boeing team investigated "potentially cost-attractive programmatic and technical alternatives."[60] These alternatives included a phased approach involving orbiter development and operation with an expendable booster for an interim period, as well as design variations to the basic vehicle. On March 15, 1972, Grumman/Boeing submitted its *Phase B Extension Final Report* (Contract No. NAS9-11160).[61]

Lockheed Missiles and Space Company began a four-month study under an extension of the Phase A Alternate Space Shuttle concepts contract (Contract No. NAS8-26362) on July 1, 1971. The study entailed examination and analysis of a two-and-one-half-stage, stage-and-one-half, and solid rocket motor (SRM) interim booster systems "for the purpose of establishing feasibility, performance, costs, and schedules for these systems concepts."[62] In mid-September, NASA directed Lockheed to concentrate orbiter analysis work on an external tank delta-wing orbiter configuration launched on either a reusable LO2/RP-fueled booster or a reusable

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[57] Grumman Aerospace Corporation, *Alternate Space Shuttle Concepts Mid-Term Report, Volume I – Executive Summary* (Huntsville, AL: Marshall Space Flight Center History Office, December 31, 1970); Grumman Aerospace Corporation, *Alternate Space Shuttle Concepts Study Final Report, Part I Executive Summary* (Huntsville, AL: Marshall Space Flight Center History Office, July 6, 1971), viii.
[58] Grumman Aerospace Corporation, *Alternate Space Shuttle Concepts*, 1-1.
[59] Grumman Aerospace Corporation, *Alternate Space Shuttle Concepts*, 1-2, 2-1. The H-33 configuration was compared with the Phase B design with internal liquid hydrogen tanks in the orbiter and a conventional booster design, referred to as the G-3 configuration.
[60] Grumman Aerospace Corporation, *Alternate Space Shuttle Concepts Study, Design Requirements and Phased Programs Evaluation, Midterm Review*, September 1, 1971, Sweetsir Collection, Accession No. N73-17877, Kennedy Space Center Archives, Florida.
[61] Grumman Aerospace Corporation, *Space Shuttle System Program Definition Phase B Extension Final Report,* March 15, 1972, Sweetsir Collection, Accession No. T72-12483, Kennedy Space Center Archives, Florida.
[62] Lockheed Missiles and Space Company, *Final Report Alternate Concepts Study Extension, Volume I Executive Summary*, November 15, 1971, iii, Sweetsir Collection, Accession No. N73-30844, Kennedy Space Center Archives, Florida.

pressure-fed ballistic booster. Work was to continue at a low level on the stage-and-one-half system and the Lockheed-recommended SRM booster. Lockheed submitted the *Final Report for the Alternate Space Shuttle Concepts Study* on June 4, 1971, and the *Alternate Concepts Study Extension Final Report* on November 15, 1971.

Also in 1971, as part of the alternate concept studies, Project SERV (Single-stage Earth-orbital Reusable Vehicle) was carried out by the Chrysler Corporation Space Division under Contract NAS8-26341. The purpose of this study was to evaluate the potential of SERV as the boost element of a candidate STS. Five technical areas affecting concept feasibility were studied, including engine performance, aerodynamic characteristics, thermal protection, subsystem weights, and the landing methods. Chrysler was supported by subcontractors North American Rockwell Corporation, Rocketdyne Division for design of the SERV aerospike engine, as well as AVCO Systems Division, for design and cost data for thermal protection systems.[63]

Concurrent with the contractor efforts, MSC continued in-house studies. Faget examined designs with expendable tanks, and in May 1971, debuted design MSC-023, which featured an orbiter with delta wings, a 15' x 60' cargo bay, and all propellants carried in a single large underbelly tank. "Here, for the first time, was the outline of a shuttle orbiter that would actually be built."[64] The following month, Faget released MSC-037, a variant with three main engines and a 40,000 pound payload. Lockheed, McDonnell Douglas, and North American Rockwell strongly endorsed this design.[65]

A radically transformed shuttle design configuration emerged, much unlike the vehicle conceived at the outset of Phase B. Further studies in Phase B showed that savings could result if both the oxygen and hydrogen tanks were carried outside the orbiter, thus permitting a reduction in the size of the orbiter.[66] In May 1971, NASA decided in favor of placing the propellant tanks outside the orbiter; hence, the "external" tank. The partially reusable design with external propellant tank and a delta-wing orbiter was about half the manufacture cost of a fully reusable vehicle. It also enhanced the aerodynamics of the orbiter and increased its safety.

By July 1971, NASA Administrator James C. Fletcher said that the preferred configuration emerging from the contractor studies, then nearing completion, was "a two-stage delta-wing reusable system in which the orbiter has external propellant tanks that can be jettisoned."[67] The

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[63] Chrysler Corporation Space Division, *Single-stage Earth-orbital Reusable Vehicle*. *Space Shuttle Feasibility Study, Final Report on Project*, Volume I, June 30, 1971, iii, Sweetsir Collection, Kennedy Space Center Archives, Florida.
[64] Heppenheimer, *The Space Shuttle Decision*, 344.
[65] In September 1971, North American Rockwell presented its own version of the MSC-037, and subsequently, NASA instructed the contractors to adopt a variant, the MSC-040, as a basis for comparison with their on-going studies. Heppenheimer, *The Space Shuttle Decision*, 344-346.
[66] David Baker, "Evolution of the Space Shuttle – North American Rockwell, Part 3," *Spaceflight* 15, (September 1973): 344.
[67] "NASA studies a new approach to developing Space Shuttle system," *Roundup*, July 2, 1971, 1.

external tank would be the only non-reusable part of the STS. NASA adopted an external LO2/LH2 tank for the baseline orbiter in August 1971.

The Final Configuration

More than twenty-nine different shuttle designs were analyzed in 1971 before NASA announced the final shuttle configuration on March 15, 1972.[68] When the decision to proceed with the development of the shuttle system was announced by President Nixon in January 1972, NASA was still studying both solid and liquid-propellant booster alternatives. However, by March, the booster question had been resolved. The fly-back booster was officially abandoned. Two solid propellant boosters would flank the LO2/LH2 tank used by the delta-winged orbiter. The booster stage would be powered by SRMs in a parallel burn configuration.[69] NASA's booster studies had shown that both solid and liquid propellant configurations would have been feasible from a technical perspective. The decision was based on the lower cost and lower technical risks shown in the studies for the solid rocket system.[70]

As NASA explained in its "Space Shuttle Fact Sheet," "the evolution to the present simpler concept resulted from in-depth studies for each of several candidate concepts, or development risk and cost in relation to the operational suitability and overall economics of the entire system."[71] The decision to use recoverable and reusable boosters with solid propellant rocket motors was based on the lower development cost ($5.15 billion), the "least capital risk per flight, and lowest technical risk of development." Compared with liquid boosters, NASA estimated that the development costs of the solid rocket motor boosters would be about $700 million lower.[72]

Launch Site Selection

Concurrent with the shuttle design studies, NASA conducted a search for a shuttle launch and recovery site. By 1970, NASA received over 100 unsolicited bids from across the US, and choosing a launch site had become a political issue. To facilitate the selection process, the Ralph M. Parsons Company of Los Angeles, California, was awarded a $380,000 contract to review potential locations. Also, a fourteen-member Space Shuttle Facilities Group was established to select the final site. After nearly a year of study, on April 14, 1972, NASA announced the selection of the John F. Kennedy Space Center (KSC) in Florida (Figure No. A-5), and Vandenberg AFB in California (Figure No. A-6), as the two launching sites.[73] Numerous variables, such as booster recovery, launch azimuth limitations, latitude and altitude effects on

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[68] Williamson, "Developing the Space Shuttle," 167, 172
[69] "Boost Stage To Be Solid Propellant," *Roundup*, March 17, 1972: 1; David Baker, "Evolution of the Space Shuttle, North American Rockwell – Part 3," *Spaceflight* 15, (September 1973): 350.
[70] NASA KSC, "Space Shuttle Decisions," NASA News Release No. KSC-60-72, March 15, 1972, Sweetsir Collection, Box 67D.6, Folder 12, Kennedy Space Center Archives, Florida.
[71] NASA, "Space Shuttle Fact Sheet," October 1972, Marshall Space Flight Center History Office, 2.
[72] NASA, Space Shuttle Fact Sheet," 2-4.
[73] Ezell, *NASA Historical Databook Volume III,* 121-124, table 2-57.

launch, and impact on present and future programs were taken into account by NASA. The fact that NASA had already invested over $1 billion in launch facilities at KSC made it a logical choice. KSC would be used for easterly launches, accounting for most missions. North-south polar orbits from KSC, however, would have been a safety risk to South Florida, the northeast US, Mexico, and Canada. They also would have flown over Cuba. Therefore, Vandenberg was to launch spacecraft for operational missions requiring high inclination, desired for military satellite deployments.[74]

Like KSC, where existing facilities could be modified and reused, the Vandenberg Launch Site (VLS) already housed a launch and landing site, Space Launch Complex Six (SLC-6), built for the Manned Orbiting Laboratory Program, which was cancelled in 1969.[75] Though smaller than KSC, the Vandenberg complex, divided between South Base and North Base, included all the buildings and structures necessary to launch, process, modify, and land an orbiter. *Discovery* was to be stationed there, primarily dedicated to DoD missions.

Center Responsibilities and Contractor Awards

In June 1971, the OMSF announced that the MSC would be the lead center for shuttle program management, overall engineering and systems integration, and basic performance requirements for the shuttle, as well as for development and testing of the orbiter.[76] MSFC was responsible for development of the space shuttle main engine (SSME), the solid rocket boosters (SRBs), the external tank (ET), and for all propulsion-related tasks. Engineering design support continued at MSC, MSFC, and Langley,[77] and engine tests were to be performed at NASA's Mississippi National Space Technology Laboratories; later named Stennis Space Center, and at the Air Force's Rocket Propulsion Laboratory in California, the Santa Susana Field Laboratory. KSC, responsible for designing the launch and recovery facilities, was to develop methods for shuttle assembly, checkout, and launch operations.[78]

On January 5, 1972, President Nixon instructed NASA to proceed with the design and building of a partially reusable Space Shuttle consisting of a reusable orbiter, three reusable main engines, two reusable SRBs, and one non-reusable ET. NASA's administrators vowed that the shuttle would fly at least fifty times a year, making space travel economical and safe.

In March 1972, NASA issued an RFP for development of a space shuttle. Technical proposals were due by May 12, 1972, with cost proposals due one week later. In its instructions, NASA noted that:

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[74] Jenkins, *Space Shuttle*, 155.
[75] Jenkins, *Space Shuttle,* 155.
[76] "Agency gets Go-ahead to Develop Shuttle," *Roundup,* January 7, 1972, 1.
[77] Jenkins, *Space Shuttle*, 122.
[78] Ezell, *NASA Historical Databook Volume III,* 121-124, table 2-57; Williamson, "Developing the Space Shuttle," 172-174.

> *The primary objective of the Space Shuttle Program is to provide a new space transportation capability that will (a) reduce substantially the cost of space operations, and (b) provide a capability designed to support a wide range of scientific, defense and commercial uses.*

Proposals were submitted by four major aerospace corporations, all of which had participated in the earlier definition studies. The Air Force, a prospective major user of the Space Shuttle, participated in the contractor selection process. The Space Division of North American Rockwell Corporation of Downey, California, was selected as the prime contractor responsible for design, development, and production of the orbiter vehicle and for integration of all elements of the Space Shuttle system. The contract was valued at $2.6 billion over a period of six years.

In July 1971, NASA's MSFC announced that Rocketdyne had been selected to design and manufacture the SSMEs.[79] The contract was confirmed in May 1972. Other contract awards followed. In August 1973, the Martin Marietta Corporation was selected to design, develop, and test the ET, with tank assembly taking place at NASA's Michoud Assembly Facility near New Orleans, Louisiana. Also in 1973, a contract covering SRM development for the SRB was awarded to Thiokol Chemical Company (now ATK Thiokol Propulsion) of Utah.

A seven-year development period was planned, resulting in full operational activities beginning in mid-1979. However, the shuttle development program formally took nine years. In a seeming prediction of future events, in 1971, David Baker noted that ". . . it is likely that shuttle development will stretch considerably beyond the predicted schedule. It can be expected that the integration of shuttle development with relatively static NASA budgets will spread the initial date of operations out to the 1981-83 period at least."[80]

The $246 billion 1973 fiscal year (FY) budget sent to Congress by President Nixon included $3.379 billion for NASA, or roughly 1.3 percent of the total budget. This request included $200 million for Space Shuttle development. At this time, the total development costs were expected to be roughly $5.5 billion with an operational system in place by the end of the decade. Thirty to forty launches per year were assumed. While specific funding for the Shuttle did not begin until 1974, by 1973 NASA already had moved from the planning and study stage to design and production.[81]

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[79] Ezell, *NASA Historical Databook Volume III,* 121-124, table 2-57.
[80] David Baker, "A Schedule for the Shuttle," *Spaceflight* 13, (December 1971): 454.
[81] Henry C. Dethloff, "The Space Shuttle's First Flight: STS-1," in *From Engineering Science to Big Science: The NASA and NASA Collier Trophy Research Project Winners,* ed. Pamela E. Mack, (Washington, DC: US Government Printing Office, 1998), 289.

Between 1973 and 1977, several discrete system designs were adopted, tested, modified, or deleted. The earliest tests of SSME principal components began in August 1973,[82] ET component testing started in 1974, and tests on the SRB components began in 1976. Wind tunnel tests on integrated shuttle components were started by 1977. Descriptions of the development and test programs for the major propulsion elements are contained in the separate sections addressing the Space Shuttle Main Engines, External Tank, and Solid Rocket Booster/Reusuable Solid Rocket Motors (Parts III, IV, and V, respectively).

Orbiter Prototype Enterprise

Rockwell International began structural assembly of the orbiter prototype, orbiter vehicle (OV)-101 in early 1975; the vehicle originally was intended to be rebuilt into a flight-capable orbiter. Although incapable of space flight, OV-101 reflected the overall design of the flight orbiter. It featured numerous substitute components as placeholders for the equipment found in vehicles built for actual space flight.[83]

Slated to be named *Constitution* in honor of the Bicentennial, as the result of a massive letter campaign, on September 8, 1976, OV-101 was officially designated *Enterprise* after the *Star Trek* television program starship. The roll-out of *Enterprise* on September 17, 1976, was attended by thousands, including *Star Trek* actors Leonard Nimoy, George Takei, and DeForest Kelly.[84] In the weeks before rollout, Rockwell oversaw a horizontal ground vibration test at Palmdale to verify structural dynamics data for a full-sized orbiter.[85] On January 31, 1977, OV-101 was moved overland from Palmdale to DFRC at Edwards AFB for use in the Approach and Landing Test (ALT) Program, as described below (Figure No. A-7). Transport of the orbiter test vehicle, which weighed approximately 150,000 pounds, proceeded at about three miles per hour.[86] Following completion of the ALT program, *Enterprise* was flown to MSFC for a series of Mated Vertical Ground Vibration Tests (MVGVT) to determine the structural integrity of the shuttle vehicle. The test program, initiated in May 1978 and completed in February 1979, simulated the period of flight just prior to SRB separation.[87] *Enterprise* was later used in a variety of other test programs, even after its transfer to the Smithsonian in 1985.

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[82] Robert E. Biggs, "Space Shuttle Main Engine, The First Ten Years," in *History of Liquid Rocket Engine Development in the United States, 1955-1980*, ed. Stephen E. Doyle (American Aeronautical Society History Series, Volume 13, Part 3, Chapter 4, 1992).
[83] "Orbiter Gets a Nose Cap," *Marshall Star*, May 19, 1976, 7.
[84] T.A. Heppenheimer, *History of the Space Shuttle*, vol. 2, *Development of the Space Shuttle, 1972-1981* (Washington, DC: Smithsonian Institution Press, 2002), 100-101.
[85] Tests in the early 1970s at Langley Research center used 1/8th-scale models to study the anticipated longitudinal oscillation frequencies, known as "pogo." A second round of model tests, at 1/4th scale, had been a joint effort of the JSC and Rockwell in 1975. Heppenheimer, *Development of the Space Shuttle*, 100, 251-252.
[86] "Enterprise Will Begin First Trip Next Monday," *Marshall Star*, January 26, 1977, 1 and 4.
[87] Andrew J. Dunar and Stephen P. Waring, *Power to Explore: A History of Marshall Space Flight Center, 1960-1990* (Washington, DC: NASA History Office, 1999), 314.

Approach and Landing Test Program: 1977

Prior to the actual test flights, wind tunnel tests in support of the ALT program were carried out at DFRC as well as NASA's Ames Research Center (Ames) at Moffett Field, California. The 1977 wind tunnel tests at DFRC used a .36-scale replica of the orbiter, fabricated by Rockwell International Corporation's Los Angeles Aircraft Division. The replica had an overall fuselage length of 38.71', a wingspan of 28.10', was 20.40' tall, and weighed 45,000 pounds. It was covered by simulated tiles made from a high-density Styrofoam, and was equipped with remotely controlled elevons, body flap, and speed brake and rudder panels, on which the control surface seals and gaps were simulated. The primary objectives of the scale model tests were to evaluate "TPS simulation effects on aerodynamic characteristics; elevon effectiveness employing flipper doors and simulated hinge line seals and gaps; body flap and rudder/speed brake effectiveness; and calibration of the flight test and air data system probe in the flow field of the vehicle."[88] A one-third scale model of the orbiter was also tested at Ames' wind tunnel to gather low speed flight data in support of the ALT program.[89]

Initial flight tests of an aircraft resembling the orbiter were performed concurrent with the assembly of OV-101. These early tests, conducted in 1975, made use of the X-24B lifting body vehicle (Figure No. A-8). Two years later, between February and October 1977, the ALT program aimed at checking out both the mating with the Boeing 747 Shuttle Carrier Aircraft (SCA) for ferry operations, as well as the orbiter's unpowered landing capabilities. NASA selected two, two-man orbiter crews for the ALT: Fred W. Haise, Jr. (Commander) and C. Gordon Fullerton (Pilot), and Joe H. Engle (Commander) and Richard H. Truly (Pilot). Crewmembers for the SCA included pilots Fitzhugh I. Fulton, Jr. and Thomas C. McMurtry, as well as flight engineers Victor W. Horton, Thomas E. Guidry, Jr., William R. Young, and Vincent A. Alvarez.[90] The first phase of the program, conducted on February 15, 1977, entailed three high-speed taxi tests at Runway 04/22, the main concrete runway at Edwards AFB. The purpose of these tests was to "assess directional stability and control, elevator effectiveness during rotation prior to takeoff, airplane response in pitch, thrust reverser effectiveness, use of the 747's brakes, and airframe buffet."[91] The tests were a success and demonstrated the flightworthiness of the SCA-orbiter combination.

The following "captive-inert" phase of testing, conducted in February and March, served to qualify the SCA for use in ferry operations. Six flights were planned at increasing speeds for the purpose of evaluating the flying and handling characteristics of the mated configuration, including such qualities as buffeting and flutter, airspeed calibration, and stability. This phase of the test series was controlled on the scene at DFRC. Given the success of the first three flights,

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[88] "Shuttle Begins Wind Tunnel Tests," *X-Press*, June 20, 1975, 3.
[89] "Orbiter Model," *X-Press*, February 27, 1976, 3.
[90] Peter Merlin, "Proving Grounds. Enterprise validated shuttle concepts," *The Dryden X-Press*, September 2011, 6-7.
[91] Heppenheimer, *Development of the Space Shuttle*, 106.

Deke Slayton, manager of the ALT program, decided to cancel the final (sixth) flight. The goal of the last two test flights was to conduct the maneuvers of an air launch.

Next, three "captive-active" tests were performed on June 18, June 28, and July 26, 1977. These tests marked the first time that the Mission Control Center at JSC controlled a shuttle in flight. During these tests, the orbiter was piloted and powered up while attached to the SCA to check how the *Enterprise* would perform in the air. The third captive-active test deployed the shuttle landing gear for the first time.[92]

The final phase of testing marked the first free flight of the orbiter. Five test free flights were conducted between August 12 and October 26, 1977 (Figure No. A-9). The third free flight on September 23 used the microwave landing system at Edwards AFB for the first time. The final flight landed on the concrete runway at Edwards AFB rather than a dry lake bed, as used before. According Peter Merlin, this landing was "an important demonstration of precision landing capabilities necessary for later operational missions."[93] The first three free tests were flown with the tail cone (fairing) on the orbiter; the fourth and fifth free flights were made with dummy engines in an effort to replicate actual flight conditions.[94] Overall, the ALT program was successful in providing both operational experience as well as "benchmarking data for the flight simulators that were the working tools of day-to-day astronaut training."[95] In addition, the test results illustrated where significant redesign of the orbiter was needed.

Mated Vertical Ground Vibration Tests: 1978-1979

Following completion of the ALT flights, *Enterprise* was flown to MSFC for the MVGVT series, the objective of which was to determine the structural integrity of the shuttle vehicle. The test program, initiated in May 1978, and completed in February 1979, simulated the period of flight just prior to SRB separation (Figure No. A-10).[96] The MVGVT series "used a set of exciters and sensors placed on the skin of the mated elements to create and monitor vibrations and resonances to those that would later be encountered during powered ascent."[97] In 1977, prior to the start of the test program, the *Pathfinder*, a 75-ton shuttle orbiter weight simulator, was built at the MSFC to validate the facilities being used for the MVGVT series (Figure No. A-11). This steel structure, which approximated the dimensions of the *Enterprise*, was used to practice lifting and handling the orbiter. It was also used to fit check the roads and facilities that were used during the MVGVT.[98]

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92 Heppenheimer, *Development of the Space Shuttle*, 121.
93 Merlin, "Proving Grounds," 7.
94 Merlin, "Proving Grounds," 7.
95 Heppenheimer, *Development of the Space Shuttle*, 121.
96 Dunar and Waring, *Power to Explore*, 314.
97 Jenkins, *Space Shuttle*, 213.
98 Jenkins, *Space Shuttle*, 215.

The earliest tests in the MVGVT series used the ET test article mated to the *Enterprise*. The LO2 tank contained deionized water and the LH2 tank was pressurized but empty. The combined orbiter-ET was suspended by a combination of air bags and cables attached to the top of the Structural Dynamic Test Facility (Building 4550). This configuration was used to simulate the high altitude portion of ascent after SRB separation. A second series of vibration tests added a set of SRBs containing inert propellant to simulate lift-off conditions. "This marked the first time that a complete set of dimensionally correct elements of the space shuttle had been assembled together."[99] The test series in the lift-off configuration was completed on September 15, 1978, and in the burn-out configuration on December 5. The final series of vibration tests, initiated in January 1979, used a configuration similar to the second series, except that the SRBs were empty.

Orbital Test Flight Program: 1981-1982

The first orbiter intended for space flight, *Columbia* (OV-102), arrived at KSC from Palmdale in March 1979. Originally scheduled to lift off in late 1979, the launch date was delayed by problems with both the SSME components as well as the thermal protection system (TPS). Upon its arrival at KSC, the orbiter was missing thousands of tiles, main engines, auxiliary power units (APUs), on-board computers, and fuel cells. About six months of assembly work needed to be done. As the result of changed requirements for increased tile strength ("densification"), for twenty months technicians at KSC worked three shifts per day, six days per week installing, testing, removing and reinstalling approximately 30,000 tiles. *Columbia* spent 610 days in the Orbiter Processing Facility (OPF), another thirty-five days in the Vehicle Assembly Building (VAB), and 105 days at Launch Complex (LC) 39A before her maiden launch.

In early November 1980, the work on the TPS was completed, the ET was mated to the SRBs, and the three SSMEs were installed. The Orbiter *Columbia* was mated to the ET and SRBs in the VAB on November 26, and powered up on December 4. Preparations for rollout and ordnance installation were begun on December 19, and ten days later, *Columbia* was transported aboard the Mobile Launcher Platform (MLP) from the VAB to Pad A of Launch Complex 39. Commanded by John W. Young and piloted by Robert L. Crippen, STS-1, the first orbital test flight and first SSP mission, finally began at 7:00 a.m. Eastern Standard Time on April 12, 1981 (Figure No. A-12). *Columbia* returned on April 14, completing her historic mission at Edwards AFB. This initial mission, which lasted two days, six hours, twenty minutes, and fifty-three seconds, demonstrated *Columbia's* ability to fly into orbit, conduct on-orbit operations, and return safely.[100] *Columbia* flew three additional test flights in 1981 and 1982, as summarized in the table that follows, all with a crew of two. On March 30, 1982, at the completion of STS-3, *Columbia* landed at White Sands Missile Range (at NASA's White Sands Space Harbor) in New Mexico because of flooding of the Edwards AFB runway due to heavy rains (Figure No. A-13). This event marked the only time in the history of the SSP that the orbiter landed at White Sands.

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[99] Jenkins, *Space Shuttle*, 213.
[100] Jenkins, *Space Shuttle*, 268.

Orbital Test Flights

Flight	Launch	Landing	Duration	Notes
STS-1	April 12, 1981	April 14, 1981	54 hr., 20 min.	16 tiles lost and 148 damaged
STS-2	Nov. 12, 1981	Nov. 14, 1981	54 hr., 13 min.	First test of Remote Manipulator System
STS-3	March 22, 1982	March 30, 1982	192 hr., 4 min.	Landed at White Sands Missile Range
STS-4	June 27, 1982	July 4, 1982	169 hr., 9 min.	First concrete runway landing

The Orbital Test Flight Program ended in July 1982 with 95 percent of its objectives completed. After the end of the fourth mission, President Ronald Reagan declared that with the next flight the shuttle would be "fully operational."

Operational Flights

STS-5, which began with the liftoff of *Columbia* on November 11, 1982, marked the first operational flight of the SSP. The mission, which lasted 122 hours and fourteen minutes, ended on November 16 with a landing at Edwards AFB. *Challenger* (OV-099) was added to the shuttle fleet in 1982, and made her first flight (STS-6) in April 1983. *Discovery* (OV-103) and *Atlantis* (OV-104) were delivered to KSC in November 1983 and April 1985, respectively. *Discovery* made her maiden flight (STS-41D) on August 30, 1984; the first space flight of *Atlantis* (STS-51-J) took place on October 3, 1985. Between 1982 and 1985, *Columbia*, *Challenger*, *Discovery*, and *Atlantis* collectively averaged four to five launches per year. Despite the 1970s projections of a maximum of sixty launches per year, in reality the nine flights in 1985 were a milestone for the SSP. All of the launches, from 1982 through 1985, were made from LC 39A at KSC, and all but six missions ended with landings at Edwards AFB.

Starting with STS-1 and continuing through STS-9, shuttle missions were numbered sequentially. Beginning with the tenth flight, a new system was introduced. The first digit designated the last digit of the FY (which starts on October 1) in which the mission was scheduled to launch. The second digit designated the launch site, with "1" for KSC and "2" for Vandenberg. Next, an alphabetical designation indicated the sequential position of the launch. For example, STS-41B was the second launch of FY 1984 from KSC. After the *Challenger* (STS-51L) accident in January 1986, this numbering system was abandoned, and NASA returned to a sequential numbering system.[101] This change coincided with the termination of Vandenberg as a launch site. Since STS-51L had been the twenty-fifth launch of the SSP, the designated return to flight on September 29, 1988, was numbered STS-26.

[101] Sometimes flights were launched out of sequence. This was mainly due to scheduling impacts such as bad weather and technical problems.

The *Challenger* Accident and Aftermath

On January 28, 1986, seventy-three seconds after the launch of *Challenger*, the spacecraft was destroyed, and the seven astronauts, Commander Francis R. Scobee; Pilot Michael J. Smith; Mission Specialists Ellison S. Onizuka, Judith A. Resnik, and Ronald E. McNair; and Payload Specialists George B. Jarvis and Sharon Christa McAuliffe, the first teacher selected to fly in space, all perished. Following this tragedy, the SSP was suspended for approximately two and one-half years. President Reagan formed a thirteen-member commission to investigate the cause of the accident. The Presidential Commission on the Space Shuttle *Challenger* Accident, known as the Rogers Commission after its chairman, William P. Rogers, was tasked with reviewing the images (video, film, and still photography), telemetry data, and debris evidence. As a result, the commission concluded:

> *The consensus of the Commission and participating investigative agencies is that the loss of the Space Shuttle Challenger was caused by a failure in the joint between the two lower segments of the right Solid Rocket Motor. The specific failure was the destruction of the seals that are intended to prevent hot gases from leaking through the joint during the propellant burn of the rocket motor. The evidence assembled by the Commission indicates that no other element of the Space Shuttle system contributed to this failure.*[102]

In addition to identifying the cause of the *Challenger* accident, the Rogers Commission report, issued on June 6, 1986, included a review of the SSP. The report concluded "that the drive to declare the Shuttle operational had put enormous pressures on the system and stretched its resources to the limit."[103] In addition to mechanical failure, the Commission noted a number of NASA management failures that contributed to the catastrophe. Nine basic recommendations were made. As a result, among the tangible actions taken were extensive redesign of the SRBs and the SRMs; upgrading of the space shuttle tires, brakes, and nose wheel steering mechanisms; the addition of a drag chute to help reduce speed upon landing; the addition of a crew escape system; and the requirement for astronauts to wear pressurized flight safety suits during launch and landing operations. Other changes involved reorganization and decentralization of the program. Experienced astronauts were placed in key NASA management positions, all documented waivers to existing flight safety criteria were revoked and forbidden, and a policy of open reviews was implemented.[104] In addition, NASA adopted a flight schedule with a reduced average number of launches, and discontinued the long-term practice of launching commercial and military payloads.[105]

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[102] Jenkins, *Space Shuttle,* 279.
[103] Columbia Accident Investigation Board (CAIB), *Report, Volume I* (Washington, DC: US Government Printing Office, 2003), 25, http://history.nasa.gov/columbia/CAIB_reportindex.html.
[104] Cliff Lethbridge, "The Challenger Legacy," 2000, http:// http://spaceline.org/challenger.html.
[105] Lethbridge, "The Challenger Legacy."

In the aftermath of the *Challenger* accident, and following the recommendation of the Rogers Commission for organizational change, NASA moved the management of the SSP from JSC to NASA Headquarters, with the aim of preventing communication deficiencies.[106] In addition, an exhaustive investigation by a Senate subcommittee resulted in the cancellation of the DoD's plans to activate the VLS in California, leaving the US without a manned polar launch capability. The subcommittee outlined potential technical and structural problems at Vandenberg that would further delay a West Coast shuttle launch until mid-1989. Prior to this time, during late 1984 and early 1985, the site was used for a series of flight verification tests using *Enterprise*. *Discovery* was to fly the first mission from the VLS in 1986, and was awaiting transport to California when the *Challenger* accident occurred. Subsequently, all launch preparations were suspended.[107] The facilities were ordered mothballed in 1988, and the SSP at Vandenberg was officially terminated in December 1989. Though $4 billion was spent, no flight orbiters ever visited.[108]

In July 1987, NASA awarded a contract to Rockwell for construction of OV-105, *Endeavour*, to replace *Challenger*. To build the new orbiter, Rockwell used structural spares previously constructed between 1983 and 1987 under contract with NASA. Assembly of OV-105 was completed in July 1990, and the orbiter was delivered to KSC in May 1991; *Endeavour* launched on its maiden flight (STS-49) on May 7, 1992.

Return to Flight

The launch of *Discovery* (STS-26) from KSC LC 39B on September 29, 1988, marked a Return to Flight (RTF) after a thirty-two-month hiatus in manned spaceflight following the *Challenger* accident. STS-26 carried a crew of five and a Tracking and Data Relay Satellite (TDRS).[109] The problem in the design of the SRMs that had caused the loss of *Challenger* had been found and corrected. Many other critical flight systems had been re-examined and recertified. The years following the STS-26 flight "were among the most productive in the Shuttle's history, as a long backlog of payloads finally made it to the launch pad."[110] Starting with the RTF, the average number of missions increased from four to five to six yearly; 1992 through 1997 were the most productive, with seven or eight yearly missions. On February 3, 1995, a program milestone was reached when *Discovery* (STS-63) became the first orbiter to complete twenty missions.

Space Station Programs: *Mir* and the ISS

On July 31, 1991, President George H.W. Bush and Russian Premier Mikhail Gorbachev formally agreed that an American astronaut would reside on *Mir* for up to six months, and a Russian cosmonaut would fly on the Space Shuttle as part of the Manned Flight Joint Working

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[106] CAIB, *Report Volume I*, 101.
[107] Jenkins, *Space Shuttle* , 217.
[108] Jenkins, *Space Shuttle*, 155, 217, 467-476.
[109] Williamson, "Developing the Space Shuttle," 186.
[110] Tony Reichhardt, ed., *Space Shuttle, The First 20 Years* (Washington, DC: Smithsonian Institution, 2002), 65.

Group. In October 1992, a second agreement was made between the space agencies of the two countries which outlined a plan for a US Space Shuttle to dock with *Mir*, and for an exchange of cosmonauts and astronauts on each others' human spaceflight missions.[111] Following a summit in Vancouver, Canada, convened in September 1993, both the US and Russia signed an agreement which instructed NASA and the Russian Space Agency to develop, by November 1, 1993, a detailed plan of activities for the space station.[112] A proposed three-phase approach for the new International Space Station (ISS) Program resulted from the summit. Phase I (1994 to 1997) was set as a joint Space Shuttle-*Mir* program. In Phase II (1998-2000), a station core was to be assembled using a US-built node, lab module, central truss and control moment gyros, and an interface for the shuttle. Russia was to build the propulsion system, initial power system, and an interface for Russian vehicles, as well as to provide crew-return vehicles. Canada was given responsibility for the construction of a remote manipulator arm. Phase III (2001-2004) called for the completion of the station with the addition of US modules, power system, and attitude control, and Russian, Japanese, and European Space Agency (ESA) research modules and equipment.[113]

In February 1994, the joint US/Russian, Space Shuttle-*Mir* Program was initiated with NASA's STS-60 mission, when Sergei Krikalev became the first Russian cosmonaut to fly on a shuttle. The first approach and flyaround of *Mir* took place on February 3, 1995, with cosmonaut Vladimir Titov aboard *Discovery* (STS-63); the first *Mir* docking was in June 1995 (STS-71).[114] In November of that year, *Atlantis* (STS-74) delivered and permanently attached a Docking Module to the *Kristall* module's androgynous docking unit, thus serving to improve clearance between the shuttle and the station for subsequent docking missions.

During the three-year Space Shuttle-*Mir* Program, from June 27, 1995, to June 2, 1998, the orbiter docked with *Mir* nine times (Figure No. A-14). In 1995, Norman E. Thagard, M.D., became the first American astronaut to live aboard the Russian space station. Arriving aboard the Russian Soyuz TM-21, Dr. Thagard stayed on *Mir* for 115 days. Over the next three years, six more US astronauts served tours on *Mir*. In 1998, the last NASA astronaut to reside on *Mir*, Andy Thomas, returned to Earth aboard *Discovery* (STS-91). The Space Shuttle served as a means of transporting supplies, equipment, and water to the space station; shuttle astronauts performed a variety of mission tasks, many of which involved earth science experiments. The Space Shuttle-*Mir* Program served to acclimate the astronauts to living and working in space, and many of the activities carried out on *Mir* were types they would perform on the ISS.[115]

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111 Roger D. Launius, S*pace Stations, Base Camps to the Stars* (Washington, DC: Smithsonian Institution, 2003), 152; Reichhardt, *Space Shuttle,* 85. *Mir* was launched by the Russians in February 1986 and remained in orbit until March 2001.

112 "Space cooperation agreement allows two years' time on Mir," *Space News Roundup*, September 13, 1993: 3.

113 Launius, S*pace Stations*, 176-181.

114 NASA KSC, "STS-63. Mission Archives," December 30, 2011, www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-63.html; NASA KSC, "STS-71. Mission Archives," November 23, 2007, www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-71.html.

115 Judy A. Rumerman, with Stephen J. Garber, *Chronology of Space Shuttle Flights 1981-2000* (Washington, DC:

On-orbit assembly of the ISS officially began in November 1998, when *Zarya,* built by Russia and financed by the US, was launched by a Russian Proton rocket from the Baikonur Cosmodrone in Kazakhstan.[116] This pressurized module provided orientation control, communications, and electrical propulsion for the station until the launch of additional modules. The late delivery of this initial element delayed the launch of subsequent ISS modules.[117] The US-built *Unity* Node 1 connecting module, along with two pressurized mating adapters (PMAs), was launched from KSC aboard *Endeavour* (STS-88) in December 1998 (Figure No. A-15). Built by The Boeing Company at the MSFC, the six-sided *Unity* connector module supplied essential ISS resources such as fluids, environmental control and life support systems, as well as electrical and data systems, to the working and living areas of the station.[118] *Unity* was connected to the orbiting *Zarya* by *Endeavour*'s crew on December 6, 1998. As noted by Ray A. Williamson, delivery of the first US-built element to the station marked, "at long last the start of the Shuttle's use for which it was primarily designed – transport to and from a permanently inhabited orbital space station."[119] The twenty-sixth flight of *Discovery* (STS-96), launched on May 27, 1999, was the first mission to dock with the ISS.

A nineteen-month hiatus followed the mating of *Zarya* and *Unity* because of Russian delays in building the *Zvezda* Service Module. Until delivery and installation of this key module, the ISS could not be inhabited without a shuttle present. *Zvezda* finally was launched on July 25, 2000, and mated with *Zarya* and *Unity*. The 42,000-pound module, similar in layout to *Mir,* provided living quarters, life support systems, electrical power distribution, data processing systems, and flight control and propulsions systems, including remote control capabilities.[120] In October 2000, the crew of *Discovery* (STS-92) delivered and connected the Z-1 Truss and the third PMA. The ISS was then officially declared ready for occupancy. One month later, the Port 6 (P6) Truss, fitted with the first set of solar arrays, was launched by *Endeavour* (STS-97). P6 was temporarily installed on top of the Z-1 Truss to provide power to the station while the remainder of the integrated truss system was completed (Figure No. A-16).

NASA History Division, 2000), 3.

[116] Launius, S*pace Stations*, 185-187; NASA JSC, *The Zarya Control Module: The First International Space Station Component to Launch*, NASA Facts (Houston: Johnson Space Center, 1999). http://spaceflight.nasa.gov/spacenews/factsheets/pdfs/zarya.pdf.

[117] As reported by Roger Launius (S*pace Stations*, 181-182), Russia was responsible for critical station modules that would derail the program if not delivered on time. As the costs for critical Russian components increased over budget, and failed to meet the schedule, the timeframe for the ISS was delayed.

[118] NASA JSC, *Unity Connecting Module: Cornerstone for a Home in Orbit. The First US-Built International Space Station Component*, NASA Facts (Houston: Johnson Space Center, January 1999). http://spaceflight.nasa.gov/spacenews/factsheets/pdfs/unity.pdf.

[119] Williamson, "Developing the Space Shuttle," 191.

[120] NASA JSC, *The Service Module: A Cornerstone of Russian International Space Station Modules*, NASA Facts, (Houston: Johnson Space Center, 1999). http://spaceflight.nasa.gov/spacenews/factsheets/pdfs/servmod.pdf.

The next major ISS component, the US-built *Destiny* Laboratory Module, arrived in February 2001, aboard *Atlantis* (STS-98). The *Destiny* module is used for research in life sciences, microgravity sciences, and Earth and space sciences research (Figure No. A-17). The astronaut crew arriving aboard *Discovery* (STS-102) in March 2001, attached and unloaded the first Multi-Purpose Logistics Module (MPLM), *Leonardo*. *Leonardo* and two other MPLMs, *Donatello*, and *Raffaello*, were built by the Italian Space Agency in Turin, and are owned by the US. The three pressurized modules were filled with racks that carried equipment, experiments, and supplies to and from the station aboard the Shuttle. They had components that provide limited life support, as well as fire detection and suppression, electrical distribution, and computer functions.

Endeavour (STS-100) delivered the Canadarm 2 in April 2001. Three months later, the Joint Airlock *Quest* arrived, which enabled the US astronauts to perform spacewalks without the Space Shuttle present. On September 15, 2001, the Russian *Pirs* Docking Compartment, launched aboard a Russian spacecraft, provided the ISS with additional spacewalking support and docking capabilities. Starboard Trusses (S0 and S1) were delivered aboard *Atlantis* (STS-110 and STS-112) in April and October 2002 (Figure No. A-18), respectively, followed by the P1 Truss in November 2002. At this point, approximately 45 percent of the station had been delivered and assembled. However, after the addition of the P1 Truss during the *Endeavour* (STS-113) mission, the configuration of the ISS was "frozen" at this stage for several years as the US SSP recovered from the *Columbia* accident.

Columbia Accident and Aftermath

On January 16, 2003, *Columbia* (STS-107) launched from LC 39A carrying a crew of seven, including the first Israeli astronaut. The landing was set for February 1, following a sixteen-day mission. Sixteen minutes prior to its scheduled touchdown at KSC, the spacecraft was destroyed during reentry over eastern Texas. All members of the crew, Commander Rick Husband; Pilot William McCool; Mission Specialists Dave Brown, Kalpana Chawla, Mike Anderson, and Laurel Clark; and Israeli Payload Specialist Ilan Ramon, were killed.

The SSP suffered its second major setback since the loss of *Challenger*, and again, was faced with explaining what had gone horribly wrong. A seven-month investigation ensued, including a four month search to recover debris. The *Columbia* Accident Investigation Board (CAIB) determined that the physical cause of the accident was a breach in the TPS on the leading edge of the left wing. This resulted from a piece of insulating foam, which separated from the ramp section of the ET after launch, and struck the wing in the vicinity of Reinforced Carbon-Carbon (RCC) panel no. 8. During reentry, this breach "allowed superheated air to penetrate through the leading edge insulation and progressively melt the aluminum structure of the left wing, resulting in a weakening of the structure until increasing aerodynamic forces caused loss of control, failure of the wing, and break-up of the Orbiter."[121]

[121] CAIB, *Report* Volume I, 9.

NASA spent more than two years researching and implementing safety improvements for the orbiters, SRBs, and ET. In the aftermath of the *Columbia* accident, the Space Shuttle fleet was grounded, and construction on the ISS was placed on hold. All access to and from the station was by way of the Russian-built Soyuz capsule. During the two-year period spanning 2003 to 2005, Russia flew fourteen resupply and crew rotation missions until *Discovery's* STS-114 RTF mission launched on July 26, 2005.[122]

On March 2, 2006, the international partners approved a new assembly sequence that dedicated the sixteen remaining shuttle flights to launching ISS elements. Truss segments P3/P4 and P5, as well as S3/S4 and S5, were delivered in 2006 and 2007. *Discovery* (STS-120) launched on October 23, 2007, carrying the Italian-built *Harmony* Node 2. This module increased crew living and working space; provided connecting ports for supply vehicles and the shuttle; and provided a passageway between the US *Destiny* lab, the Japanese *Kibo* Experiment Module, and the ESA-built *Columbus* Laboratory. The *Kibo* and *Columbus* modules, as well as the Canadian-built robotic device *Dextre,* arrived at the station in early 2008.

The last major US truss segment, S6, and the final pair of power-generating solar array wings, were delivered to the station aboard *Discovery* (STS-119) in March 2009. The same year, the *Kibo* Japanese Experiment Module Exposed Facility and Experiment Logistics Module Exposed Section were delivered aboard *Endeavour* (STS-127). The module provides an environment in which astronauts can conduct microgravity experiments. The exposed facility is a platform outside the module where Earth observation, communication, scientific, engineering, and materials science experiments are performed.[123]

In February 2010, the *Tranquility* Node 3 and its cupola were delivered aboard *Endeavour* (STS-130). The node and viewing port were built by the Italian company Thales Alenia Space and commissioned by the ESA.[124] The *Tranquility* node provides needed space and a centralized home for the station's environmental control equipment, as well as other essential services. By April 2010, following the conclusion of *Discovery's* (STS-131) mission, the non-Russian segment of the ISS was virtually complete. In May, *Atlantis* (STS-132) delivered the Russian-built Mini-Research Module (MRM) 1 *Rassvet*. MRM 2 *Poisk* was delivered earlier, in November 2009, aboard a Russian spacecraft. The *Rassvet* was used for science research and cargo storage. It also provided an additional docking port for Russian Soyuz and Progress transport vehicles.[125] In February and May, 2011, *Discovery* (STS-133) and *Endeavour* (STS-

[122] Launius, S*pace Stations,* 214-216.
[123] NASA, "Kibo Japanese Experiment Module," 2007, http://www.nasa.gov/mission_pages/station/structure/elements/jem.html.
[124] Thales Group, "A Room with a View: Node Tranquility and the Cupola, Both Supplied by Thales Alenia Space, Are Ready for Launch to Complete the ISS Assembly," news release, February 4, 2010, www.thalesgroup.com/Pages/PressRelease.aspx?id=11582.
[125] NASA MSFC, "A New "Dawn" in Space," May 14, 2010. www.nasa.gov/mission_pages/station/science/10-051.html.

134) delivered the permanent Multipurpose Module *Leonardo* and the Express Logistic Carrier 4, followed by the Express Logistic Carrier 3 and Alpha Magnetic Spectrometer 2, respectively.

By the close of the SSP, the three US Space Shuttles, *Discovery*, *Atlantis*, and *Endeavour*, had delivered all but three of the major station elements to the ISS. Additionally, the shuttles transported *Leonardo*, *Raffaello*, and *Donatello* to and from the ISS, as well as four of the first five Expedition crews, between March 2001 (Expedition 2; STS-102) and June 2002 (Expedition 5; STS-111).[126]

There has been a continuous human presence on the ISS since November 2000. In the aftermath of the *Columbia* accident, the ISS crew size was reduced from three to two, and instead of a three month period of residency, all crew were scheduled to stay for approximately 180 days. Expedition 12, launched on September 30, 2005, was the last two-person crew; Expedition 13, launched on March 29, 2006, marked a return to the three-person long duration crew. Expedition 20, in May 2009, marked a new milestone with the first permanent crew of six people. Also, with the arrival of Expedition 20, all participating space agencies had a representative on the ISS for the first time.

Orbiter Milestones, Missions and Payloads

Orbiter Milestones

A total of 135 Space Shuttle missions were launched from the KSC between April 1981 and July 2011. As summarized in the tables below, at the close of the SSP, *Discovery* was the orbiter fleet leader with a total of thirty-nine launches. *Atlantis* completed thirty-three missions, and twenty-five were flown by *Endeavour*.

[126] The Russian Soyuz launched the first Expedition crew to the ISS on October 30, 2000 (Launius, S*pace Stations*, 192-193; NASA JSC, *Flight 2R: First Crew On the International Space Station*, NASA Facts (Houston: Johnson Space Center, 1999), http://spaceflight.nasa.gov/spacenews/factsheets/pdfs/flt2r.pdf.

Tabulation of Space Shuttle Missions by Year and Orbiter, 1981 through 2011

Year	**OV-102** ***Columbia***	**OV-099** ***Challenger***	**OV-103** ***Discovery***	**OV-104** ***Atlantis***	**OV-105** ***Endeavour***	**Yearly Total**
1981	2					2
1982	3					3
1983	1	3				4
1984		3	2			5
1985		3	4	2		9
1986	1	1				2
1987						0
1988			1	1		2
1989	1		2	2		5
1990	2		2	2		6
1991	1		2	3		6
1992	2		2	2	2	8
1993	2		2		3	7
1994	2		2	1	2	7
1995	1		2	2	2	7
1996	3			2	2	7
1997	3		2	3		8
1998	1		2		2	5
1999	1		2			3
2000			1	2	2	5
2001			2	2	2	6
2002	1			2	2	5
2003	1					1
2004						0
2005			1			1
2006			2	1		3
2007			1	1	1	3
2008			1	1	1	3
2009			2	2	1	5
2010			1	1	2	4
2011			1	1	1	3
Totals	28	10	39	33	25	135

Summary of Orbiter Vehicle Accomplishments[127]

Orbiter Vehicle (OV-)	***Challenger* OV-99**	***Columbia* OV-102**	***Discovery* OV-103**	***Atlantis* OV-104**	***Endeavour* OV-105**	**Totals**
Total miles traveled	23,661,290	121,696,993	148,221,675	125,935,769	122,883,151	575,535,047
Total days in space	62	300	365	307	299	1,333 (3.6 years)
Total orbits	995	4,808	5,830	4,848	4,671	21,152
Total flights	10	28	39	33	25	135
Total crew members	60	160	252	207	173	852
Mir dockings	0	0	1	7	1	9
ISS dockings	0	0	13	12	12	37
Satellites deployed	10	8	31	14	3	66

Collectively, the five orbiters in the shuttle fleet circled the Earth 21,152 times, and travelled more than 575 million miles. The time in space was approximately 1,333 days, or 3.6 years. The fleet carried a total of 852 fliers, with many crew members making multiple flights. Three hundred fifty-five individuals representing sixteen different countries flew on shuttle flights. Two American astronauts, Jerry Ross and Franklin Chang Diaz, each flew on seven shuttle missions. Story Musgrave is the only astronaut to have flown all five shuttles. The shuttle docked with *Mir* nine times, and the ISS thirty-seven times; deployed sixty-six satellites; and retrieved, repaired, then re-deployed seven payloads.[128]

<u>Missions and Payloads</u>

The Space Shuttles flew several dedicated DoD missions, as well as launched a number of planetary and astronomy missions, including the Hubble Space Telescope (HST), the Galileo probe to Jupiter, Magellan to Venus, and the Upper Atmospheric Research Satellite. In 1984, the Solar Max satellite was retrieved, repaired, and reorbited. In the same year, two malfunctioning commercial communications satellites were retrieved in orbit and brought back to Earth; in 1985, another satellite was fixed in orbit.[129] In addition, a series of Spacelab research missions (1983-1998) carrying dozens of international experiments in disciplines ranging from materials science to plant biology were accomplished. Noteworthy missions and milestones of the SSP are described in the individual orbiter sections, as well as the *Discovery* narrative in Part II. A summary of DoD, Spacelab, and HST missions follows.

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[127] NASA KSC, *Space Shuttle Era Facts*, NASA Facts (Florida: Kennedy Space Center, 2011), http://www.nasa.gov/pdf/566250main_2011.07.05%20SHUTTLE%20ERA%20FACTS.pdf ; NASA, "STS-135 Mission of Space Shuttle Atlantis by the Numbers," July 21, 2011, http://www.nasa.gov/topics/shuttle_station/features/135numbers.html.
[128] NASA KSC, *Space Shuttle Era Facts*.
[129] Rumerman, *Chronology of Space Shuttle Flights*, 2.

DoD Missions

STS-4, launched on June 27, 1982, carried the first classified DoD payload, the Cryogenic Infrared Radiance Instrumentation for Shuttle (CIRRUS) telescope, and several other small experiments. Controlled from the Air Force's Station in Sunnyvale, California, "this was the only NSS [National Security Space] mission where the NSS flight controllers talked directly to the shuttle crew."[130] Also in 1982, the DoD bought nine shuttle flights from NASA for $268 million; a tenth mission was purchased at a later date. Mission data is summarized in the table that follows. These flights, managed by the Air Force, were mainly to launch classified payloads including experimental, radar imaging, communications, and early warning satellites. For the DoD flights, "flight controllers at KSC and JSC used secure launch and flight control rooms separate from rooms used for non-DoD flights to protect the classified nature of these missions."[131] The first completely classified, DoD-dedicated flights began in 1985 with STS-51-C, launched in January; the last dedicated military payload was carried aboard *Discovery* on STS-53, launched in December 1992. Due to the nature of these payloads, little information is publicly available.[132] STS-39, launched in April 1991, marked the first time that flight details were released to the public. The focus of this mission was Strategic Defense Initiative research into sensor designs and environmental phenomena.[133] The next dedicated DoD flight, STS-44, flown in November 1991, deployed a Defense Support Program satellite "designed to detect nuclear detonations, missile launches, and space launches from geosynchronous orbit."[134] This mission marked the end of shuttle flights for non-NASA military payload specialists. Between 1982 and 1992, NASA and the DoD-related National Security Space programs completed eleven missions. However, after the *Challenger* accident, NASA made the decision to end dedicated DoD missions.

In addition to the payloads on DoD-dedicated flights, more than 250 military payloads and experiments flew on ninety-five other shuttle missions.[135] In the Appendix to *Wings in Orbit*, a total of eighty-nine flights are listed as carrying DoD payloads.[136] This comprises roughly two-thirds of all SSP flights.

[130] Jeff DeTroye, et al., "National Security," in *Wings in Orbit: Scientific and Engineering Legacies of the Space Shuttle, 1971-2010*, ed. Wayne Hale (Washington, DC: US Printing Office, 2010), 46.
[131] Jennifer Ross-Nazzal and Dennis Webb, "Major Milestones," in *Wings in Orbit*, 20; DeTroye, et al., "National Security," 47.
[132] Jenkins, *Space Shuttle*, 328.
[133] DeTroye, et al., "National Security," 47.
[134] DeTroye, et al., "National Security," 47.
[135] DeTroye, et al., "National Security," 49.
[136] Hale, *Wings in Orbit*, Appendix, 527-529.

Summary of Dedicated Department of Defense Missions[137]

Flight	Orbiter	Launch Date	Payload	Comments
STS-51-C	*Discovery*	Jan. 24, 1985	ORION-1, an eavesdropping satellite for signals intelligence	The first dedicated, classified DoD mission.[138]
STS-51-J	*Atlantis*	Oct. 3, 1985	Pair of Defense communications satellites	
STS-27	*Atlantis*	Dec. 2, 1988	LACROSSE-1 radar imaging satellite (speculation only)	First post-*Challenger* military mission
STS-28	*Columbia*	Aug. 8, 1989	SDS B-1, a Satellite Data System spacecraft for relaying imagery from spy satellites	
STS-33	*Discovery*	Nov. 22, 1989	ORION-2, an eavesdropping satellite (unconfirmed)	Mission Specialists Story Musgrave and Kathy Thornton were the only civilians ever assigned to secret missions.
STS-36	*Atlantis*	Feb. 28, 1990	MYSTY (var. MISTY), a reconnaissance satellite	
STS-38	*Atlantis*	Nov. 15, 1990	SDS-B2, probably a data relay satellite	
STS-39	*Discovery*	April 28, 1991	AFP-675, a reflight of the CIRRUS military payload flown on STS-4, and UHS, the Ultraviolet Horizon Scanner)	This mission was declassified before launch, making it the first unclassified DoD mission.
STS-44	*Atlantis*	Nov. 24, 1991	Defense Support Program (DSP) F-16 ("Liberty"), a satellite for early warning of missile launching.	Last of the original nine DoD flights. Declassified months before launch.
STS-53	*Discovery*	Dec. 2, 1992	SDS B-3, assumed to be a data relay satellite	The final dedicated DoD mission; partially classified.

Spacelab: 1983-1998

On September 24, 1973, the ESA and NASA signed a Memorandum of Understanding, agreeing to design and develop Spacelab. The decision to develop Spacelab "resulted almost entirely from Germany's strong desire to get involved in manned space flight, and its willingness to finance 52 percent of Spacelab's costs."[139] Spacelab was a manned, reusable, microgravity laboratory flown into space in the rear of the Space Shuttle cargo bay. It was developed on a modular basis, allowing assembly in a dozen arrangements depending on the specific mission requirements.[140]

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[137] Jenkins, *Space Shuttle*, 328-331; Michael Cassutt, "Secret Space Shuttles," in *Air & Space* magazine, August 2009, 2, http://www.airspacemag.com/space-exploration/secret-space-shuttles.html.
[138] According to Michael Cassutt ("Secret Space Shuttles," 3), "for the first time in NASA history, there was no pre-launch public affairs commentary until nine minutes before liftoff. During the flight, the Air Force lifted the veil of secrecy only to admit that the payload was successfully deployed, and that an Inertial Upper Stage was used."
[139] Jenkins, *Space Shuttle*, 101.
[140] NASA, *NSTS Shuttle Reference Manual* (Florida: Kennedy Space Center, 1988), http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts_asm.html.

MSFC was responsible for Spacelab development and missions, as well as payload control during missions. Actual construction of the Spacelab pressurized modules was started by ERNO-VFW Fokker in 1974. The first lab, LM1, was donated to NASA in exchange for flight opportunities for European astronauts. Later, NASA purchased LM2, the second lab. The first Spacelab mission, carried aboard *Columbia* (STS-9), began on November 28, 1983, and concluded December 8, 1983 (Figure No. A-19). As part of this mission, the first protein crystals were grown in space, the energy output of the sun was measured, and the effects of radiation and weightlessness were studied.[141]

Challenger flew the next three Spacelab missions, STS-51B, -51F, and -61A, between April and November 1985. Following a five-year hiatus in the aftermath of the *Challenger* disaster, the next Spacelab mission, STS-35 launched in December 1990, carried the astronomical observatory, ASTRO-1. Twenty-three Space Shuttle missions carried Spacelab hardware before the program was decommissioned in 1998. Spacelab flew the International Microgravity Laboratory, the Atmospheric Laboratory for Applications and Science, the US Microgravity Laboratory, and the Microgravity Science Laboratory, among other payloads.[142] In addition to astronomical, atmospheric, microgravity, and life sciences missions, Spacelab was used as a supply carrier to the HST[143] and the Soviet space station *Mir*. STS-90, launched in April 1998, was the last with a Spacelab payload. Known as Neurolab, it carried life-science experiments that sought to study the behavior of nervous systems in zero-gravity.[144] In 1998, the Spacelab program was retired since the experiments conducted on it could now be performed on the ISS.

Hubble Space Telescope

Calls for a telescope in orbit, far away from the lights emitted from Earth, began as far back as the 1920s. The proposal slowly gained traction in the decades following World War II. In 1978, a breakthrough was made when the US Congress appropriated funding for the Large Space Telescope and work got under way. It was renamed the Hubble Space Telescope in 1983 after astronomer Edwin Hubble. Originally slated to launch in 1983, setbacks delayed its debut until April 24, 1990, when *Discovery*, on its tenth flight (STS-31), deployed the telescope into orbit (Figure No. A-20). Two months later, an aberration was discovered in Hubble's primary mirror. Five Shuttle missions to repair and maintain the HST followed: STS-61 (*Endeavour*; December 1993; Figure No. A-21), STS-82 (*Discovery*; February 1997), STS-103 (*Discovery*; December 1999), STS-109 (*Columbia*; March 2002), and STS-125 (*Atlantis*; May 2009). Collectively, these

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[141] Richard W. Orloff, ed., *Space Shuttle Mission STS-9 Press Kit*, November 1983, http://www.scribd.com/doc/19964486/NASA-Space-Shuttle-STS9-Press-Kit.
[142] NASA, "Spacelab Payloads on Shuttle Flights," 2007, http://www.nasa.gov/mission_pages/shuttle/launch/spacelab_shuttle.html.
[143] Kim Dismukes, "STS-103 Payloads Servicing Mission 3A Configuration," 2002, http://spaceflight.nasa.gov/shuttle/archives/sts-103/cargo/index.html.
[144] Heppenheimer, *Development of the Space Shuttle*, 48.

Shuttle missions extended the HST's operating life with the replacement of aging hardware. The installation of advanced science instruments also enhanced scientific capability.[145]

The first servicing mission (SM), SM1, made by the crew of *Endeavour* (STS-61) in December 1993, corrected the defect in the optics and installed new instruments. In February 1997, during SM2, new instruments were installed, which improved the HST's productivity. The third servicing mission was divided into two parts after the third of Hubble's six gyroscopes failed. SM3A in December 1999 (STS-103) included the installation of six new gyroscopes and other equipment. In March 2002, *Columbia's* STS-109 crew installed the Advanced Camera for Surveys. SM4, the fifth and final servicing mission, flown by *Atlantis* (STS-125) in May 2009, included the installation of two new scientific instruments, the Cosmic Origins Spectrograph and Wide Field Camera 3. Two failed instruments, the Space Telescope Imaging Spectrograph and the Advanced Camera for Surveys, were brought back to life by the first SSP on-orbit repairs.

Transition and Retirement

On January 14, 2004, President George W. Bush announced that in 2010, following completion of the ISS, the Space Shuttle would be retired after nearly thirty years of service.[146] The shuttle would not be upgraded to serve beyond this time. On the thirtieth anniversary of the maiden launch of the SSP, April 12, 2011, NASA Administrator Charles Bolden announced that the Space Shuttle fleet would be displayed permanently at institutions across the country. *Enterprise* will be moved from the Smithsonian's National Air and Space Museum's (NASM) Steven F. Udvar-Hazy Center in Chantilly, Virginia, to the Intrepid Sea, Air and Space Museum in New York. The Udvar-Hazy Center will become the new home for *Discovery*. *Endeavour* will go to the California Science Center in Los Angeles, and *Atlantis* will be displayed at the KSC Visitor Complex in Florida.[147]

Transition and Retirement (T&R) Flow

Prior to their relocation, each orbiter underwent safing and post-mission deservicing, in accordance with NSTS 60585, *Space Shuttle End State Safing Requirements Document*, prepared by The Boeing Company (see Figure Nos. A-22 through A-25 for representative photographs of the safing and deservicing process).[148] In addition, specific display site configuration work was

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[145] NASA, "The Hubble Space Telescope Servicing Missions," 2010, http://hubble.nasa.gov/missions/info.php.
[146] Weekly Comp. Pres. Docs., Remarks at the National Aeronautics and Space Administration, Vol. 40, Issue 3 (January 19, 2004), http://www.gpo.gov/fdsys/pkg/WCPD-2004-01-19/content-detail.html.
[147] David Weaver, "NASA Announces New Homes For Shuttle Orbiters After Retirement," release: 11-107 (Washington, DC: NASA Headquarters, April 12, 2011), http://www.nasa.gov/home/hqnews/2011/apr/HQ_11-107_Orbiter_Disposition.html.
[148] NASA JSC, *Space Shuttle End-State Subsystems Requirements Document* (Houston: Johnson Space Center, September 10, 2010); William J. Roberts, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project*, August 25, 2010, 9, http://www.jsc.nasa.gov/history/oral_histories/STS-R/RobertsWJ/RobertsWJ_8-25-

performed, as per the requirements of the recipient museum. *Discovery* was the first Shuttle orbiter to complete T&R processing; *Endeavour* was the second, and *Atlantis* was the last.

The T&R flow began with Down Mission Processing (DMP), which required approximately two months for each of the three orbiters. This work was conducted in OPF-1 and OPF-2 at KSC. During this time, the Forward Reaction Control System (FRCS) module and Orbiter Maneuvering System (OMS) pods were removed, and sent to the Hypergolic Maintenance Facility for initial safing prior to transport to NASA's White Sands Test Facility in New Mexico for disassembly and removal of hypergolic propellants.[149]

Discovery underwent DMP in OPF-2 for four months, and then was transported to High Bay 4 of the VAB where it was stored for approximately one month while *Endeavour* was undergoing DMP in OPF-2. *Discovery* was then moved to OPF-1 for a series of final T&R activities. These End State Safing operations entailed the removal of all critical government equipment that cannot be permanently displayed with the orbiter. This included hazardous commodities and components.[150] A total of forty end-state safing and display requirements for nine subsystems were addresssed.

Next, specific display site operations configuration work was performed, per the requirements of the recipient museum. This two-stage process included the installation of replica shuttle main engines (RSMEs). The RSMEs are previously scrapped and cosmetically repaired nozzles installed into the aft of the retired orbiter via a newly-designed nozzle adapter. Pratt & Whitney Rocketdyne designed, manufactured, repaired and provided the nine RSME kits. The nine nozzles required cosmetic and structural repairs to the forward manifold adapter attach point, aft manifold and heat shield clips. The nozzle adapter was designed using Boeing dynamic load criteria for ferry flight.[151]

After a final power-down, the FRCS module and OMS pods, returned from White Sands, were installed. At the end of final display operations, the orbiter was considered "ready for ferry." Each orbiter was moved to the VAB for storage, until it was scheduled to be transported to its destination. The OMS pod engines were replaced with replicas before they were reattached to the Shuttle for public display.[152] From the VAB, *Discovery* and *Endeavour* were towed to the SLF and mated to the SCA. *Discovery* made its final ferry flight on April 17, 2012.[153] After the

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10.htm.
[149] Steven Siceloff, "Retirement a New Beginning for Discovery," March 16, 2011, http://www.nasa.gov/mission_pages/shuttle/behindscenes/discoveryretire_prt.htm.
[150] Chris Gebhart, "*Endeavour* and *Discovery* swap places—New Retirement Dates Planned," August 11, 2011, http://www.nasaspaceflight.com/2011/08/endeavour-discovery-swap-places-new-retirement-dates-planned/.
[151] Chris Bergin, "Replica engines recommended for retired orbiters – Flown SSMEs for HLV," October 21, 2010, http://www.nasaspaceflight.com/2010/10/replica-engines-retired-orbiters-flown-ssmes-hlv/NASASpaceflight.com.
[152] Steven Siceloff, "Retirement a New Beginning for Discovery."
[153] Henry Taylor, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project*, August 26, 2011, http://www.jsc.nasa.gov/history/oral_histories/STS-R/TaylorHT/TaylorHT_8-26-11.htm; Chris Gebhart,

delivery of *Discovery*, the SCA ferried *Enterprise* to New York, on April 27, 2012 for display at the Intrepid Sea, Air and Space Museum. According to Henry Taylor, *Enterprise* probably will "sit on the SCA" for four to six weeks before the equipment arrives to take it off. After *Enterprise*, the SCA will go back to Edwards AFB and finally, in September 2012, the SCA will pick up *Endeavour* in Florida, and fly it to the Los Angeles International Airport in preparation for its transport to the California Science Center. At the final location, two large cranes will be used to help demate each orbiter from the SCA.[154]

T&R Processing Timetable (Planned)[155]

Activity	***Discovery***	***Endeavour***	***Atlantis***
Down Mission Processing	March 9 to mid-July 2011	June 1 through Mid-August 2011	July 21 through mid-October 2011
Storage in VAB	Mid-July 2011	Mid-August to mid-October 2011	Mid-October 2011
End State Safing	August to early November 2011	Mid-October 2011 through mid-March 2012	January- May 2012
FRCS/OMS pods shipped to White Sands for safing and processing			Mid-March 2012
Installation of RSMEs	Late October 2011	Early January 2012	Mid-May
Final power-down	Mid-October	Early February 2012	May 2012
Return of FRCS/OMS pods	Late October/early November 2011	Late March 2012	Mid-May to mid-June 2012
Display configuration ops, Part 2; installation of FRCS/OMS pods	November through mid-December 2011	Late March 2012	Early July through mid-September
Processing completed ("ready for ferry")	January 3, 2012	Mid-May 2012	Mid-September 2012
Storage in VAB	January 3 through April 10, 2012	Mid-May through July	Mid-September until February 2013
Roll out for transport; tow to SLF	April 10, 2012	August 2, 2012	February 1, 2013

As of late 2011, NASA planned to retain the SSMEs for potential later use. After all the orbiters are delivered, plans called for both SCAs to be transferred to the Stratospheric Observatory for Infrared Astronomy (SOFIA) Program; the SOFIA Program wanted the engines as spares, so the SCAs "probably won't fly anymore."[156] The SOFIA Program is a large infrared telescope in a 747, operated by DFRC out of the Palmdale Airport. The SCAs will not be modified.

"*Endeavour* and *Discovery* swap places."
[154] Chris Bergin, "Discovery's Elaborate Deservicing Plan Put Into Work Amid Managerial Praise," March 14, 2011, http://www.nasaspaceflight.com/2011/03/discoverys-deservicing-plan-work-amid-praise/.
[155] Chris Gebhardt, "Endeavour and Discovery swap places."
[156] Henry Taylor, interview, 16-17.

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]

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[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.

<u>OV-095</u>

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]

[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

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[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.

[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]

[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]

<u>*Endeavour* (OV-105)</u>

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.

[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.

Early Research and Development

> "*We knew it would be hot in the nose and the wings and not as hot on the top side. That's what we started out with.*"[271]

As captured in the statement of Wendell D. Emde, former supervisor of North American Rockwell's TPS group, there was no precedent for the thermal protection system required by the STS. NASA first experimented with ablative heat shields for the Mercury, Gemini, and Apollo programs, but by 1970, for the future space shuttle, the agency sought a type of heat shield that was reusable. In early 1971, NASA MSC awarded contracts to three companies for the development of new orbiter "surface materials." The recipients of the contracts, valued at about $320,000 each, were McDonnell Douglas Corporation; General Electric Company, Aerospace Group; and the Lockheed Missiles and Space Company. The contracts covered the design, development and testing of a ceramic insulator class of materials, including the delivery of sample tiles sized to 12" x 12" x 2".[272]

One of the alternate reusable heat shields under consideration was known as reusable surface insulation (RSI). RSI, in turn, led directly to the development of thermal ceramic tiles. Lockheed's research center in Palo Alto, California, had undertaken research and development for this type of thermal protection shield, beginning in the early 1960s. By 1970-1971, Lockheed had a functioning pilot plant to manufacture silica RSI tiles. Experimentation for improved tile materials continued, and in late 1972, NASA ran a series of tests at several of its centers. At the MSC (now JSC) in Houston, Lockheed RSI tiles were the only ones that survived the final series of thermal-acoustic tests.[273] The final tiles had two different coatings, as well as size and thickness dimensions, dependent on which area of the shuttle they were to cover. NASA testing and evaluation of the tiles continued through the 1970s, most notably at Ames.

Manufacture

Following their award as the orbiter and shuttle integration prime contractor, North American Rockwell selected the Lockheed Missile and Space Company as the subcontractor for the manufacture of most of the shuttle's TPS. Production of the insulating tiles which covered the orbiter's surface was initiated at Lockheed's new facility in Sunnyvale, California, on September 15, 1976.[274] The first shipment of HRSI was delivered to Rockwell in early 1977. Subsequently, in the mid-1980s, Rockwell took over the manufacture of TPS materials at Palmdale, where

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[271] Wendell D. Emde, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project,* August 27, 2010, http://www.jsc.nasa.gov/history/oral_histories/STS-R/EmdeWD/EmdeWD_8-27-10.htm
[272] "MSC Awards Three Contracts For Shuttle Surface Materials," *Roundup*, July 16, 1971, 1.
[273] Joan Lisa Bromberg, *NASA and the Space Industry* (Baltimore: Johns Hopkins University Press, 1999), 100.
[274] "Orbiter insulation production begins," *Roundup*, September 24, 1976, 2.

NASA constructed Building 154 for work on protective tile adhesives, gap fillers, thermal barriers, and foam, during 1983-1984.[275] Rockwell fabricated FRSI in various thicknesses.

Supplementing the tile assembly and manufacturing capabilities at Lockheed's Sunnyvale plant and at Rockwell's Palmdale plant was the Thermal Protection System Facility (TPSF) at KSC, completed in 1988. The first tiles made at KSC were produced in the OPF-2. Later, the manufacture and repair of the Space Shuttle's tiles, gap fillers, and insulation blankets, as well as coatings and adhesives, were moved to the TSPF. Each unique tile underwent a process which took it from raw materials through finished product; the gap fillers and blankets were assembled from pre-made fabrics. Following their manufacture, TPS products were delivered to the OPF for installation on the orbiter. The first tiles produced at KSC flew on *Columbia* in January 1990.[276]

NASA encountered major challenges in the tile adhesive process. The tiles were fragile and required an intermediate, flexible layer next to the skin of the shuttle. A SIP, made of Nomex nylon felt, served this purpose. Rockwell individually bonded the tiles to SIPs. Workmen glued them to the shuttle in arrays, with small gaps set between the tiles. At their Palmdale plant, Rockwell workers painted the exterior of the shuttle with a green epoxy corrosion inhibiter at the start of the tile application process. Rockwell also used a blueprint-like guide printed on Mylar to assist in tile layout. Typically, the tiles also required extensive post-mission reworking after each shuttle flight.

TPS Testing

Qualifying a new TPS material required extensive testing. Critical to the testing process were NASA's arc jet facilities at both Ames and JSC; the arc jets simulated flight entry conditions. Ames also played a leading role in the development and testing of plugs, patches, pastes, and other materials used to repair damage to the shuttle's TPS while in orbit.

Between December 1979 and November 1980, approximately sixty flights were flown during a 12-month flight test program at NASA's DFRC. Both the F-15 and F-104 aircraft were used to test some of the TPS tiles from the orbiter to demonstrate tile performance up to 104 percent of the dynamic pressure planned for shuttle operations.[277] Six different tile articles were constructed identical to the areas of the orbiter surface being represented. The tested locations were the closeout tile aft of the wing leading edge area; the forward wing glove area; the vertical tail leading edge; the window post area; and the elevon leading edge and elevon hinge areas. As a

[275] Boeing, *Space Exploration – Palmdale, CA: AF Plant 42, Site 1 North* (Palmdale, California: The Boeing Company, 2006).
[276] Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Thermal Protection System Facility (John F. Kennedy Space Center)," HAER No. FL-8-11-L. Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, April 2011, 13.
[277] "Dryden to Participate in More Shuttle Tests," *X-Press*, October 5, 1979, 2-3; "Tile Tests Continued," *X-Press*, August 22, 1980, 2.

result, several design changes were made to the TPS in several areas.[278] "These changes consisted of revision of attachment techniques to improve binding forces, modified gap filler assemblies to prevent detachment, and improved installation and testing techniques to ensure satisfactory compliance with design requirements."[279] These changes were later incorporated into the orbiter.

Beginning in late 1982, DFRC conducted tests of AFRSI, as part of Ames' investigation of new thermal protection materials. Following initial wind tunnel tests conducted at Ames, the baseline test program at DFRC used the F-140 aircraft to subject the AFRSI to air loads that were equal and up to 1.4 times those experienced in actual flights. Variations in the materials tested in the baseline series included insulation fabricated using heavy and light surface fabric, felt layers of differing thicknesses, and varying joint configurations. Later tests at DFRC, in early 1983, investigated the drag characteristics of the insulation materials, as well as more severe thermal and aerodynamic environments to help determine the long-term durability.[280]

TPS Evolutionary Changes

Throughout the SSP, the TPS that safeguarded the shuttle's frame from the intense heat of space was regularly modified. Changes were both in response to technological advances as well as to correct problems detected after flight. Early in the SSP, for example, plasma flow was discovered where the wings and elevons met. Hence, the LRSI tiles on *Discovery* and *Atlantis* were replaced by FRCI and HRSI tiles and gap fillers.[281] In other areas not exposed to high temperatures, the LRSI tiles were replaced by AFRSI blankets, developed after *Columbia* was delivered to KSC in 1979. The blankets were stronger, lighter, quicker to install, and cheaper than the LRSI tile alternative. After its seventh flight, *Columbia* was modified to replace most of the LRSI tiles with AFRSI, and AFRSI blankets gradually replaced most of the LRSI tiles on *Discovery* and *Atlantis*. The LRSI tiles on *Columbia*'s mid-fuselage, payload bay doors, and vertical stabilizer were also replaced, and *Endeavour* was built with many AFRSI blankets already in place.[282] Damaged HRSI tiles were replaced by the more durable FRCI tiles, which were developed after the construction of the Space Shuttle. Furthermore, in 1988, the HRSI tiles near the nose cap were regularly damaged upon reentry, so they were replaced with a RCC chin. TUFI tiles successfully debuted in 1994 on *Endeavour*'s base heat shield between the three SSMEs. From then on, TUFI tiles were used to replace damaged HRSI tiles on the base heat shield and lower body flap surface, because the TUFI tiles were more likely to dent than break when struck.

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[278] "Shuttle Tile Tests Being Completed," *X-Press*, November 21, 1980, 2; "Shuttle Tile Test Completed," *X-Press*, January 16, 1981, 2.
[279] "Shuttle Tile Test Completed."
[280] "Dryden Starts Shuttle Insulation Tests," *X-Press*, January 7, 1983, 2; "Space Shuttle Insulation Tested Here for Air Load Data," *X-Press*, March 18, 1983, 2 and 4.
[281] Jenkins, *Space Shuttle*, 400.
[282] Jenkins, *Space Shuttle*, 401.

As a result of the trend to replace some tiles with Flexible Insulation Blankets (FIBs), while the earlier orbiters used as many as 34,000 tiles, the last addition to the orbiter fleet, *Endeavour*, was protected by approximately 26,000 tiles. Beginning in 1996, AFRSI blankets were replaced by the lighter FRSI tiles to reduce weight in preparation for flights to the ISS. During major modification periods, the FRSI tiles were added to the shuttle midfuselage and aft fuselage, payload bay doors, and upper wing surfaces.[283]

The wing leading edge RCC upper panels were designed to withstand up to 1”-long penetrations and still block plasma flow. However, some of the lower panels could not suffer any damage without letting heat from the plasma flow reach the leading attach fittings and front spar in the wings. Starting in 1998, during major modifications, insulation was added to the lower panels.[284]

The *Columbia* accident demonstrated that the shuttle’s TPS design was vulnerable to impact damage from the existing debris environment. As a result, NASA initiated a program to harden the orbiter against impacts.[285] In 2003, spar sneak flow protection was added to the wing leading edges to prevent hot gas flow from potentially reaching the RCC tiles. In addition, the horse collar gap fillers were redesigned to prevent hot gas from passing into the wing leading edges in case a tile broke off.[286] Beginning with STS-121 in July 2006, NASA replaced the existing FRCI belly tiles with the more impact-resistant Boeing Rigid Insulation (BRI) tiles around the main landing gear door, nose landing gear door, ET umbilical doors, wing leading edge carrier panels, and windows. These changes were made during orbiter processing between flights.[287]

ID. Shuttle Carrier Aircraft

Two NASA-owned SCAs, N905NA and N911NA, supported the SSP. These aircraft were modified four-engine intercontinental range Boeing 747 jetliners, originally manufactured for commercial use (Figure Nos. A-34, A-35).

Historical Overview

In 1973, early in the SSP, NASA considered both the C-5A cargo aircraft, manufactured by Lockheed,[288] and the Boeing 747 “jumbo jet” as potential vehicles to ferry the orbiter cross country. In August and October 1973, contracts were awarded to Boeing and Lockheed, respectively, to conduct preliminary feasibility studies to evaluate whether the orbiter could

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[283] Jenkins, *Space Shuttle*, 398-401.
[284] Jenkins, *Space Shuttle*, 398-401.
[285] NASA, *NASA’s Implementation Plan for Space Shuttle Return to Flight and Beyond*, vol. 1 (Washington, DC: NASA Headquarters, 2007), 1-21.
[286] Boeing, *Atlantis OV-104, Volume II*, 74.
[287] NASA, *NASA’s Implementation Plan*, 1-25.
[288] The original version of the C-5A was manufactured by Lockheed between 1968 and 1973. This large military transport aircraft, which featured a heavy airlift capacity, was used primarily by the US Air Force.

separate from the back of the carrier aircraft. NASA's DFRC awarded a $56,000 contract to Boeing to study the feasibility of using a large aircraft to ferry the orbiter. The contract was the result of an unsolicited proposal submitted by Boeing. The objective of the 60-day study was to define operational requirements, performance, cost, schedules and preliminary systems design for such a carrier aircraft.[289] The Lockheed contract covered wind tunnel tests simulating the use of a C-5A as a ferry aircraft. The tests of a scale model of the orbiter mounted atop a scale model of the C-5A were conducted in Lockheed's Low Speed Tunnel in Burbank, California. The objectives were to determine if the plan was technically feasible, and if so, to determine the optimum location for positioning the orbiter on the C-5A.[290]

Test results demonstrated that the 747 had several advantages over the C-5A. The 747 was shown to be safer, and to be capable of a nonstop transcontinental flight without the need for refueling. Additionally, it could use shorter runways, and had a longer structural life. As a result, by June 1974, NASA replaced its earlier plans to install six air-breathing engines on the orbiter for ferry flights in favor of using a Boeing 747 to transport the orbiter. Following the request of authorization made by Christopher Kraft, director of NASA's JSC, in June 1974, NASA's Space Shuttle Program Office approved the purchase of a Boeing 747 airplane for use as the SCA.[291]

On July 18, 1974, NASA purchased a used Boeing 747-123 jetliner from American Airlines for approximately $15.6 million. At the time of purchase, the aircraft had logged about 9,000 flight hours. It was given the registration number N905NA.[292] Before being modified, the aircraft was initially used as part of a DFRC study of trailing wake vortices; this research was not directly connected to the SSP.[293] Subsequently, the Boeing 747 was used in a shuttle program-related simulated separation maneuver test. On August 2, 1976, modifications were started by Boeing at their production facilities near Everett, Washington. Work under this $30 million contract was completed in December. Under a separate contract, four Pratt and Whitney JT9D-3A engines were altered for use on the SCA.[294] In January 1977, the modified aircraft was flown to Edwards AFB for use with the *Enterprise* during the ALT Program. The tests were a success and demonstrated the flightworthiness of the aircraft-orbiter combination.[295]

N905NA was the only SCA until November 1990. In the wake of the 1986 *Challenger* accident, the Rogers Commission recommended that increasing the ferry capacity would enhance

[289] "Boeing Gets Contract For Shuttle Ferry," *X-Press*, August 3, 1973, 2.
[290] "Shuttle Ferry Wind Tunnel Tests Slated," *X-Press*, October 26, 1973, 4.
[291] "747 To Be Used For Orbiter Transport," *X-Press*, June 21, 1974, 2.
[292] Heppenheimer, *Development of the Space Shuttle,* 94.
[293] Jenkins, *Space Shuttle*, 196.
[294] Jenkins, *Space Shuttle*, 197. The Pratt & Whitney JT9D engine was a large commercial turbo fan engine initially used on Boeing's 747-100.
[295] T.A. Heppenheimer, *Development of the Space Shuttle,* 121.

reliability of ferry operations and would eliminate a "single point failure from the program."[296] In accordance, in February 1988, NASA announced plans to acquire a second 747 to serve as backup to N905NA.[297] A surplus Japan Air Lines domestic passenger aircraft (747-100SR) with about 32,000 hours of flight time was acquired for NASA by Boeing in April 1988. Boeing began modifications to the aircraft in 1988, at the Boeing Military Airplanes manufacturing facility in Wichita, Kansas, under a $55 million contract, which included the cost of purchase.[298] After the structural work was completed, the aircraft was delivered to Chrysler Technologies in Waco, Texas, for painting.[299] SCA N911NA was added to the NASA fleet on November 20, 1990.[300] It was first used in May 1991, to deliver the new orbiter *Endeavour* (OV-105) to KSC.

Structural modifications to N905NA and N911NA to support ferry operations included stripping each airplane down to the "skin;" adding bracing for structural support; adding two vertical stabilizers, one on each end of the standard horizontal stabilizer; and adding three mounting struts, one forward and two aft, for attachment of the orbiter. Also, extra layers of aluminum skin were added to various stress points throughout the airplane.[301] Inside, aft of the forward doors, all of the standard internal furnishings, seats, overhead bins, etc. were removed (Figure A-35). A few seats were retained for transport of support personnel. Redundant power supplies and cabling were added, primarily to power orbiter fluid system heaters and water coolant loop pumps during ferry operations.[302] New controls and displays for the cockpit were added to monitor these devices. Modifications increased the basic weight of the aircraft by about 2,800 pounds.[303] Some modifications were reversible, including the support struts, the horizontal tip fans, and associated cabling and umbilicals.[304] Improvements also were made to the Pratt and Whitney JT-9D engines to provide more power. In late 1995, the NASA worm logo on the vertical stabilizer of N911NA was repainted with a new stylized tail logo. A few months later, the old logo was replaced on N905NA.

The two SCAs are nearly identical. Each aircraft measures approximately 231'-10" in length, with a wing span of 195'-8". The height to the top of the cockpit area is 32'-1", and 63'-5" to the

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[296] Barbara Schwartz, "NASA Announces Delivery of Second Shuttle Carrier Aircraft," NASA News Release, November 16, 1990, http://www.nasa.gov/centers/johnson/pdf/83142main_1990.pdf; Jeff Carr, "Ferry fleet doubles in size," *Space News Roundup*, November 16, 1990, 1 and 4.
[297] Jenkins, *Space Shuttle*, 198.
[298] Jeffrey E. Carr, "NASA Buys Second Shuttle Carrier Aircraft," NASA News Release, August 10, 1988, http://www.nasa.gov/centers/johnson/pdf/83140main_1988.pdf.
[299] Schwartz, "Second Shuttle Carrier Aircraft."
[300] Jenkins, *Space Shuttle*, 198.
[301] Taylor, interview, 29.
[302] Donald L. McCormack, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project*, March 24, 2011, http://www.jsc.nasa.gov/history/oral_histories/STS-R/McCormackDL/McCormackDL_3-24-11.htm. The SCA provided power to the orbiter during the ferry mission. If the orbiter lost power, some of the circulation systems and coolant loops became affected, Taylor, interview, 9.
[303] Marty Curry, ed., "Shuttle Carrier Aircraft," NASA Fact Sheets, July 21, 2006, http://www.nasa.gov/centers/dryden/news/FactSheets/FS-013-DFRC.html.
[304] NASA, *NSTS Shuttle Reference Manual*, "Shuttle Carrier Aircraft," August 31, 2000.

top of the vertical stabilizer. Each has a maximum gross taxi weight of 713,000 pounds. SCA N905NA has a basic weight of 318,053 pounds; N911NA weighs 323,034 pounds.[305] N911NA has five upper-deck windows on each side and N905NA has only two. To balance the SCA when it was carrying the orbiter, nearly 2 tons of pig iron and 3.5 tons of pea gravel were used as ballast. The pig iron is secured up front in the former first class section; the pea gravel is contained in cargo containers in the lower forward cargo bay.[306]

Ferry Flights

The two SCAs transported all five orbiters from California to KSC following their assembly at Palmdale. Cross-country ferry flights also were made following post-mission landings at Edwards AFB, as well as for orbiter maintenance and modifications in Palmdale (prior to September 2002).

Between March 1979, when SCA N905NA delivered *Columbia* to KSC, and September 2009, when SCA N911NA returned *Discovery* after mission STS-128, the two SCAs completed a total of seventy-six ferry flights comprised of 238 legs.[307] Almost three-quarters of the ferry flights were made by SCA N905NA, which actively served the SSP between 1979 and 2007.[308] SCA N911NA completed twenty ferry flights during its eighteen years of service (1991 through 2009), which began with the initial delivery of *Endeavour* to KSC in May 1991.

Tabulation of Ferry Flights and Flight Legs, by SCA and Flight Purpose

SCA	Initial Delivery No. Flights/No. Legs	Post-Mission No. Flights/No. Legs	OMM/OMDP No. Flights/No. Legs	Totals No. Flights/No. Legs
N905NA	4/11	42/126	10/29	56/166
N911NA	1/6	13/47	6/19	20/72
Totals	5/17	55/173	16/48	76/238
Average No. Legs	3.4	3.2	3.0	3.1

With the exception of *Endeavour*, the newly assembled orbiters were towed from Palmdale to Edwards AFB and mated to SCA N905NA using the MDD at DFRC. *Endeavour* was the only new orbiter delivered by SCA N911NA, and the only one to be mated to the SCA at Palmdale using the OLF.

305 Curry, "Shuttle Carrier Aircraft."
306 Gray Creech, "Gravel Haulers: NASA's 747 Shuttle Carriers," August 22, 2003, http://www.nasa.gov/news/special/747_Shuttle_Carriers_prt.htm.; Pete Seidl, interview by Joan Deming and Patricia Slovinac, September 18, 2006.
307 A leg was the distance traveled between stops for fueling or other purposes.
308 In 1977, SCA N905NA was used in NASA's ALT Program. It also carried the orbiter prototype *Enterprise* to KSC for various fit checks and facility tests. The last post-mission (STS-128) landing of a SCA at Edwards AFB was on September 11, 2009. The final seven missions of the SSP ended with landings at KSC.

Early in the SSP, Edwards AFB was the preferred post-mission landing site because of more stable weather conditions as well as a choice of concrete and dry lake beds. However, KSC later became the primary landing site because it saved processing time to prepare for the next mission. The first landing at KSC was at the end of mission STS-41B, on February 11, 1984. Overall, approximately 74 percent of the first fifty missions, between 1981 and 1992, ended with a landing in California, resulting in thirty-seven ferry flights to return the orbiter to KSC. Of these, all but four of the thirty-seven used SCA N905NA. The first mission-related use of SCA N911NA was in support of STS-40 in June 1991. For the next fifty shuttle flights, between 1992 and 2000, only ten (25 percent) of the landings were made at Edwards AFB. The SCAs were placed into service equally, with five ferry flights each. In total, throughout the SSP, fifty-five post-mission ferry flights were made between California and Florida. SCA N905NA carried the orbiters forty-two times and SCA N911NA was used for thirteen flights. *Discovery* was the fleet leader, with a total of fifteen ferry flights, followed by *Columbia* and *Atlantis*, with thirteen each; *Challenger* and *Endeavour* rode atop the SCA seven times each.

Tabulation of Post-Mission Ferry Flights, by Orbiter and SCA

SCA	**OV-099** ***Challenger***	**OV-102** ***Columbia***	**OV-103** ***Discovery***	**OV-104** ***Atlantis***	**OV-105** ***Endeavour***	**Totals**
N905NA	7	12	12	9	2	42
N911NA	0	1	3	4	5	13
Totals	7	13	15	13	7	55

Post-mission ferry flights averaged three legs per flight. All but four ferry flights were made in two to four legs. *Columbia*, *Discovery*, and *Atlantis* each had a single five-leg ferry flight following missions STS-35, STS-42, and STS-76, respectively. The initial delivery of *Endeavour* entailed a six-leg journey.

In addition to initial delivery and mission-related flights, between 1985 and 2001, the SCAs were used to transport the orbiters between KSC and Palmdale, sixteen times in support of eight vehicle maintenance and major modifications.[309] Ten flights were made by SCA N905NA and six by SCA N911NA. On *Columbia's* first trip back to Palmdale, it was demated and mated at the DFRC MDD and towed to and from Palmdale. After the *Challenger* accident, the OLF was assembled at Palmdale and used to mate and demate the orbiter from the SCA. For cost-saving reasons, beginning in September 2002, NASA relocated the orbiter overhaul and upgrade operations from Palmdale to KSC. Thus, since late 2002, the SCAs have provided ferry flight service only in situations where bad weather requires a landing in California. A list of SSP ferry flights follows.

Notably, in 2001, a unique event in the history of the SSP took place in the form of simultaneous dual ferry missions. As related by Donald McCormack, *Columbia* was at Palmdale for maintenance, and scheduled to be ferried back to KSC in late February using SCA N905NA. On

[309] *Columbia* made four trips to Palmdale, *Atlantis* two, and *Discovery* and *Endeavour*, one trip each.

February 20, 2001, *Atlantis* concluded the STS-98 mission with a landing at Edwards AFB; turnaround processing began immediately. Since *Atlantis* would be flown again sooner than *Columbia*, NASA decided that the *Columbia* ferry mission could not interfere with the *Atlantis* ferry. Also, neither could interfere with the launch of the STS-102 (*Discovery*) mission, scheduled for March 8. Subsequently, two independent ferry missions were accomplished, with *Atlantis* using SCA N911NA. *Columbia* was prepared first, but the ferry mission was delayed by rain. By this time, *Atlantis* was also ready. Therefore, on March 1, 2001, *Columbia* was flown to Dyess AFB in Abilene, Texas, and *Atlantis* was flown to Altus AFB near Altus, Oklahoma, on the first leg of their respective ferry flight. Both *Atlantis* and *Columbia* arrived at KSC on March 4. *Atlantis* went to the KSC SLF and *Columbia* went to the skid strip at Cape Canaveral Air Force Station (CCAFS). Following the demating of *Atlantis*, *Columbia* was moved to the SLF on March 5.[310]

Space Shuttle Ferry Flights (exclusive of OV-101)

Seq. No.	Flight	Orbiter	SCA	Flight Legs	Flight Route/Date	Initial Delivery	Post-Mission	OMM/ OMDP
1	Delivery to KSC	OV-102	905	4	EDW-BIF/Mar. 20, 1979 BIF-SKF/ Mar. 22, 1979 SKF-VPS/ Mar. 23, 1979 VPS-X68/ Mar. 24, 1979	X		
2	STS-1	OV-102	905	2	EDW-TIK/ Apr. 27, 1981 TIK-X68/ Apr. 28, 1981		X	
3	STS-2	OV-102	905	2	EDW-BSM/Nov. 24, 1981 BSM-X68/Nov. 25, 1981		X	
4	STS-3	OV-102	905	2	SNG-BAD/Apr. 6, 1982 BAD-X68/Apr. 6, 1982		X	
5	Delivery to KSC	OV-099	905	2	EDW-EFD/July 4, 1982 EFD-X68/July 5, 1982	X		
6	STS-4	OV-102	905	2	EDW-DYS/July 14, 1982 DYS-X68/July 15, 1982		X	
7	STS-5	OV-102	905	2	EDW-SKF/Nov. 21, 1982 SKF-X68/ Nov. 22, 1982		X	
8	STS-6	OV-099	905	2	EDW-SKF/Apr. 14, 1983 SKF-X68/Apr. 14, 1983		X	
9	STS-7	OV-099	905	2	EDW-SKF/June 28, 1983 SKF-X68/June 29, 1983		X	
10	STS-8	OV-099	905	2	EDW-SPS/Sept. 9, 1983 SPS-X68/Sept. 9, 1983		X	
11	Delivery to KSC	OV-103	905	3	EDW-VBG/Nov. 6, 1983 VBG-FWH/Nov. 8, 1983 FWH-X68/9 Nov. 9, 1983	X		

[310] McCormack, interview, 19-20.

Seq. No.	Flight	Orbiter	SCA	Flight Legs	Flight Route/Date	Initial Delivery	Post-Mission	OMM/ OMDP
12	STS-9	OV-102	905	4	EDW-BIF/Dec. 14, 1983 BIF-SKF/Dec. 14, 1983 SKF-VPS/Dec. 15, 1983 VPS-X68/Dec. 15, 1983		X	
13	Mods	OV-102	905	2	X68-SKF/Jan. 26, 1984 SKF-EDW/Jan. 27, 1984			X
14	STS-41C	OV-099	905	2	EDW-SKF/Apr. 17, 1984 SKF-X68/Apr. 18, 1984		X	
15	STS-41D	OV-103	905	2	EDW-LTS/Sept. 9, 1984 LTS-X68/Sept. 10, 1984		X	
16	Delivery to KSC	OV-104	905	2	EDW-EFD/Apr. 12, 1985 EFD-X68/Apr. 13, 1985	X		
17	STS-51B	OV-099	905	2	EDW-SKF/May 10, 1985 SKF-X68/May 11, 1985		X	
18	STS-51G	OV-103	905	2	EDW-BSM/June 28, 1985 BSM-X68/June 28, 1985		X	
19	Mods	OV-102	905	2	EDW-OFF/July 14, 1985 OFF-X68/July 14, 1985			X
20	STS-51F	OV-099	905	4	EDW-DMA/Aug. 10, 1985 DMA-SKF/Aug. 10, 1985 SKF-VPS/Aug. 11, 1985 VPS-X68/Aug. 11, 1985		X	
21	STS-51I	OV-103	905	2	EDW-SKF Sept. 7, 1985 SKF-X68/Sept. 8, 1985		X	
22	STS-51J	OV-104	905	2	EDW-SKF/Oct. 11, 1985 SKF-X68/Oct. 11, 1985		X	
23	STS-61A	OV-099	905	4	EDW-DMA/Nov. 10, 1985 DMA-SKF/Nov. 10, 1985 SKF-VPS/Nov. 11, 1985 VPS-X68/Nov. 11, 1985		X	
24	STS-61B	OV-104	905	2	EDW-SKF/Dec. 7, 1985 SKF-X68/Dec. 7, 1985		X	
25	STS-61C	OV-102	905	4	EDW-DMA/Jan. 22, 1986 DMA-SKF/Jan. 22, 1986 SKF-VPS/Jan. 23, 1986 VPS-X68/Jan . 23, 1986		X	
26	STS-26	OV-103	905	2	EDW-SKF/Oct. 8, 1988 SKF-X68/Oct. 8, 1988		X	
27	STS-27	OV-104	905	3	EDW-DMA/Dec. 11, 1988 DMA-SKF/Dec. 12, 1988 SKF- -X68/Dec. 13, 1988		X	
28	STS-29	OV-103	905	2	EDW-SKF/Mar. 23, 1989 SKF-X68/Mar. 24, 1989		X	

Seq. No.	Flight	Orbiter	SCA	Flight Legs	Flight Route/Date	Initial Delivery	Post-Mission	OMM/ OMDP
29	STS-30	OV-104	905	4	EDW-BIF/May 13, 1989 BIF-DFW/May 15, 1989 DFW-WRB/May 15, 1989 WRB-X68/May 15, 1989		X	
30	STS-28	OV-102	905	4	EDW-EDW/Aug. 18, 1989 EDW-SPS/Aug. 20, 1989 SPS-WRB/Aug. 20, 1989 WRB-X68/Aug. 21, 1989		X	
31	STS-34	OV-104	905	3	EDW-BIF/Oct. 28, 1989 BIF-CBM/Oct. 28, 1989 CBM-X68/Oct. 29, 1989		X	
32	STS-33	OV-103	905	4	EDW-EDW/Dec. 2, 1989 EDW-SKF/Dec. 3, 1989 SKF-VPS/Dec. 3, 1989 VPS-X68/Dec. 4, 1989		X	
33	STS-32	OV-102	905	3	EDW-DMA/Jan. 25, 1990 DMA-SKF/Jan. 25, 1990 SKF-X68/Jan. 26, 1990		X	
34	STS-36	OV-104	905	4	EDW-EDW/Mar. 10, 1990 EDW-BIF/Mar. 11, 1990 BIF-CBM/Mar. 13, 1990 CBM-X68/Mar. 13, 1990		X	
35	STS-31	OV-103	905	3	EDW-SPS/May 5, 1990 SPS-WRB/ May 6, 1990 WRB-X68/ May 7, 1990		X	
36	STS-41	OV-103	905	3	EDW-SPS/Oct. 15, 1990 SPS-VPS/Oct. 15, 1990 VPS-X68/Oct. 16, 1990		X	
37	STS-35	OV-102	905	5	EDW-EDW/Dec. 16, 1990 EDW-BIF/Dec. 18, 1990 BIF-SKF/Dec. 18, 1990 SKF-BAD/Dec. 19, 1990 BAD-X68/Dec. 21, 1990		X	
38	STS-37	OV-104	905	4	EDW-SKF/Apr. 16, 1991 SKF-CBM/Apr. 16, 1991 CBM-MCF/Apr. 17, 1991 MCF-X68/Apr. 18, 1991		X	
39	Delivery to KSC	OV-105	911	6	PMD-PMD/May 2, 1991 PMD-BIF/ May 3, 1991 BIF-SKF/May 5, 1991 SKF-EFD/May 6, 1991 EFD-CBM/May ‘6, 1991 CBM-X68/ May 7, 1991	X		

Seq. No.	Flight	Orbiter	SCA	Flight Legs	Flight Route/Date	Initial Delivery	Post-Mission	OMM/ OMDP
40	STS-40	OV-102	905	4	EDW-BIF/June 19, 1991 BIF-SKF/June 20, 1991 SKF-CBM/June 20, 1991 CBM-X68/June 21, 1991		X	
41	OMDP	OV-102	911	4	X68-X-68/Aug. 9, 1991 X68-MCF/Aug. 10, 1991 MCF-SKF/Aug. 12, 1991 SKF-PMD/Aug. 13, 1991			X
42	STS-48	OV-103	911	4	EDW-BIF/Sept. 24, 1991 BIF-TIK/ Sept. 24, 1991 TIK-CBM/Sept. 25, 1991 CBM-X68/Sept. 26, 1991		X	
43	STS-44	OV-104	911	2	EDW-SPS/Dec. 7, 1991 SPS-X68/Dec. 8, 1991		X	
44	OMDP	OV-102	905	3	PMD-PMD/Feb. 7, 1992 PMD-SKF/Feb. 9, 1992 SKF-X68/Feb. 9, 1992			X
45	STS-42	OV-103	905	5	EDW-EDW/Feb. 11, 1992 EDW-BIF/Feb. 14, 1992 BIF-CBM/Feb. 15, 1992 SKF-CBM/Feb. 16, 1992 CBM-X68/Feb. 16, 192		X	
46	STS-49	OV-105	911	4	EDW-EDW/May 21, 1992 EDW-BIF/May 27, 1992 BIF-SKF/May 29, 1992 SKF-X68/May 30, 1992		X	
47	OMDP	OV-104	911	3	X68-GGG/Oct. 18, 1992 GGG-BIF/Oct. 18, 1992 BIF-PMD/Oct. 18, 1992			X
48	STS-53	OV-103	911	3	EDW-SKF/Dec. 15, 1992 SKF-VPS/Dec. 18, 1992 VPS-X68/Dec. 18, 1992		X	
49	STS-55	OV-102	905	4	EDW-BIF/May 11, 1993 BIF-SKF/May 12, 1993 SKF-CBM/May 12, 1993 CBM-X68/May 14, 1993		X	
50	STS-58	OV-102	911	4	EDW-BIF/Nov. 7, 1993 BIF-SKF/ Nov. 7, 1993 SKF-CBM/ Nov. 7, 1993 CBM-X68/Nov. 8, 1993		X	
51	STS-59	OV-105	911	4	EDW-EDW/Apr. 26, 1994 EDW-ELP/Apr. 30, 1994 ELP-LRF/May 1, 1994 LRF-X68/May 3, 1994		X	

Seq. No.	Flight	Orbiter	SCA	Flight Legs	Flight Route/Date	Initial Delivery	Post-Mission	OMM/ OMDP
52	OMDP	OV-104	911	4	PMD-BIF/May 27, 1994 BIF-CBM/ May 28, 1994 CBM-WRB/May 28, 1994 WRB-X68/May 29, 1994			X
53	STS-64	OV-103	905	2	EDW-SKF/Sept. 26, 1994 SKF-X68/Sept. 27, 1994		X	
54	OMDP	OV-102	905	4	X68-HSV/Oct. 8, 1994 HSV-EFD/Oct. 10, 1994 EFD-BIF/Oct. 11, 1994 BIF-PMD/Oct. 11, 1994			X
55	STS-68	OV-105	911	4	EDW-BIF/Oct. 19, 1994 BIF-DYS/Oct. 19, 1994 DYS-VPS/Oct. 20, 1994 VPS-X68/Oct. 20, 1994		X	
56	STS-66	OV-104	911	3	EDW-SKF/Nov. 21, 1994 SKF-VPS/Nov. 21, 1994 VPS-X68/Nov. 22, 1994		X	
57	STS-67	OV-105	905	3	EDW-DYS/Mar. 26, 1995 DYS-CBM/Mar. 27, 1995 CBM-X68/Mar. 27, 1995		X	
58	OMDP	OV-102	905	2	PMD-EFD/Apr. 11, 1995 EFD-X68/Apr. 14, 1995			X
59	OMDP	OV-103	905	3	X-68-NFW/Sept. 27, 1995 NFW-SLC/Sept. 27, 1995 SLC-PMD/Sept. 28, 1995			X
60	STS-76	OV-104	905	5	EDW-EDW/Apr. 6, 1996 EDW-DMA/Apr. 11, 1996 DMA-DYS/Apr. 11, 1996 DYS-VPS/Apr. 12, 1996 VPS-X68/Apr. 12, 1996		X	
61	OMDP	OV-103	911	4	PMD-PMD/June 25, 1996 PMD-LTS/June 28, 1996 LTS-WRB/June 28, 1996 WRB-X68/June 29, 1996			X
62	OMDP	OV-105	911	2	X68-SKF/July 30, 1996 SKF-PMD/July 30, 1996			X
63	OMDP	OV-105	905	4	PMD-PMD/Mar. 25, 1997 PMD-NFW/Mar. 26, 1997 NFW-WRB/Mar. 26, 1997 WRB-X68/Mar. 27, 1997			X
64	OMDP	OV-104	911	2	X-68-TIK/ Nov. 11, 1997 TIK-PMD/Nov. 14, 1997			X
65	OMDP	OV-104	905	4	PMD-PMD/Sept. 22, 1998 PMD-GRK/Sept. 23, 1998 GRK-HOP/Sept. 23, 1998 HOP/X68/ Sept. 27, 1998			X

Seq. No.	Flight	Orbiter	SCA	Flight Legs	Flight Route/Date	Initial Delivery	Post-Mission	OMM/ OMDP
66	OMM	OV-102	905	2	X68-SZL/Sept. 24, 1999 SZL-PMD/Sept. 25, 1999			X
67	STS-9	OV-103	905	3	EDW-LTS/Nov. 2, 2000 LTS-SZL/Nov. 2, 2000 SZL-X68/Nov. 3, 2000		X	
68	OMM	OV-102	905	3	PMD-DYS/Mar. 1, 2001 DYS-CCAS/Mar. 4, 2001 CCAS-X68/Mar. 5, 2001			X
69	STS-98	OV-104	911	4	EDW-LTS/Mar. 1, 2001 LTS-BAD/Mar. 3, 2001 BAD/VPS/Mar. 3, 2001 VPS-X68/Mar. 4, 2001		X	
70	STS-100	OV-105	905	3	EDW-LTS/May 8, 2001 LTS-LRF/May 8, 2001 LRF-X68/May 9, 2001		X	
71	STS-111	OV-105	911	3	EDW-LTS/June 28, 2002 LTS-SZL/June 28, 2002 SZL-X68/June 29, 2002		X	
72	STS-114	OV-103	905	3	EDW-LTS/Aug. 19, 2005 LTS-BAD/Aug. 19, 2005 BAD-X68/Aug. 21, 2005		X	
73	STS-117	OV-104	905	4	EDW-AMA/July 1, 2007 AMA-OFF/July 1, 2007 OFF-HOP/July 2, 2007 HOP-X68/July 3, 2007		X	
74	STS-126	OV-105	911	4	EDW-BIF/Dec. 10, 2008 BIF-NFW/Dec. 10, 2008 NFW-BAD/Dec. 11, 2008 BAD-X68/Dec. 12, 2008		X	
75	STS-125	OV-104	911	4	EDW-BIF/June 1, 2009 BIF-SKF/June 2, 2009 SKF-CBM/June 2, 2009 CBM-X68/June 2, 2009		X	
76	STS-128	OV-103	911	4	EDW-AMA/Sept. 20, 2009 AMA-NFW/Sept. 20, 2009 NFW-BAD/Sept. 20, 2009 BAD-X68/Sept. 21, 2009		X	

SCA Ferry Flight Stops

Identifier	Airfield	Identifier	Airfield
ATL	Atlanta Intl., GA	IAD	Dulles Intl., VA
AMA	Rick Husband Amarillo Intl., TX	LRF	Little Rock AFB, AR
BAD	Barksdale AFB, LA	LTS	Altus AFB, OK
BFM	Mobile Downtown Airport, AL	PMD	Palmdale Plant, CA
BIF	Biggs Army Airfield/Ft. Bliss, TX	MCF	MacDill AFB, FL
BSM	Bergstrom AFB, TX	NFW	NAS Fort Worth, TX*
CBM	Columbus AFB, MS	OFF	Offutt AFB, NE
CCAS	Cape Canaveral AFS, FL	MCI	Kansas City Intl, MO
DEN	Denver Intl., CO	SKF	Kelly AFB/Kelly Field Annex, TX
DMA	Davis-Monthan AFB, AZ	SLC	Salt Lake City Intl., UT
DYS	Dyess AFB, TX	SNG	Northrop Strip, NM
EDW	Edwards AFB, CA	SPS	Sheppard AFB, TX
EFD	Ellington Field, TX	SZL	Whiteman AFB, MO
FWH	Carswell AFB, TX	STL	St. Louis Intl., MO.
GGG	Gregg County Airport, TX	TUL	Tulsa Intl., OK
GRK	Robert Gray Army Airfield/Ft. Hood, TX	VBG	Vandenberg AFB, CA
HIF	Hill AFB, UT	VPS	Eglin AFB, FL
HOP	Fort Campbell Army Airfield, KY	WRB	Warner/ Robbins AFB, GA
HSV	Huntsville Intl., AL	X68	KSC Shuttle Landing Facility, FL

*Formerly FWH