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

---

[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.

---

[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).

---

[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]

---

[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]

---

[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

---

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]

---

[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,

---

268.
[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

---

[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

---

[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

---

[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:

---

[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]

---

[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.

---

[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,

[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]

---

[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.

---

[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]

---

[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

---

[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]

---

[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]

Missions and Payloads

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.

---

[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]

---

[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

---

[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

[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

---

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.