Chapter Two

Developing the Space Shuttle[1]

by Ray A. Williamson

Early Concepts of a Reusable Launch Vehicle

Spaceflight advocates have long dreamed of building reusable launchers because they offer relative operational simplicity and the potential of significantly reduced costs compared to expendable vehicles. However, they are also technologically much more difficult to achieve. German experimenters were the first to examine seriously what developing a reusable launch vehicle (RLV) might require. During the 1920s and 1930s, they argued the advantages and disadvantages of space transportation, but were far from having the technology to realize their dreams. Austrian engineer Eugen M. Sänger, for example, envisioned a rocket-powered bomber that would be launched from a rocket sled in Germany at a staging velocity of Mach 1.5. It would burn rocket fuel to propel it to Mach 10, then skip across the upper reaches of the atmosphere and drop a bomb on New York City. The high-flying vehicle would then continue to skip across the top of the atmosphere to land again near its takeoff point. This idea was never picked up by the German air force, but Sänger revived a civilian version of it after the war. In 1963, he proposed a two-stage vehicle in which a large aircraft booster would accelerate to supersonic speeds, carrying a relatively small RLV to high altitudes, where it would be launched into low-Earth orbit (LEO).[2] Although his idea was advocated by Eurospace, the industrial consortium formed to promote the development of space activities, it was not seriously pursued until the mid-1980s, when Dornier and other German companies began to explore the concept, only to drop it later as too expensive and technically risky.[3]

As Sänger's concepts clearly illustrated, technological developments from several different disciplines must converge to make an RLV feasible. Successful launch and return depends on all systems functioning in concert during the entire mission cycle as they pass through different environmental regimes. In the launch phase, the reusable vehicle and

---

1. In addition to the discussion of the Space Shuttle in this essay and the documents associated with it, there are several other places in the *Exploring the Unknown* series in which substantial attention is paid to issues related to the Space Shuttle, with related documents included. In particular, Chapter Three of Volume I discusses the presidential decision to develop the Space Shuttle; see John M. Logsdon, gen. ed., with Linda J. Lear, Jannelle Warren-Findley, Ray A. Williamson, and Dwayne A. Day, *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume I, Organizing for Exploration* (Washington, DC: NASA SP-4407, 1995), 1: 386–88, 546–59. Chapter Two of Volume II discusses NASA-Department of Defense relations with respect to the Shuttle; see John M. Logsdon, gen. ed., with Dwayne A. Day and Roger D. Launius, *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume II: External Relationships* (Washington, DC: NASA SP-4407, 1996), 2: 263–69, 364–410. Chapter Three of this volume discusses issues associated with the use of the Shuttle to launch commercial and foreign payloads. Future volumes will contain discussion and documents related to the use of the Shuttle as an orbital research facility.

2. Irene Sänger-Bredt, "The Silver Bird Story, a Memoir," in R. Cargill Hall, ed., *Essays on the History of Rocketry and Astronautics: Proceedings of the Third Through the Sixth History Symposia of the International Academy of Astronautics,* Vol. 1 (Washington, DC: NASA, 1977), pp. 195–228. (Reprinted as Vol. 7-1, American Astronautical Society History Series, 1986.)

3. Helmut Muller, "The High-Flying Legacy of Eugen Sänger," *Air & Space,* August/September 1987, pp. 92–99.

its booster, with any associated propellant tankage, must operate as a powerful rocket, lifting hundreds of thousands of pounds into LEO. While in space, the reusable vehicle functions as a maneuverable orbiting spacecraft in which aerodynamic considerations are moot. However, when reentering the atmosphere and slowing to subsonic speeds, aerodynamics and heat management quickly become extremely important, because the reusable vehicle must fly through the atmosphere, first at hypersonic speeds (greater than Mach 5), then at supersonic and, ultimately, at subsonic speeds. Finally, the vehicle must fly or glide to a safe landing. Because RLVs must be capable of flying again and again, and because they must reenter the atmosphere, they are subject to stresses on the materials and overall structure that expendable launchers do not have to withstand. Hence, building an RLV imposes extraordinarily high demands on materials and systems.

The conceptual origins of the world's first partially reusable vehicle for launch, NASA's Space Shuttle, reach back at least to the mid-1950s, when the Department of Defense (DOD) began to explore the feasibility of an RLV in space for a variety of military applications, including piloted reconnaissance, anti-satellite interception, and weapons delivery. The Air Force considered a wide variety of concepts, ranging from gliders launched by expendable rockets to a single-stage-to-orbit Aerospaceplane that bore a remarkable resemblance to the conceptual design for the National Aerospace Plane (NASP) of the late 1980s. The X-20 Dyna-Soar (Dynamic Soaring), the Air Force's late 1950s project to develop a reusable piloted glider, would also have had a small payload capacity.[4] NASA joined the Dyna-Soar project in November 1958.[5] The Air Force and NASA envisioned a delta-winged glider that would take one pilot to orbit, carry out a mission, and glide back to a runway landing. It would have been boosted into orbit atop a Titan II or III. As planned, the Dyna-Soar program included extensive wind tunnel tests and an ambitious set of airdrops from a B-52 aircraft. The Air Force chose six Dyna-Soar pilots, who began their training in June 1961. However, Dyna-Soar always competed for funding with other programs, including NASA's Project Gemini after 1961. Rising costs and other competing priorities led to the program's cancellation in December 1963.

Nevertheless, the testing that began during the Dyna-Soar program continued in other Air Force projects, such as the Aerothermodynamic-Elastic Structural Systems Environment Tests (ASSET) and Precision Recovery Including Maneuvering Entry (PRIME) projects. ASSET began in 1960 and was designed to test heat resistant metals and high-speed reentry and glide. PRIME was a follow-on project that began in 1966 and tested unpiloted lifting bodies (so called because they have a high ratio of lift over drag) that were boosted into space atop Atlas launchers. The Air Force also tested several models of piloted lifting bodies that were generally carried to high altitudes and released to a gliding landing. Among other things, these programs demonstrated that sufficient control could be achieved with a lifting body to land safely without a powered approach. This result later proved of great importance in the design of the Space Shuttle orbiter.

In 1957, the Air Force commissioned a conceptual study that examined recoverable space boosters.[6] From this came the concept called the Recoverable Orbital Launch System, which Air Force designers hoped would be capable of taking off horizontally and reaching orbits as high as 300 miles with a small payload. In a design that preceded the NASP concept, it would have had a hydrogen-fueled propulsion system that took its source of oxygen directly from the air by compressing and liquefying it in a "scramjet" engine,

4. Clarence J. Geiger, "History of the X-20A Dyna-Soar," Air Force Systems Command Historical Publications Series 63-50-I, October 1963. (Report originally classified, but declassified in 1975.)

5. See Chapter Two in Logsdon, gen. ed., *Exploring the Unknown,* 2: 249–62, for a complementary account of the Dyna-Soar program.

6. See Air Force Study Requirement SR-89774 (1957), Air Force Historical Research Agency, Maxwell Air Force Base, AL.

capable of operating at hypersonic speeds.[7] Designers quickly saw that the challenge of designing a propulsion system, or systems, capable of operating through three speed regimes—subsonic, supersonic, and hypersonic—placed extreme demands on available engine and materials technology. It was clearly not possible to build a single-stage-to-orbit vehicle with the technologies of the day.[8]

In 1962, in an effort to save the reusable concept, Air Force designers turned to a two-stage design for a concept they began to call the Aerospaceplane. Seven aerospace companies received contracts for the initial design.[9] Through these and several follow-on contracts, the companies not only produced paper studies, but undertook research on ramjet and scramjet propulsion, explored new structures and materials, and made significant advances in understanding hypersonic aerodynamics. However, reality never lived up to the designers' aspirations. By October 1963, after watching the Aerospaceplane program for some time with concern, DOD's Scientific Advisory Board reached the conclusion that the program was leading the Air Force to neglect conventional problems in launch research.[10] The Aerospaceplane program was quickly shut down.

NASA also sponsored a series of studies investigating reusable concepts for a variety of crews and payload sizes. By June 1964, NASA's Ad Hoc Committee on Hypersonic Lifting Vehicles with Propulsion issued a report urging the development of a two-stage reusable launcher.[11]

During the early 1960s, under government sponsorship, all of the major aerospace companies also developed their own version of a two-stage launch vehicle employing a lifting-body reentry vehicle. In each of these studies, the industrial concerns depended to a high degree on NASA and the Air Force to furnish the initial configuration on which to base their own version. The firms were concerned about straying too far from the concepts that their government "customers" were promoting.[12] This continued the practice evident in Project Mercury, in which the government agencies not only set the design goals and laid out the technical specifications but also instructed industry how to achieve them.

Origins of the Space Shuttle Program

No single action or decision similar to President Kennedy's May 25, 1961, "we should go to the moon" speech marks the beginning of the focused NASA program to develop the Space Shuttle. Rather, the program emerged over time in increments while NASA was simultaneously completing work on the Saturn V and launching the Apollo astronauts to the Moon and back. By the time President Nixon made the 1972 decision to proceed with Space Shuttle development, most major aspects of its design had been set.[13]

---

7. A scramjet (supersonic combustion ramjet) is an engine in which air compression, fuel mixing, and combustion all occur at supersonic speed.

8. Some even advocated refueling the Recoverable Orbital Launch System in hypersonic flight, using the X-15 to validate the concept. Fortunately, this extremely risky and dangerous concept was never tried. See Richard P. Hallion and James O. Young, "Space Shuttle: Fulfillment of a Dream," in Richard P. Hallion, ed., *The Hypersonic Revolution: Eight Case Studies in the History of Hypersonic Technology,* Volume II (Dayton, OH: Wright-Patterson Air Force Base, Special Staff Office, Aeronautical Systems Division, 1987), p. 948.

9. Boeing, Douglas, General Dynamics, Goodyear, Lockheed, North American Aviation, and Republic received contracts for system design studies. General Dynamics, Douglas, and North American received funding for detailed development plans. Martin built a full-scale model that explored the concept of incorporating the wings with the fuselage.

10. Hallion and Young, "Space Shuttle: Fulfillment of a Dream," p. 951.

11. Report of the NASA Special Ad Hoc Panel on Hypersonic Lifting Vehicles with Propulsion, June 1964. See also the memorandum from Floyd L. Thompson to James Webb, June 18, 1964. Copies in the NASA Historical Reference Collection, NASA History Office, NASA Headquarters, Washington, DC.

12. "In each case, whether dealing with Air Force-inspired configurations or NASA-inspired ones, contractors generally danced to an Air Force or NASA tune as regards the overall configuration itself." Hallion and Young, "Space Shuttle: Fulfillment of a Dream," p. 957.

13. See Logsdon, gen. ed., *Exploring the Unknown,* 1: 386–88.

As early as August 24, 1965, more than two years before the first Saturn V rose from the launch pad, the Air Force and NASA established an Ad Hoc Subpanel on Reusable Launch Vehicle Technology under the joint DOD-NASA Aeronautics and Astronautics Coordinating Board. Its objective was to determine the status of the technology base needed to support the development of an RLV. The report, which was issued in September 1966, concluded that many cost and technical uncertainties needed to be resolved, but it projected a bright future for human activities in Earth orbit. [II-1, II-2] Because the panel could find no single launch concept that would satisfy both NASA and DOD, it included ideas for a variety of fully reusable and partially reusable vehicles. Interestingly, the panel projected that partially reusable vehicles would be much cheaper to develop than fully reusable ones. Even so, engineers within both NASA and the Air Force continued to focus on fully reusable launch systems for several years, in the belief that once the difficult design and development problems were solved, such systems would prove much less costly to operate.[14] Some designers favored fully reusable designs that would employ a reusable booster and a cryogenic-powered orbiting vehicle. Others felt that the surest path to success was a small lifting body mounted on top of an expendable launch vehicle, such as a Titan III. Other design concepts lay between these two extremes.

As NASA began to think in depth about its post-Apollo human spaceflight programs after 1966, its top-priority objective became gaining approval for an orbital space laboratory—a space station. NASA planners also began to recognize that there was a need to reduce the costs of transporting crews and supplies to such an orbital outpost if it was to be affordable to operate. This, in turn, led to a focus on an Earth-to-orbit transportation system—a space shuttle. The idea that such a vehicle was an essential element in whatever might follow Apollo was first publicly discussed in an August 1968 talk by NASA Associate Administrator for Manned Space Flight George Mueller. [II-3]

In December 1968, as planning for the post-Apollo space program gained momentum, NASA convened the Space Shuttle Task Group to determine the agency's needs for space transportation. [II-4] This task group set out the basic missions and characteristics of the kind of vehicle that NASA hoped to gain approval to develop. Through the Manned Spacecraft Center and Marshall Space Flight Center, the Space Shuttle Task Group in mid-1969 issued a request for proposals (RFP) for what it termed an Integral Launch and Reentry Vehicle (ILRV) system. The RFP specified an emphasis on "economy and safety rather than optimized payload performance."[15] The eight-month studies that resulted formed the beginning of the Space Shuttle Phase A study effort.[16] Four aerospace contractors won ILRV study contracts—General Dynamics, Lockheed, McDonnell Douglas, and North American Rockwell.

The Space Shuttle Task Group final report, issued in July 1969, concluded that an ILRV should be capable of:

- Space station logistical support
- Orbital launch and retrieval of satellites

14. In the 1980s and 1990s, the goal of achieving vastly cheaper operational costs continued to elude designers. For a discussion of the technical issues, see U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

15. NASA Manned Spacecraft Center and Marshall Space Flight Center, "Study of Integral Launch and Reentry System," RFP MSC BG721-28-9-96C and RFP MSFC 1-7-21-00020, October 30, 1968. Copy in Johnson Space Center historical archives. Quoted in Hallion and Young, "Space Shuttle: Fulfillment of a Dream," p. 995.

16. NASA had created a four-phase project development scheme, which finally became codified in August 1968. Phase A consisted of advanced studies (or later, preliminary analysis); Phase B, project definition; Phase C, design; and Phase D, development and operations. See Hallion and Young, "Space Shuttle: Fulfillment of a Dream," pp. 995–96. See also Arnold S. Levine, *Managing NASA in the Apollo Era* (Washington, DC: NASA SP-4102, 1982), pp. 158–61.

- Launch and delivery of propulsive stages and payloads
- Orbital delivery of propellant
- Satellite servicing and maintenance
- Short-duration manned orbital missions

The report considered three classes of vehicles. Class I referred to reusable orbiting vehicles launched on expendable boosters. Class II applied to vehicles using a stage and a half. Class III meant two-stage vehicles in which both the booster and the orbiter were fully reusable.

On February 13, 1969, President Richard M. Nixon requested that a high-level study be conducted to recommend a future course of activities for the overall civilian space program.[17] The Space Task Group (STG), chaired by Vice President Spiro T. Agnew, delivered its report on September 15, 1969.[18] The STG also recommended an RLV that would:

- Provide a major improvement over the present way of doing business in terms of cost and operational capability
- Carry passengers, supplies, rocket fuel, other spacecraft, equipment, or additional rocket stages to and from LEO on a routine, aircraft-like basis
- Be directed toward supporting a broad spectrum of both DOD and NASA missions

As conceptualized in the STG report, a reusable space transportation system would have as the following components:

- A reusable chemically fueled **shuttle** operating between Earth's orbit and LEO in an airline-type mode (Figures 2–1 and 2–2)
- A chemically fueled **space tug** or vehicle for moving people and equipment to different Earth orbits and as a transfer vehicle between the lunar-orbit base and the lunar surface

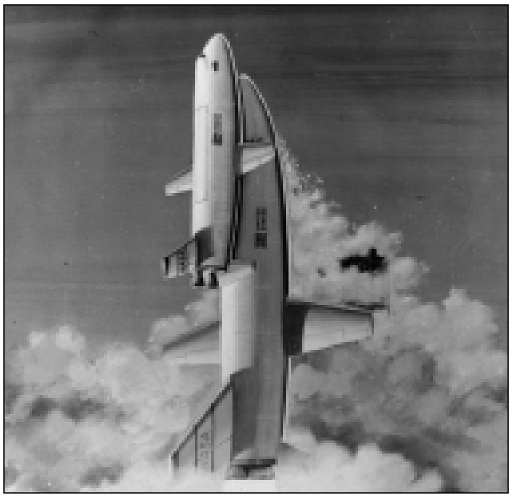

Figure 2–1. This 1969 artist's rendering depicts what a fully reusable Space Shuttle would look like during takeoff. (NASA photo)

Figure 2–2. This artist's conception, also from 1969, shows a fully reusable Space Shuttle at the point of separation when the orbiter leaves the atmosphere. The larger vehicle that boosted the orbiter was then to be piloted back to Earth. (NASA photo)

17. See Logsdon, gen. ed., *Exploring the Unknown,* 1: 383–85.
18. See Document III-25 in *ibid.,* 1: 522–43.

- A reusable **nuclear stage** for transporting people, spacecraft, and supplies between Earth orbit and lunar orbit and between LEO and geosynchronous orbit and for other deep space activities[19]

Of these elements, only the Space Shuttle has been built to date.

As noted above, many aerospace engineers within both NASA and industry favored the Class III fully reusable shuttle-type vehicles because they seemed to offer the cheapest operations costs, especially at high launch rates. [II-5][20] Proponents admitted that such vehicles were much more demanding technically and also required greater development risk and costs, but they felt that if the technical issues could be overcome, such vehicles would provide the basis for an increased overall investment in space. North American Rockwell (later, Rockwell International), for example, proposed a series of Class III designs that used a large booster and orbital vehicle to carry the necessary volume of liquid oxygen/liquid hydrogen fuel. NASA's "chief designer," Maxime Faget at the Manned Spacecraft Center, advocated a two-stage concept that mounted a relatively small orbiter atop a much larger recoverable booster. [II-6] Both vehicles were powered, and both had straight wings. Faget's orbiter would carry only a small payload and had only small cross-range capability.[21] Although by January 1971 many at NASA had begun to view a partially reusable design employing an external propellant tank and a delta-wing orbiter as probably the best overall choice when weighing development costs and technical risks, NASA engineers nevertheless continued to consider the Faget concept until almost the end of 1971.[22]

The Air Force, which was also involved at senior levels in the work of the STG, was highly critical of the Faget design, arguing that reentry would put extremely high thermal and aerodynamic loads on the orbiter's straight wings. The Air Force Flight Dynamics Laboratory argued forcefully that a delta-wing design would provide a safer orbiter with much greater cross range.[23] Ultimately, the Air Force's wish for high cross range and large payload capacity, as well as reduced expectations for NASA's future budget, forced NASA to give up on the Faget concept and begin serious work on the partially reusable concept that became the final Space Shuttle design. By the time NASA had reached this decision, many other Shuttle concepts had been explored, were found wanting, and had faded from the scene. NASA awarded Phase B design study contracts for the Shuttle to McDonnell Douglas and North American Rockwell in June 1970; these studies used the Faget two-stage fully reusable concept as their baseline. NASA also awarded Lockheed and a Grumman/Boeing team additional contracts to conduct Phase A studies for systems using some expendable components, should the two-stage concepts examined in the Phase B studies prove too expensive or technically demanding. In the meantime, NASA pursued its own internal studies, in part, to improve the competence of its engineers and to give them better insight into the contractors' work.[24]

As noted earlier, logistics support for the space station was cited as one of the principal justifications for the Shuttle. However, by its September 1970 budget submission to the

19. Slightly paraphrased from *ibid.,* 1: 534.

20. As in the other chapters in this volume of *Exploring the Unknown,* the documents that follow this essay are not necessarily in chronological order, but rather follow in numerical sequence with the context of the essay.

21. An orbiter with high cross range is capable of altering its orbital plane significantly. The Air Force tended to favor high cross-range capability on the assumption that it might wish to fly only a single orbit and return to Earth at the same location from which it had been launched. However, during that one orbit, Earth will have rotated sufficiently to require the Shuttle to change latitude to reach the launch site, thus requiring the orbiter to have sufficient cross range. NASA had minimal need for high cross-range capability.

22. Hallion and Young, "Space Shuttle: Fulfillment of a Dream," p. 1031.

23. Eugene S. Love, "Advanced Technology and the Space Shuttle," 10th von Kármán lecture, 9th annual meeting, American Institute of Aeronautics and Astronautics, Washington, DC, January 1973 (AIAA Paper 73-31).

24. Interview of Milton Silveira by Joseph Guilmartin and John Mauer, November 14, 1984, p. 6, transcript in NASA Historical Reference Collection.

White House, NASA officials realized that the Nixon administration and Congress were unwilling to support simultaneous development of both a space station and a Space Shuttle. A complete restructuring of NASA's expectations was in order. Between September 1970 and May 1971, the focus of NASA's attention was gaining White House approval for developing a two-stage fully reusable Shuttle. By May 1971, the expectations for NASA's future budget were reduced sufficiently that having the resources needed to develop such a two-stage, fully reusable design was out of the question. NASA estimated it would need at least $10–12 billion to build a two-stage Shuttle, but with a fiscal year 1971 budget of only $3.2 billion and little hope of future funding increases, the agency was forced to examine concepts with several expendable components as a means of lowering development costs. [II-7]

An important technical issue also led to the abandonment of the fly-back reusable booster. As designs began to mature, it became clear that for this concept to be feasible, the orbiter staging velocity (that is, the velocity at which the booster would release the orbiter) had to be 12,000 to 14,000 feet per second. Achieving this velocity would require an extremely large booster incorporating enormous fuel tanks. Upon returning through the atmosphere at these velocities, the booster would have to sustain extremely high heat loads. NASA engineers became increasingly uncomfortable about their ability to build such a booster, given the technology then available and generally poor knowledge about atmospheric reentry of large structures.

The ultimate design of the Shuttle orbiter and other system components depended on decisions about five key orbiter characteristics:

- Payload bay load capacity and size
- Extent of cross-range maneuverability
- Propulsion system
- Glide or power-assisted landing
- Primary structural material[25]

The first two were of greatest concern to the Air Force. Because NASA needed Air Force support in the White House and congressional debates over the Shuttle, in January 1971, the space agency agreed to the following design criteria:

- Fifteen-foot by sixty-foot payload bay
- A total of 65,000 pounds of easterly payload lift capacity (40,000 pounds for polar orbits from Vandenberg Air Force Base)
- A cross range of 1,100 nautical miles[26]

With these decisions made, NASA was then able to focus on what combination of orbiter design, propellant tank, and booster best fit the required characteristics. Throughout 1971, Manned Spacecraft Center and Marshall Space Flight Center designers analyzed a remarkable twenty-nine different Shuttle designs, incorporating a wide variety of orbiter capacity, hydrogen and oxygen fuel tank, and boosters (see Table 2–1).[27]

While still evaluating two-stage Shuttle designs, NASA engineers had found that the existing F-1 and J-2 engines, both of which were by then out of production, were inadequate to meet the safety and weight requirements of the Shuttle without significant

25. Scott Pace, "Engineering Design and Political Choice: The Space Shuttle, 1969–1972," M.S. thesis, Massachusetts Institute of Technology, May 1982.

26. For more details on the design criteria, see Document II-32 in Logsdon, gen. ed., *Exploring the Unknown*, 2: 369–77.

27. None of these designs, however, were sized to carry 65,000 pounds to orbit (100-nautical-mile circular orbit), although several had a fifteen-foot by sixty-foot payload bay and could reach the 1,100-nautical-mile cross range.

Table 2–1. Shuttle Configurations Evaluated by the Manned Spacecraft Center (1969–1971)

Vehicle	Landing Weight (thousands)	Wing	Wing Area (ft^2)	Payload Size (ft)	Payload Weight (thousands)	Body Length (in.)	Features
020	130	St (AR7)	1,275	15 by 30	20	1,272	Ext H_2 , Int O_2, 4 Eng. Orbiter, SRM Booster
021	85	St (AR7)	785	15 by 40	20	1,080	Ext H_2 , Int O_2, SRM Booster
122	95	St (AR5)	792	15 by 40	20	1,064	Ext H_2 , Int O_2, SRM Booster
022A	—	45˚ LE SW	1,120	15 by 40	20	1,064	Ext H_2 , Int O_2
022B	—	Delta	2,100	15 by 40	20	1,064	Ext H_2 , Int O_2
023	135	Delta	2,700	15 by 60	40	1,325	Ext H_2 , Int O_2, Reusable Booster
024	125	St (AR5)	1,000	15 by 60	40	1,315	(Stretched 022) Ext H_2 , Int O_2
025	—	45˚ LE SW	1,414	15 by 60	40	1,315	(Stretched 022A) Ext H_2 , Int O_2
026	125	Delta	2,500	12 by 40	40	1,200	Ext H_2 , Int O_2, Reusable Booster
027	95	Delta	1,500	12 by 40	40	1,120	Ext H_2 , Int O_2, Main Engine, OWB Tanks in rear, SRM Booster
028	128	Delta	2,360	15 by 40	40	1,080	(Shortened 023) Ext H_2 , Int O_2, Reusable Booster
029	—	Delta	1,900	12 by 40	40	1,080	OWB Tanks Amidships, Ext Main Engine
030	105	St (AR5)	860	15 by 40	20	1,140	3 J-28 Engines
031	153	St (AR5)	1,110	15 by 60	40	—	3 J-28 Engines
032	130	Delta	2,600	15 by 40	40	1,140	3 J-28 Engines, SRM Booster
033	100	Delta	2,000	12 by 40	20	1,200	(Modified 026) SRM Booster
034	95	Delta	1,500	15 by 30	20	960	(Shortened 025 & 028), SRM Booster
035	135	45˚ SW	1,200	12 by 40	40	1,440	(Modified 035)
035A	135	45˚ SW	1,700	12 by 60	40	1,440	(Stretched 035)
036	110	Delta	2,200	15 by 40	20	1,110	3 J28 / SRM Booster
036A	110	Delta	2,200	15 by 40	20	1,180	3 J28 / SRM Booster
036B	110	Delta	2,200	15 by 40	20	1,110	3 J28 / SRM Booster
036C	114	Delta	2,500	15 by 40	20	1,060	3 J25 / Pressure-Fed Booster
037	145	Delta	2,900	15 by 60	40	1,400	3 Uprate J28 / Recoverable Booster
037A	145	Delta	2,900	15 by 60	40	1,140	3 Super Uprate J25 / (036) SRM Booster
038	100	Delta	2,000	15 by 40	20	1,070	550K M1Pc / Solid Booster
039	115	30˚ SW	1,290	15 by 40	20	1,110	3 J28 / Pressure-Fed Booster
040	140	Delta	3,100	15 by 60	25	1,315	4 J28 / Pressure-Fed Booster
040A	140	Delta	3,180	15 by 60	25	1,315	4 J25 / Pressure-Fed Booster
040B	140	Delta	3,180	15 by 60	25	1,315	4 J28 Retractable / Pressure-Fed Booster
040C	190	60˚ Delta	2,900	15 by 60	40	1,315	3 MiPc, SRM Boosters
040C-1	190	50˚ Delta	3,200	15 by 60	40	1,315	3 MiPc, 150-ft^2 Canard, Twin Tail

Table 2–1 continued

Vehicle	Landing Weight (thousands)	Wing	Wing Area (ft^2)	Payload Size (ft)	Payload Weight (thousands)	Body Length (in.)	Features
040C-2	190	35˚/–19˚ Delta	3,000	15 by 60	40	1,315	3 MiPc, 300-ft^2 Wing Clove, Twin Tail, SRM Boosters
040C-3	190	50˚ Delta	4,150	15 by 60	40	1,315	3 MiPc
040C-4	190	60˚ Delta	4,440	15 by 60	40	1,315	3 MiPc
040C-5	150	50˚ Delta	3,200	15 by 60	40	1,315	3 MiPc, 100-ft^2 Canard, Twin Tail
040C-6	150	55˚/–19˚ Delta	2,800	15 by 60	40	1,315	3 MiPc, 150 ft^2 Canard, Twin Tail
041	114	30˚ SSW	1,290	15 by 60	15	1,300	3 J28/Pressure-Fed Booster
041A	114	30˚ SW	1,290	15 by 60	15	1,365	3 J25/Pressure-Fed Booster
042A	110	Delta	2,500	15 by 60	25	1,260	Glider, TIII L6 Booster
042B	105	30˚ SW	1,255	15 by 60	25	1,260	Glider, TIII L6 Booster
043	83	30˚ SW	900	10 by 30	27	770	Glider, 2 MiPc oo Ext Tank, PF Booster
044	100	60˚ Delta	2,000	10 by 30	25	880	2 MiPc, PF Booster
045	—	—	—	—	—	—	—
046	165	—	—	14 by 45	25	—	3 MiPc, Twin Tail, SRM Boosters
047	185	49˚/–5˚ Delta	3,450	15 by 60	40	1,315	2 MiPc, Twin Tail, SRM Boosters
048	205	35˚/–19˚ Delta	3,240	15 by 60	40	1,315	4 MiPc, 324-ft^2 Wing Clove, Twin Tail, SRM Boosters
048A	195	35˚/19˚ Delta	3,080	15 by 60	40	1,315	4 400K, 308-ft^2 Wing Clove, Twin Tail, SRM Boosters
049	205	75˚/55˚ DBL Delta	1,150/ 3,420	15 by 60	40	1,315	3 Hi Pc, 350 ft^2 Wing Clove, Twin Tail, 156” SRM, 62” ASRM
049A	215.3	75˚/55˚ DBL Delta	1,250/ 3,600	15 by 60	40	1,315	3 Hi Pc, 425 ft^2 Wing Clove, Twin Tail, 178” SRM, 62” ASRM
050	—	—		—		—	— —
051	165	35˚ Delta	2,000	15 by 60 up	25	1,050	3 Hi Pc Swing Engines, 156” SRM, 180-ft^2 Canard
052	175	35˚ Delta	2,120	15 by 60 up	25	1,250	3 Hi Pc Swing Engines, 149” SRM, 75’ Bay with OWB in rear, 180-ft^2 Canard
053	185	35˚ Delta	2,240	15 by 60 up	25	1,250	4 CC Swing Engines, 120” SRM, 75’ Bay, 190-ft^2 Canard
054	185	35˚ Delta	2,240	15 by 60 up	25	1,250	4 Hi Pc Swing Engines, 140” SRM, 75’ Bay, 190-ft^2 Canard

Source: Richard P. Hallion and James O. Young, “Space Shuttle: Fulfillment of a Dream,” in Richard P. Hallion, ed., *The Hypersonic Revolution: Eight Case Studies in the History of Hypersonic Technology*, Volume II (Dayton, Ohio: Wright-Patterson Air Force Base, Special Staff Office, Aeronautical Systems Division, 1987), pp. 1049–50.

redesign. NASA favored an engine having higher specific impulse than either of these, which would require the use of only three, rather than four, engines in the orbiter. The agency decided to build a completely new engine; in July 1971, it awarded the development contract to Rocketdyne for its staged combustion design, which became known as the Space Shuttle Main Engine (SSME).[28]

Although NASA continued to explore a wide variety of payload bay sizes and overall payload capacity during its exploration of the optimum Shuttle design, throughout 1970 and 1971, it favored a fifteen-foot by sixty-foot payload bay. After the decision to defer an attempt to gain approval for developing a Saturn V–launched space station, among the reasons for favoring a payload bay of this size was that it was compatible with the growing desire to use the Shuttle like a truck, routinely using it to place large payloads in orbit. The Air Force was also interested in the larger cargo bay for hauling some of its national security payloads. In addition, the larger bay made balancing the orbiter for launch easier and therefore carried less flight risk than a shorter payload bay. In the fall of 1971, the White House Office of Management and Budget (OMB) asked NASA to examine the benefits and drawbacks of a smaller Shuttle, having a shorter, narrower payload bay. NASA analyses showed, however, that developing a smaller orbiter would have relatively small effect on the overall inert or gross launch weight of the Shuttle system, and thus its development costs. [II-8] NASA engineers also pointed out that a larger payload bay made the handling of multiple payloads more efficient.

By late 1971, designers both within NASA and industry had begun to realize that the most cost-effective design for the Shuttle system was a vertically launched delta-winged orbiter mounted to an external tank carrying liquid oxygen and liquid hydrogen, flanked by booster rockets. [II-9, II-10] Putting all of the launch fuel and oxidizer in an external tank allowed designers to reduce the size of the orbiter. It also made the design and construction of the propellant tanks simpler and therefore cheaper. The design allowed the Shuttle to carry a greater payload as a fraction of total vehicle inert weight compared to a two-stage, fully reusable Shuttle system.[29]

Throughout the final months of 1971, OMB persisted in its pressure to lower Shuttle development costs (see Document II-7). On December 29, 1971, NASA Administrator James C. Fletcher sent OMB Deputy Director Caspar W. Weinberger a letter summarizing the results of NASA's most recent analyses, which showed that a Shuttle with a fifteen-foot by sixty-foot payload bay was still the "best buy." However, yielding to OMB pressure, NASA recommended that President Nixon approve a design with a smaller bay.[30] [II-11] Five days later, on January 3, 1972, much to NASA's surprise, President Nixon authorized the space agency to proceed with developing a Space Shuttle with the larger payload bay. There were many factors involved in the decision to authorize NASA to proceed with the Shuttle program it preferred.[31] Among them was the desire on the part of Nixon and his political advisors to initiate during the 1972 presidential election year a large aerospace program with significant employment impacts in key electoral states. [II-12] Nixon met with

---

28. Staged combustion involves partially burning the propellants before burning them completely in a second phase of combustion. NASA chose this design from among three: an "Aerospike" or plug-nozzle design that did away completely with the expansion bell and two expansion bell designs. See J.P Loftus, S.M. Andrich, M.G. Goodhart, and R.C. Kennedy, "The Evolution of the Space Shuttle Design," unpublished manuscript, Johnson Space Center, Houston, TX, 1986, pp. 15–24.

29. See Document III-30 in Logsdon, gen. ed., *Exploring the Unknown,* 1: 549–55.

30. For a fuller discussion of the process leading to Space Shuttle approval, see John M. Logsdon, "The Space Shuttle Program: A Policy Failure?," *Science,* May 30, 1986, pp. 1099–1105; Thomas Heppenheimer, *The Space Shuttle Decision: NASA's Quest for a Reusable Space Vehicle* (Washington, DC: NASA SP-4221, 1999). See also the discussion of the Shuttle decision in *ibid.,* 1: 386–88, 549–59.

31. See Document III-28 in *ibid.,* 1: 546–47.

Fletcher and NASA Deputy Administrator George M. Low on January 5, 1972; afterwards, the White House issued a statement announcing Nixon's approval of the Space Shuttle.[32]

The January 3 decision left open several issues, including whether the Shuttle's strap-on boosters would use solid or liquid fuel. [II-13] In Shuttle system configuration 040C (see Table 2–1), the external tank was flanked by two large, "strap-on" solid rocket boosters (SRBs). This design ultimately became the foundation of the Space Shuttle's configuration. Nevertheless, until March 1972, other possible designs were still on the table, and each had their supporters. For example, in preparation for choosing the booster rockets, NASA studied three general types: large solid-fuel boosters; liquid, pressure-fed boosters; and liquid, pump-fed boosters. To reduce operations costs, NASA decided to make the boosters reusable. After separation from the Shuttle at about forty kilometers altitude, they would fall back to the ocean on large parachutes and be recovered from the sea soon after launch (Figure 2–3).

Technical discussions over the relative merits of these designs centered on which type of booster was safest, most easily refurbished, and cheapest to develop and manufacture. Proponents of liquid motors pointed out that NASA and the Air Force had extensive experience with liquid motors and that they offered greater safety. Liquid engines had the distinct advantage that if system malfunctions were detected in the startup prior to launch, they could be shut down immediately and the launch safely aborted. If an engine failed after launch, it could be shut down and the launch aborted to an overseas airstrip after

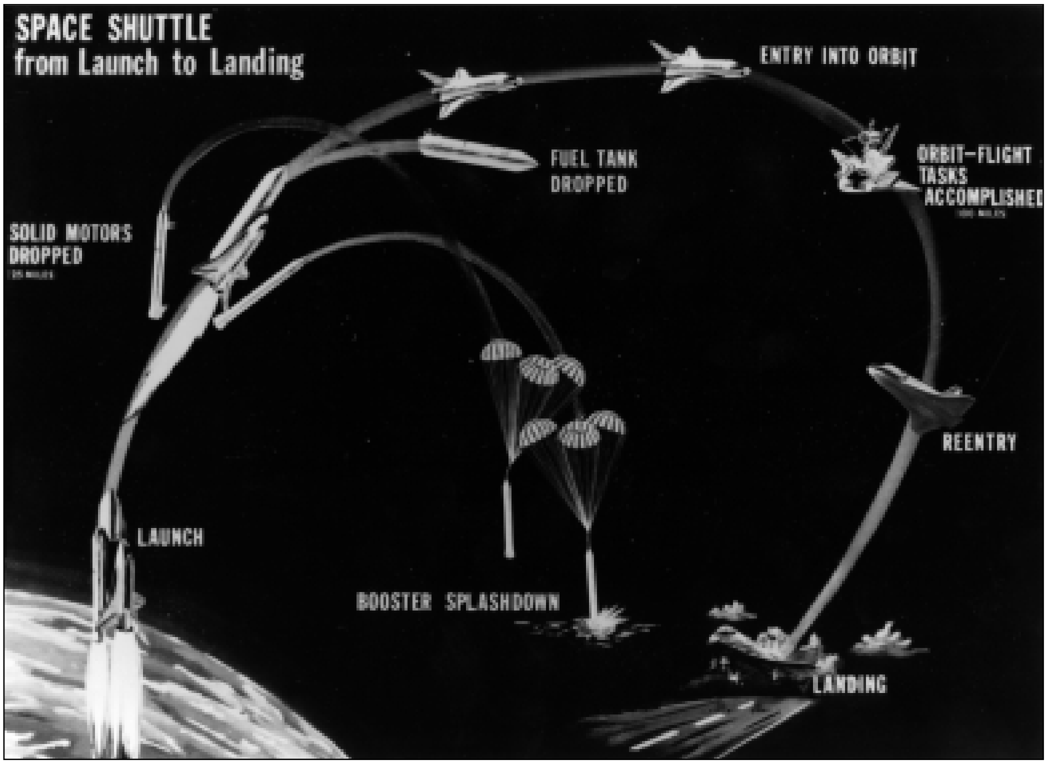

Figure 2–3. This is the standard mission profile for the partially reusable Space Shuttle that actually emerged from the political approval process. (NASA photo)

32. See Document III-32 in *ibid.*, 1: 558–59.

the boosters and the external tank were dropped off. By contrast, once the SRBs were ignited, they could not be shut down (although it was possible to terminate their thrust by blowing off the top of the booster), and the abort potential was decreased. In addition, solid rocket motors of the size NASA was considering (156-inch diameter) had never been used, although the Air Force had tested such large engines and felt they would be sufficiently reliable. Advocates of the big dumb booster designs of the 1960s felt that the pressure-fed design offered greater overall simplicity, which would contribute both to lower costs and to safety.[33] Supporters of solid rocket motors cited the high reliability of solids, as well as their lighter weight and greater simplicity compared to liquid designs.[34] Also, NASA had strong concerns about its ability to refurbish liquid rocket motors after they had been subjected to the corrosive action of an ocean bath. By March 1972, driven primarily by cost considerations, the pendulum of apparent advantages swung in favor of large solid rocket engines, and NASA officials decided to proceed with solid rocket motor development, judging that such motors offered sufficient reliability and ease of handling to be used for human spaceflight.[35] [II-14] NASA announced its choice of solid boosters on March 15, 1972, as it defended the Shuttle program before Congress. [II-15]

The prime contractor for the Shuttle orbiter still had to be decided. Grumman, Lockheed, McDonnell Douglas, and North American Rockwell had all submitted competitive designs for a Shuttle based on the Marshall Space Flight Center 040C design. A NASA-Air Force Source Evaluation Board rated North American Rockwell the highest, based on an evaluation of contractor strengths in:

- Manufacturing, test, and flight-test support
- System engineering and integration
- Subsystem engineering
- Maintainability and ground operations
- Key personnel and organizational experience
- Management approaches and techniques
- Procurement approaches and techniques

On July 26, 1972, NASA Administrator James Fletcher met with Deputy Administrator George Low and Associate Administrator for Organization and Management Richard C. McCurdy to make the final Shuttle contractor decision. This choice was essentially between North American Rockwell and Grumman, the two companies that had received the highest ratings from the Source Evaluation Board. After considerable discussion, the three adopted the board's recommendation. [II-16] In August 1972, North American Rockwell received the contract to design and develop the Shuttle orbiter. Later, Morton Thiokol was selected to produce the SRBs.[36] [II-17] NASA also selected Martin Marietta to develop the external tank. The Manned Spacecraft Center assumed responsibility for supervising overall orbiter development. Marshall Space Flight Center was to supervise the development and manufacturing of the SRB, the SSME, and the external tank, and

---

33. Arthur Schnitt and F. Kniss, "Proposed Minimum Cost Space Launch Vehicle System," Report no. TOR 0158(3415)-1, Aerospace Corporation, Los Angeles, CA, July 18, 1966. For a general discussion of the big dumb booster concept, see U.S. Congress, Office of Technology Assessment, *Big Dumb Boosters: A Low-Cost Space Transportation Option?* (Washington, DC: Office of Technology Assessment, February 1989).

34. For example, the Minuteman and Polaris, both of which use solid propellants, had proved highly reliable.

35. Eagle Engineering, Inc., "Technology Influence on the Space Shuttle Development," Report No. 86-125C, NASA Johnson Space Center, Houston, TX, June 8, 1986, pp. 5–20, 21.

36. As noted above, NASA had awarded the contract for the SSME to Rocketdyne in 1971.

Figure 2–4. Ames Research Center scientists tested the aerodynamic properties of a Space Shuttle wind tunnel model in 1973. (NASA photo)

Kennedy Space Center was to develop methods for Shuttle assembly, checkout, and launch operations.

Even after the development contracts were let, determining the best design was still a major task that required close cooperation among the design teams (Figure 2–4). During liftoff and throughout the short passage through the atmosphere, the shape and placement of each of the major Shuttle components would affect flight success. [II-18] Changes in any one of the elements—wing shape, the diameter and length of the SRBs, and the diameter of the external tank—would alter the performance of the others. Thus, the configuration of the Shuttle system and precise shapes of each component passed through several steps to reach the final overall shape and structure.[37]

North American Rockwell began fabricating Orbiter Vehicle (OV)-101 on June 4, 1974; the company rolled out the orbiter from its Palmdale, California, plant on September 17, 1976. The OV-101 lacked many subsystems needed to function in space. It was thus capable of serving only as a full-scale mockup capable of atmospheric flight; this flying testbed proved invaluable in testing the orbiter's ability to maneuver in the atmosphere and to glide to a safe landing. Flight-testing began in February 1977 at Edwards Air Force Base.

Earlier, NASA had purchased a used Boeing 747-100 to ferry the orbiters from landing sites in California and potentially other parts of the world to Kennedy Space Center for refurbishment and launch.[38] This airplane was also used to conduct flight tests with *Enterprise*, as OV-101 came to be called. A NASA committee typically chose the orbiter, but fans of the Star Trek television series had lobbied NASA and Congress to name OV-101 the title of the starship of that series. [II-19]

Enterprise underwent three major types of tests: (1) captive flight, in which NASA tested whether it could take off, fly, and land the 747 with the orbiter attached; (2) captive-active flight, in which an astronaut crew rode in *Enterprise* during captive flight; and

---

37. See Hallion and Young, "Space Shuttle: Fulfillment of a Dream," pp. 1125–42, for a summary discussion of these points.

38. Once the Shuttle began flying, NASA established backup landing sites in several other countries, should a launch failure allow an abort landing elsewhere or extraordinary conditions at both Edwards Air Force Base and Kennedy Space Center prevent landing at those two primary locations.

(3) free flight, in which *Enterprise* was released to glide back to Earth on its own. By August 1977, NASA had successfully completed the first two test phases and was ready to test the orbiter in free flight. On August 12, 1977, the 747 carried *Enterprise* to 24,100 feet, where it was released for a five-minute glide to a successful landing at Edwards.[39] After four additional test glides, NASA wound up its atmospheric flight testing program and turned to vibration and other ground tests of *Enterprise*.

Two major technical problems kept Shuttle development from proceeding smoothly: (1) a series of test failures and other problems with the SSME and (2) difficulties achieving a safe, lightweight, robust thermal protection system. SSME development proved challenging on several grounds: NASA needed a reusable, throttleable staged-combustion engine that would achieve much higher combustion chamber pressures than any previous engine. The United States had not yet built a rocket engine that was both reusable and capable of being throttled. Such an engine required high-pressure turbopumps capable of higher speeds and internal pressures than any developed to date. Reusability and the fact that the SSME would be used on a vehicle rated to carry people imposed special demands on the engine. Despite a nine-month delay in starting SSME development, caused by a Pratt & Whitney challenge to the Rocketdyne contract, as well as difficulty in procuring the necessary materials for the engine, Rocketdyne completed the first development engine in March 1975, one month ahead of schedule.

Engine tests were performed at NASA's Mississippi National Space Technology Laboratories (later named Stennis Space Center) and at the Air Force's Rocket Propulsion Laboratory at Santa Susana, California. Although the first test firing was successful, problems began to surface as the tests became more demanding. The turbopumps were particularly troublesome because their turbine blades tended to crack under the severe mechanical stresses they experienced. The engines also experienced a variety of nozzle failures during tests.[40] These problems caused significant delays in the testing program. This prompted the Senate Subcommittee on Science, Technology, and Space of the Committee on Commerce, Science, and Transportation in December 1977 to request an independent review of SSME development by the National Research Council. The report, presented in a March 31, 1978, Senate Subcommittee hearing, noted that the problems NASA was experiencing in the test program were typical of such development efforts, but also recommended a number of possible SSME modifications and a delay in the timetable for the first Shuttle flight.[41] The National Research Council committee, generally called the Covert Committee after its chair, Eugene Covert, a professor at the Massachusetts Institute of Technology, also recommended that NASA relax its goal of launching the Shuttle with the SSMEs operating at 109 percent of full power level, to reduce stress on the turbopump components.

Because NASA was then behind schedule, it decided to save SSME development time by conducting some tests using all three engines in their flight configuration. They were attached to an orbiter simulator using identical components to those on the flight article. NASA also used an external tank to supply propellant to the engines and attached it to the

39. Astronauts Fred W. Haise and Gordon G. Fullerton were the pilot and co-pilot for the first free flight of *Enterprise*.

40. Hallion and Young, "Space Shuttle: Fulfillment of a Dream," pp. 1158–59.

41. Eugene Covert, "Technical Status of the Space Shuttle Main Engine," report of the Ad Hoc Committee for Review of the Space Shuttle Main Engine Development Program, Assembly of Engineering, National Research Council. Printed in U.S. Congress, Senate Committee on Commerce, Science, and Transportation, Subcommittee on Science, Technology and Space, *Space Shuttle Main Engine Development Program. Hearing*, March 31, 1978, 95th Cong., 2d sess. (Washington, DC: U.S. Government Printing Office, 1978), pp. 16–57.

test stand in a manner identical to its connection to the SRBs on the launch pad. NASA began its main propulsion testing in April 1978, but continued to experience test delays and failures. Despite the delays and problems, the basic SSME design was considered sound. Rocketdyne proceeded with the manufacturing of the three engines needed for *Columbia* (OV-102). In May 1978, Rocketdyne finally received approval to start manufacturing the nine additional production SSMEs needed for OV-099 (*Challenger*), OV-103, and OV-104.

Nevertheless, development problems continued. One of the largest setbacks was a fire that destroyed an engine on December 27, 1978. The Covert Committee, which had been preparing a second report on the SSME program, reviewed this and an additional fire. [II-20] Once again, the committee report recommended changes in procedures and further tests, noting: "It appears unlikely that the first manned orbital flight will occur before April or May 1980."[42] The test program continued, "and by 1980 the SSME was no longer perceived to be a pacing factor for the first launch . . . the thermal protection system was considered the pacing item."[43]

Thermal protection for the Shuttle's reentry was a major issue from the earliest design concepts through the first several flights of the Shuttle. NASA engineers had solved the reentry problem for the Mercury, Gemini, and Apollo capsules by using ablative materials that heated up and burned off as the capsule encountered the upper atmosphere upon reentry. However, these capsules were not designed to suffer the rigors of multiple flights and reentries and were thus retired after use. Each Shuttle orbiter was designed to experience up to 100 launches and returns. Its thermal protection system had to be robust enough to stand repeated heating loads and the structural rigors of reentry. The system had to be relatively light to keep the orbiter's overall weight acceptably low. In addition, it had to be relatively cheap to refurbish between flights.

Between 1970 and 1973, NASA studied a wide variety of technologies to protect the orbiters' bottom and side surfaces. It investigated:

- "Hot structures," in which the entire structure took the heat load
- Heat shields separated from a lightweight orbiter structure by insulation
- Ablative heat shields over a lightweight structure
- Low-density ceramic heat shields (tiles) bonded to a lightweight structure

The "hot structures" would have required developing exotic and expensive titanium or other alloys that could dissipate reentry heating and simultaneously withstand the mechanical loads from aerodynamic pressure. The heat-resistant panels separated by insulation would transfer the mechanical load while shielding the underlying structure from atmospheric heating. This concept suffered from excessive weight and difficulties in designing the shielding to avoid buckling or excessive deflection. NASA's estimates showed that the ablative heat shields would require costly refurbishment.

Therefore, NASA chose the fourth option after extensive testing, in part because the agency decided that using tiles would lead to the lowest overall cost. A ceramic heat shield also allowed NASA engineers to use aluminum for the Shuttle orbiter's structure—

---

42. National Academy of Sciences, National Research Council, Assembly of Engineering, *Second Review—Technical Status of the Space Shuttle Main Engine: Report of the Ad Hoc Committee for Review of the Space Shuttle Main Engine Development Program* (Washington, DC: National Academy of Sciences, February 1979), p. 21.

43. U.S. Congress, Congressional Research Service, *United States Civilian Space Programs 1958–1978*, report prepared for the Subcommittee on Space Science and Applications of the Committee on Science and Technology, U.S. House of Representatives, 97th Cong., 1st sess. (Washington, DC: U.S. Government Printing Office, January 1981), p. 473.

a material with which they had considerable experience. The particular ceramic material chosen was foamed silica coated with borosilicate glass. The shield was divided into thousands of small tiles to enable the stiff material to conform to the shape of the orbiter skin. (The tiles are what give the orbiters' lower surfaces the look of being constructed of blocks.)

No one had ever used such materials over an aluminum structure, and many experts expressed concerns about NASA's ability to develop an appropriate means to bond the brittle, nonpliable ceramic tiles to an aluminum structure that would deform slightly under aerodynamic loads. Fitting and attaching the tiles became a major effort, one that was highly labor intensive. Each tile is approximately fifteen centimeters square and is individually cut and fitted to match its neighbor. Because every tile is slightly different in size and shape, it carries its own number and has its own documentation.[44] The orbiter nose cap and its wing leading edges, which experience heating of above 1,500 degrees Kelvin during reentry, are protected by a high-temperature, high-cost, carbon-carbon material. Other temperature-resistant materials are used on the upper parts of the orbiter.

Problems with installing the tiles caused NASA to deliver the first flight-qualified orbiter, *Columbia*, to Kennedy Space Center in early 1979 before NASA technicians had completed installation. Attaching the tiles then became the critical element in scheduling the first Shuttle launch. Originally planned for 1978, by March 1979, the schedule had slipped at least two years.[45] Work on the tiles went on twenty-four hours a day for six days a week, as technicians struggled to install more than 30,000 individual tiles. While NASA worked on methods to speed up the process, it also continued to explore better materials to develop a method that would make the tile stronger without adding weight.

In the meantime, as Rockwell and NASA engineers began to understand the extent of the aerodynamic loads the orbiter's surface would experience during the launch phase, they developed concerns that some tiles might loosen, or even fall off. Upon reentry, they feared, weakened tiles might peel away, causing the underlying aluminum structure to overheat. Thus NASA also explored various means to examine the Shuttle while in orbit to check on the tiles, and the agency began to develop a tile repair kit.[46] [II-21]

Shuttle development problems were so severe during the late 1970s that some within the Carter administration's OMB proposed that the program be cancelled. This led to a series of external reviews of the program during 1979. [II-22] Even before this recommendation, OMB had been resisting NASA's attempt to gain approval for building a fifth Shuttle orbiter. NASA believed that a five-orbiter fleet would be needed to provide adequate capability to meet anticipated launch demand. [II-23, II-24] While not authorizing the construction of a fifth orbiter (an issue NASA continued to press until the 1986 *Challenger* accident), President Jimmy Carter was persuaded that ending the program was not a good move. [II-25, II-26, II-27] After extraordinary efforts, by early 1980, NASA felt it was bringing its tile problems under control and was able to project a launch date of March 1981. [II-28]

Before NASA could launch *Columbia*, however, it had to attend to thousands of details, both large and small. In addition to the tiles, the agency had to install and test many other Shuttle orbiter subsystems. For this work, *Columbia* was rolled into the Orbiter Processing Facility at Kennedy Space Center. Because virtually everything about the Shuttle system was different from the Saturn V, launch operations crews had to learn new methods for handling the vehicle, its SRBs, and the external tank. NASA altered the Vehicle Assembly Building

---

44. Paul A. Cooper and Paul F. Holloway, "The Shuttle Tile Story," *Astronautics and Aeronautics,* January 1981, pp. 24–34.

45. U.S. Congress, House Committee on Science and Technology, 1980 NASA Authorization Hearings before a subcommittee on H.R. 1756, 96th Cong., 1st sess., February and March 1979, pt. 4, p. 1664.

46. NASA, "On-Orbit Tile Repair Kit Being Produced," Press Release 80-10, January 23, 1980.

(VAB) and the Mobile Launch Platform that had been developed for Apollo to accommodate the Shuttle.[47] NASA also made substantial alterations to launch pads 39A and 39B.

For each Shuttle launch, the first elements of the launch system to be erected are the two large SRBs. Each is about twelve feet in diameter, 149 feet long, and composed of nine major elements—a nose cap, a frustrum, a forward skirt, four individually cast solid rocket motor segments, a nozzle, and an aft skirt. NASA technicians begin assembly of the Shuttle by attaching the aft skirt of each of the two SRBs to support posts on the Mobile Launch Platform. Then, piece by piece, technicians hoist each SRB element atop the next one and bolt it down. The motor segments are joined to their neighbors by tang-and-clevis joints and secured by steel pins located along the circumference of each joint.[48] For safety reasons, all nonessential personnel must evacuate the VAB while the SRBs are being assembled. After the two SRBs are safely bolted to the Mobile Launch Platform, a crane hoists the external tank to a vertical position and mates it with the twin SRBs. Then the orbiter is transferred from the Orbiter Processing Facility to the VAB, lifted by its nose more than 100 feet off the floor, and lowered into place and mated with the external tank.

Although NASA could have made the first launch, reentry, and touchdown in an automated mode, NASA engineers felt confident enough in the safety and reliability of the Space Shuttle system to believe that such a procedure was unnecessary.[49] [II-29] In this they were strongly supported by the astronaut corps, which was anxious to return to space. (The last crewed flight was the Apollo-Soyuz Test Project in July 1975.) Besides, preparing the orbiter for automated landing would have entailed additional expense and weight for the avionics and would have injected additional uncertainty in the interpretation of the flight results.

The first launch of the Space Shuttle *Columbia* was scheduled for April 10; it was to be piloted by astronauts John Young and Robert Crippen. After a delay caused by computer problems, the launch actually took place at 7:00 a.m. on April 12, 1981 (Figure 2–5). When the countdown clock reached T–3.8 seconds, NASA started up the SSMEs, allowing the launch directors to determine that they were firing properly. At about T+3.0 seconds, they fired up the SRBs, irrevocably committing NASA to the launch. At an altitude of 400 feet, eight seconds after lifting off the pad on a column of flame and smoke, computer instructions caused *Columbia* to roll over on its back and continue its upward climb over the Atlantic Ocean. About two minutes later, at an altitude of twenty-seven nautical miles, the SRBs, which had completed their part of the launch sequence, separated from the orbiter and fell to the ocean on orange and white parachutes. Eight minutes and fifty-two seconds after liftoff, *Columbia* reached orbit and jettisoned the nearly empty external tank, which fell back through the atmosphere into the Indian Ocean. A short burn of *Columbia*'s orbital maneuvering system rockets circularized the orbit at 130 nautical miles.

Young and Crippen orbited Earth thirty-seven times while testing the various Shuttle components, such as the large cargo bay doors, which they opened and closed. One of NASA's major concerns was the condition of the tiles. Upon opening the payload doors, the astronauts discovered that several tiles on the fairings for the orbital maneuvering and reaction control engines had separated during launch. Although the loss of these tiles, which were on the upper side of the orbiter, would not have prevented a safe reentry, Mission Control in Houston remained unsure about the condition of *Columbia*'s underside, which could not be seen from the cockpit. As the orbiter circled Earth, NASA

---

47. For example, because the Shuttle does not make use of the tower and gantry required by the Saturn V, these were removed.

48. The tang-and-clevis joints are called "field joints" because they are assembled at the launch site ("in the field") rather than at the factory.

49. The Soviet Union flew its *Buran* shuttle orbiter in an automated mode in its first and only flight in November 1988.

Figure 2–5. The Space Shuttle is finally realized with the launch of Columbia *from Launch Complex 39A on April 12, 1981, on its first orbital mission. (NASA photo)*

arranged for Air Force cameras to photograph *Columbia*'s underside to confirm tile integrity. Finding the tiles in apparently good order, NASA Mission Control notified the two astronauts to prepare for return.

Fifty-four hours after takeoff, *Columbia* glided to a successful landing at Edwards Air Force Base. Although *Columbia* landed at a faster speed than planned and rolled nearly 3,100 feet beyond its planned stopping point, the flight proved the feasibility of the Shuttle's design. [II-30] NASA made three more test launches with *Columbia*—on

November 12, 1981, March 22, 1982, and June 27, 1982. Each time, *Columbia* experienced some anomaly that had to be resolved.[50]

In the aftermath of the first Shuttle flight, the Reagan administration considered the longer term future of the program. A variety of uses and management approaches were evaluated; ultimately, President Ronald Reagan decided to keep NASA in the lead role in managing the Space Transportation System (STS). He reiterated the policy that once the Shuttle became operational, it would be used to launch all U.S. government missions. [II-31, II-32]

The last test flight of *Columbia* ended symbolically on July 4, 1982, when the orbiter glided to a landing before President and Mrs. Reagan and a crowd of about 750,000 visitors at Edwards Air Force Base.[51] To enhance public attention to the July 4th event, NASA had arranged to fly *Challenger*, the second of four planned orbiters, to Kennedy Space Center shortly after *Columbia* rolled to a stop. *Challenger* took off atop NASA's Boeing 747 carrier plane as Reagan was giving his speech, circled the field, and dipped its wings to the crowd. [II-33]

Space Shuttle Operational Flights—Phase I

Columbia's four successful test flights led NASA to declare that the Shuttle fleet was operational—meaning, in theory, that further development of Shuttle systems would be minimal. With *Challenger* in preparation for its first flight, and *Discovery* and *Atlantis* in production, NASA officials were now ready to push up the flight rate and extend the use of the STS to a wide variety of payloads and customers (Figure 2–6). [II-34] (Chapter 3 discusses the use of the Space Shuttle to launch commercial payloads.)

When NASA began the Shuttle's development, the agency expected the vehicle to assume the entire burden of lifting U.S. satellites and other payloads to orbit soon after reaching full operational status. [II-35] NASA also expected other nations to use the Shuttle for access to space, and the agency projected a flight rate of forty-eight per year beginning in 1980. Such a high rate would, in NASA's estimation, have led to a low cost per flight and even allowed NASA to recoup much of its investment in the Space Shuttle system.[52] By the mid- to late 1980s, NASA hoped, reduced costs for operating the Shuttle system would allow the agency to fund other projects, such as a future space station. This so-called "Shuttle funding wedge" became a tenant of NASA policy and the agency's expectations for major future projects.

The number of future projected flights allowed NASA to set its first pricing policy in 1975 to garner as many Space Shuttle flights as possible. This policy was intended in part "to effect early transition from expendable launch vehicles."[53] NASA had arrived at a price of $18 million (1975 dollars) by averaging projected development and operational costs over a total of 572 flights from 1980 through 1991.

In the early 1980s, expectations for such a high flight rate had decreased, but were still relatively high. In July 1983, for example, Rockwell International forecast that by 1988, overall U.S. demand for space transportation services for civilian and military uses would require a yearly flight rate of twenty-four launches.[54] Based on an expectation of increasingly shorter "turnaround time" for processing each orbiter, NASA expected to meet that

50. For example, during the second flight (STS-2), one of the orbiter's three fuel cells failed, causing NASA to bring *Columbia* back after only two and a half days, rather than the planned five.

51. NASA extended *Columbia*'s time in space by one orbit to accommodate the presidential visit.

52. U.S. Congress, Congressional Budget Office, *Pricing Options for the Shuttle* (Washington, DC: Congressional Budget Office, March 1985).

53. C.M. Lee and B. Stone, "STS Pricing Policy," presented at the AIAA Space Systems Conference, Washington, DC, October 18–20, 1982, p. 1.

54. Rockwell International, "Projection of Future Space Shuttle Traffic Demand," July 1983, Rockwell Corporation, Downey, CA.

Figure 2-6. The STS-8 mission on Challenger *was the first nighttime launch of the Shuttle era on August 30, 1983. (NASA photo)*

rate by 1988. Such forecasts assumed that the Shuttle would fly commercial, as well as government, payloads. It also anticipated that a fifth Shuttle orbiter would be built. [II-36]

The orbiter turned out to be much more difficult and time consuming to refurbish and prepare for launch than NASA had expected. This resulted in part from the need to correct system design deficiencies throughout the orbiter, which in turn kept the system in a state of continual development.[55] Orbiter "turnaround" time became the pacing item in efforts to improve the Shuttle launch rate. From 1983 through 1985, NASA steadily increased the flight rate until, in 1985, it was able to launch nine flights. NASA accomplished this feat in part by significantly reducing the damage to the protective tiles after liftoff and by making small improvements in the SSMEs to reduce the amount of inspection time needed.[56] Nevertheless, many observers remained skeptical that NASA would

55. Charles R. Gunn, "Space Shuttle Operations Experience," paper presented at the 38th Congress of the International Astronautical Federation, Brighton, England, October 1987.

56. *Ibid.*

ever be able to reach and maintain a rate close to twenty-four flights per year, given the complications of preparing the Shuttle orbiter and other subsystems for launch.

In the early 1980s, the Reagan administration, strongly encouraged by NASA, had established the policy that all government payloads would be launched on the Shuttle and that the Delta, Atlas, and Titan expendable launch vehicles (ELVs) would be phased out. NASA ordered no more Delta or Atlas ELVs after 1982. Their manufacturers moved to shut down production lines. Because this action removed these launch vehicles from use by commercial interests, commercial communications satellite owners and a few other private payload customers were forced to use either the Shuttle or the European-built Ariane rocket. (See Chapter 3 for a discussion of the competition between the Shuttle and Ariane.)

The Shuttle was maintained under NASA control, although several groups urged policies that would put the Shuttle under the operational control of private industry (or even the Air Force). They argued that the private sector would reduce operational costs faster and more effectively than NASA. Although some officials of the Reagan administration flirted briefly with the concept, they finally concluded that, in the words of the congressional Office of Technology Assessment, the "Shuttle is an important instrument of national policy and is needed primarily for government civilian and military payloads."[57]

As noted, the operational Space Shuttle turned out to be much more complicated to operate than had been expected, took longer to refurbish, and cost much more to operate than NASA had estimated.[58] Nevertheless, between its first flight in 1981 and January 1986, it served to carry a variety of life science and engineering experiments into orbit, launched communications satellites and scientific payloads, and launched DOD payloads.[59]

From the beginning, Shuttle planners expected to launch high-inclination payloads, especially polar-orbiting payloads, from Vandenberg Air Force Base in California, because only at Vandenberg is there an available high-inclination launch path (to the south) that would not jeopardize populated areas. DOD and the National Reconnaissance Office were especially interested in using this capability to launch several reconnaissance satellites, which require polar orbit for effectiveness. DOD funded the development of launch preparation facilities and a launch pad at the site of the Space Launch Complex-6 (SLC-6, pronounced "Slick-6") to launch from Vandenberg.[60] However, the Space Shuttle proved unable to meet its payload weight goal of 65,000 pounds to LEO (twenty-eight-degree inclination), which was necessary to launch about 40,000 pounds into polar orbit. That problem, combined with the loss of *Challenger* in 1986 and the development of the Titan IV, led to the abandonment of SLC-6 as a Shuttle launch site, but only after DOD had poured several billion dollars into upgrading the launch pad and constructing appropriate supporting facilities.

The Complementary Expendable Launch Vehicle

Not everyone in the government agreed with the move toward total government dependence on the Space Shuttle. Some influential officers within the Air Force, which had the responsibility for launching all national security payloads, especially the critical

57. U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities,* OTA-ISC-239 (Washington, DC: U.S. Government Printing Office, 1985), p. 10.

58. Roger A. Pielke, Jr., "A Reappraisal of the Space Shuttle Programme," *Space Policy,* May 1993, pp. 133–57.

59. See Logsdon, gen. ed., *Exploring the Unknown,* 2: 263–69, for a discussion of DOD disenchantment with the Space Shuttle.

60. SLC-6 was originally meant for the launch site of Dyna-Soar; it was then refurbished for the Manned Orbital Laboratory. Both programs, of course, were cancelled, so the site remained unused.

reconnaissance satellites, worried about the frequent delays in Shuttle launches and the length of time between manifesting a payload on the Shuttle and the actual flight (about twenty-four months).[61] They reasoned that any major problems encountered in a Shuttle subsystem could delay the flight of a critical payload. No matter how successful the Shuttle fleet was, there were likely to be times when it would be grounded for safety purposes, just as entire aircraft fleets may be grounded while investigators examine the causes of major subsystem failures and determine appropriate repairs. Privately, some analysts worried that the Shuttle might fail catastrophically at some point, leaving the fleet grounded for an extended period. In addition, some argued that even if NASA were able to sustain an average Shuttle flight rate of twenty-four per year, that rate would not accommodate the needs of the Air Force, along with the projected demand from civilian public- and private-sector uses.

Hence in 1983, with the strong endorsement of Secretary of the Air Force Pete Aldridge, the Air Force began to examine the benefits and costs of developing a new vehicle that it called the Complementary Expendable Launch Vehicle (CELV) to provide "assured access to space." On January 7, 1984, Secretary of Defense Caspar Weinberger approved a defense space launch strategy that included the development of a CELV with sufficient capacity to launch payloads of up to 40,000 pounds.[62]

Air Force officials chose the adjective "complementary" to avoid the appearance of competition with the Shuttle and to emphasize that the CELV would be expected to service DOD launch demand should the Shuttle be unable to meet it for any reason. Aldridge was also interested in improving Air Force launch flexibility and maintaining the technology base and production capability that might otherwise be lost.

Congressional reaction was mixed. DOD's authorization and appropriations committees generally supported the move. However, supporters of NASA's Space Shuttle expressed concern that CELV development would divert DOD attention away from the Shuttle and undercut the funding supporting Shuttle operations. The Shuttle was developed in part to serve DOD needs, which led to higher operations costs than NASA had anticipated. Continued DOD use of the Shuttle was needed to help pay for Shuttle upgrades and keep the costs of operations as low as possible.

Despite the concerns of some members of Congress, especially those of the House Committee on Science and Technology, DOD's plans nevertheless carried the day. DOD issued a request for proposals (RFP) on August 20, 1984, for the development of a launcher capable of lifting 10,000 pounds to a geostationary transfer orbit from DOD's Eastern Test Range. The initial RFP called for a total buy of ten launchers. In 1984, the Air Force had no official plans to launch the CELV from the Western Test Range at Vandenberg Air Force Base, but intended instead to rely on the Shuttle to lift payloads of up to 32,000 pounds into low-Earth polar orbit from Vandenberg.[63]

Martin Marietta won the contract to build an upgraded version of its Titan 34D in February 1985, over competing designs from General Dynamics and from NASA, which had proffered a launch vehicle based on Shuttle technology. This vehicle, which became known as the Titan IV, is capable of lifting 40,000 pounds to LEO or 10,000 pounds to geostationary transfer orbit. Martin Marietta achieved the improved payload capacity by stretching the liquid propellant tanks and by upgrading the Titan's solid rocket motors to

61. Ironically, the vehicle that resulted from the Air Force need to launch national security payloads, the Titan IV, has proved nearly as difficult to make operational and almost as costly as the Shuttle.

62. See Documents II-40 through II-44 in Logsdon, gen. ed., *Exploring the Unknown,* 2: 390–410.

63. Discussion between Congressman George Brown and Secretary of the Air Force Pete Aldridge, "Space Shuttle Requirements, Operations, and Future Plans," hearings before the Subcommittee on Space Science and Applications of the Committee on Science and Technology, U.S. House of Representatives, 98th Cong., 2d. sess., July 31–August 2, 1984, p. 86.

seven segments rather than the five and a half segments used by the Titan 34D.[64] Fairings of up to 86 feet long would accommodate Shuttle-size payloads. The Titan IV was designed with the capability to carry no upper stage, a Centaur upper stage, or an inertial upper stage (IUS).[65] The first Titan IV was launched on June 14, 1986, with an IUS upper stage. In October 1987, Martin Marietta contracted with Hercules to develop and manufacture SRBs with graphite-epoxy casings, capable of adding 8,000 pounds capacity to LEO. After the failure of the Shuttle *Challenger*, the Air Force's plans to develop the CELV seemed almost prescient.

Losing *Challenger*

Although every knowledgeable observer recognized that there was some potential for a major Shuttle failure, the press and the broader public in the early 1980s paid little attention to the risks of human spaceflight. Even those close to the Shuttle system let down their guard. As one successful launch followed another, some engineers and flight directors began to submerge their concerns about troublesome items that lay on the critical path to a safe launch. Hence, the nation was dealt an extremely rude shock when, on January 28, 1986, the orbiter *Challenger*, carrying seven crew members, seemed to disappear behind a huge fireball just over a minute after liftoff and disintegrated before the eyes of thousands of observers at the launch site and millions more watching the launch on live television coverage. It was a numbing sight, played over and over again on television, as people all over the world attempted to come to grips with what had happened.[66]

Launch vehicle reliability has always been a concern; most launch vehicles have demonstrated launch success rates of between 90 and 98 percent. Launch officials worry especially about the safety of vehicles that carry human crews. As long ago as 1977, former NASA Administrator James Fletcher had expressed his concerns to then NASA Deputy Administrator Alan M. Lovelace about the overall Space Shuttle system and whether NASA had the right people working the problem of launch reliability and safety. [II-37]

Engineers and other observers familiar with the Shuttle's many systems and points of potential weakness had their theories about the cause of the catastrophic failure, yet because of the complexity of the Shuttle system, it took careful analysis by a large team of experts to determine the exact cause. NASA began to work on the problem immediately by pulling together all of the available film footage, launch operations documents, and other materials that might be relevant to the investigation. NASA even employed a deep sea diving company to locate and retrieve parts of the failed launcher from the ocean floor. Although senior NASA officials would have preferred to carry out their own analysis outside the glare of publicity, as had been the case following the Apollo 1 fire, the highly public and dramatic loss of life that had occurred on January 28 made an independent external review almost inevitable. On February 3, President Reagan signed Executive Order 12546, which directed the establishment of a high-level commission, chaired by former Secretary of State William P. Rogers, to examine the evidence and determine not only what had happened, but also why it had. [II-38] The Presidential Commission on the Space Shuttle *Challenger* Accident, supported by NASA and other federal agencies, gathered evidence, investigated the chain of events, and held public hearings.

---

64. The first stage was stretched by almost eight feet to increase propellant volume by 10 percent, and the second stage was stretched almost two feet, resulting in increased propellant volume of 5 percent. The solid rocket motors are manufactured by the Chemical Systems Division of United Technologies.

65. With the IUS and a fifty-six-foot fairing, the Titan IV stands 174 feet tall.

66. The incident was especially numbing because NASA had worked particularly hard to generate public interest in the flight, which carried teacher Christa McAuliffe, who would have been the first teacher in space.

As the investigation revealed, the joint between the first and second motor segment was breached about fifty-nine seconds into the flight. Flames from the open joint struck the external tank and caused its liquid hydrogen and liquid oxygen tanks to rupture. At seventy-six seconds, fragments of *Challenger* could be seen against the backdrop of a large fireball, caused by the ignition of thousands of pounds of hydrogen from the external tank. The orbiter was torn apart by the enormous aerodynamic forces, which greatly exceeded the orbiter's design limits. Large parts of *Challenger* began to tumble through the atmosphere and fall back toward the Atlantic Ocean. The forward fuselage and the crew module, both of which remained largely intact, plunged into the waves a few seconds later, killing all seven astronauts on board.[67]

This description of the sequence of events during the failure of the vehicle was gained only through a meticulous examination of the photographs and the recovery and detailed inspection of many *Challenger* parts from the ocean floor. It also required a methodical analysis of the sequence of events during launch. This analysis also contributed to a more precise understanding of the O-ring failure that caused the loss of *Challenger*. Knowledge of the structural details of the SRBs became widespread as newspapers printed detailed drawings of the Shuttle system and the joint that held the motor segments together. The "tang-and-clevis" joint, which was supposed to hold the segments together with seventeen bolts and a rubber O-ring seal, received special attention from the media as well from experts, because it was this critical part of the Shuttle system that had failed. During engine firing, the joint was subject to enormous pressure. NASA and Morton Thiokol had intended to design the joint so that the O-ring would deform under pressure and fill in any small openings between the tang and clevis, preventing a "blow-by" of the hot ignition gases during motor firing. However, as NASA's own tests during SRB development had shown, the O-rings would occasionally suffer damage during firing.[68] During the second Shuttle flight (STS-2) and on several subsequent flights, the O-rings sustained both erosion and blow-by, indicating problems that could become worse. Of particular concern, as the temperature of the joint fell, the O-ring material would stiffen up and prevent it from properly squeezing into any voids, even when under pressure. Although several NASA officials and Morton Thiokol engineers were aware of the problem and the catastrophic failure it could cause, the two organizations failed to act to redesign the joint. Instead, they tried a number of other fixes, including tightening the joint and adding putty to the joint to assist the O-ring in sealing the joint.

The open hearings of the Rogers Commission, which NASA officials opposed, gave the public extraordinary insight into the almost overwhelming complexities of preparing and operating the Shuttle. In one particularly dramatic moment during the hearings, commission member Richard Feynman placed a short section of the O-ring in ice water, demonstrating on live television how inflexible the material becomes with cold. His simple demonstration dramatized a major problem that NASA officials had virtually ignored. As noted in the commission's report, "Prior to the accident, neither NASA nor Thiokol fully understood the mechanism by which the joint sealing action took place."[69]

The hearings and the report that resulted from it also exposed publicly a number of crucial management deficiencies within NASA, among which was the difficulty contractor personnel and mid-level NASA engineers had in conveying the seriousness of known technical problems to senior-level managers. [II-39] The hearings also made it clear that senior NASA officials had subtly but inexorably shifted their attitude regarding the launch

---

67. *Report of the Presidential Commission on the Space Shuttle Challenger Accident* (Washington, DC: U.S. Government Printing Office, June 6, 1986), pp. 19–39.

68. *Ibid.*, p. 120.

69. *Ibid.*, p. 148.

of the Shuttle. At first, the engineers had to demonstrate that the Shuttle was safe to launch. The shift was that by the time of the ill-fated *Challenger* launch (STS 51-L), they had to demonstrate that it was not safe to launch. At one point in the hearings, for example, Roger M. Boisjoly, a Morton Thiokol engineer, noted that "we were being put in a position to prove that we should not launch rather than being put in the position and prove that we had enough data to launch."[70] Decision-making regarding the Shuttle had become "a kind of Russian roulette . . . [the Shuttle] flies [with O-ring erosion] and nothing happens. Then it is suggested, therefore, that the risk is no longer so high for the next flights. We can lower our standards a little bit because we got away with it last time. . . . You got away with it, but it shouldn't be done over and over again like that."[71]

Return to Flight

Returning the Space Shuttle to space after the loss of *Challenger* was a challenging task. While the Rogers Commission investigated the technical and managerial causes of the failure, NASA had the difficult chore not only of redesigning the faulty SRBs, but also of increasing public confidence in its procedures. On March 24, 1986, well before the detailed causes of the Shuttle's failure were definitively established, the new Associate Administrator for Space Flight, former astronaut Richard H. Truly, announced a strategy for returning the Shuttle to flight status. [II-40] Among other things, his memorandum called for reassessing the entire program management structure and operation, and it laid out a plan for a "conservative return to operations."

Three weeks before Truly's memo, veteran astronaut John W. Young wrote a highly critical memorandum critiquing the management of the Shuttle program and outlining many of the steps needed to assure safety of flight. His views were representative of many who had been aware of the increasing acceptance of risk in Shuttle operations. [II-41] During the hiatus in flight, NASA examined every vulnerable element of Shuttle design and rethought Shuttle launch preparation and operations. NASA instituted many new safety procedures and replaced system components. For example, when first witnessing the huge fireball and destruction of *Challenger*, many engineers immediately concluded that one of the SSME turbopumps, which were highly susceptible to breakdown, might have failed. NASA used the "standdown" to go over the SSME piece by piece to improve its safety and reliability. NASA also increased its contractor staff at Kennedy Space Center to handle the load of new procedures for safety and quality assurance and documentation paperwork. The amount of time NASA technicians took to refurbish the orbiters after flight, to prepare the entire Shuttle system for launch, and to follow new safety and quality procedures more than doubled. The procedures were not only lengthened but became more complicated and intensive, making it increasingly doubtful that NASA could ever achieve its planned yearly launch rate of twenty-four flights, even if sufficient funding for Shuttle payloads and launch services became available to support such a rate.[72] Most important, however, NASA redesigned and tested the Shuttle's solid rocket motors so they would be much less likely to fail again, especially at the joints between motor segments.

---

70. *Ibid.*, p. 93.

71. Richard Feynman, quoted in *ibid.*, p. 148.

72. Generally missing in most NASA Space Shuttle briefings of the 1980s was a sense of the connection between launch rate and the overall costs for both payloads and Shuttle launch services. This was a case of radical optimism. Payload costs (on the launch vehicle) hovered between $40,000 and an astounding $650,000 per pound, depending on the amount of inexpensive elements in the payload (such as fuel) and the technical difficulties encountered in designing and building the spacecraft. See U.S. Congress, Office of Technology Assessment, *Affordable Spacecraft: Design and Launch Alternatives,* OTA-BP-ISC-60 (Washington, DC: U.S. Government Printing Office, January 1990).

The shock of losing *Challenger* and its crew also forced officials within the Reagan administration to reconsider what types of payloads the Shuttle would carry. For example, well before the failure, some observers had complained that using the Shuttle to launch commercial communications satellites, which could routinely be launched by ELVs, was a waste of federal resources and competed with possible commercial ELV efforts (see Chapter 3). In August 1986, the administration issued a statement on Shuttle use, followed by a formal policy statement in December. [II-42, II-43] That policy restricted Shuttle payloads to those requiring the unique capabilities of the Shuttle or needing the Shuttle for national security purposes. In particular, the Shuttle would no longer be used to launch commercial communications satellites.

The costs of losing *Challenger* were high, not only to the crew members and their families, but also in economic terms. NASA's Office of Space Flight estimated that the nation lost about seventy equivalent Shuttle flights over a period of ten years as a result of the loss of *Challenger,* as well as the loss of two Titan 34Ds and the Atlas-Centaur within a few months.[73] Europe's Ariane launched many of these lost payloads. Others were launched much later on ELVs or were never launched.[74]

The Reagan administration and Congress moved relatively quickly to replace the lost orbiter. NASA was able to proceed promptly with construction because, in April 1983, the agency had awarded Rockwell International a contract to construct long-lead-time structural spares, which were to have been completed by 1987. In part, the 1983 decision was prompted by the concern that eventually a fifth orbiter would be needed to handle the expected demand for Space Shuttle launch services. NASA officials also wanted to have crucial replacement parts on hand in case of a major failure of the Shuttle system. The administration requested funding to build a replacement orbiter in mid-1986. In an unusual move, Congress approved the entire package of funding of $2.1 million as part of a supplemental appropriations for fiscal year 1987.[75] The new vehicle (OV-105) was delivered to Kennedy Space Center in May 1991 and made its first flight in May 1992.[76] Congress had directed NASA to establish a contest to name the orbiter, involving elementary and secondary school students. In May 1989, President George Bush announced that the vehicle would be named *Endeavour,* after Captain Cook's famous ship.

On September 29, 1988, the Shuttle *Discovery* lifted off Pad 39B at the Kennedy Space Center, conveying a crew of five into orbit (STS-26). [II-44] *Discovery* also carried the replacement for NASA's Tracking and Data Relay Satellite (TDRS), one of the payloads lost when *Challenger* exploded in January 1986. The successful flight of *Discovery* and launch of TDRS held special significance because it marked the return of the Space Shuttle program to flight status and the end of a painful reevaluation of U.S. access to space. As an editorial in *Aviation Week & Space Technology* opined, "The launch, witnessed by the largest gathering of spectators and press since the Apollo 11 launch to the Moon in 1969, was balm to the wounds remaining from the *Challenger* accident. It was a long time coming. . . . It was a moment worth waiting for. . . . The *Discovery* mission should be savored as a triumph for NASA, the U.S. space program and the nation." The article also quoted

73. Cited in U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide,* OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988), p. 23.

74. Most of the payloads eventually launch on ELVs had to be reconfigured, as the support points had been configured for horizontal integration into the Shuttle, rather than the vertical configuration required for ELV launch. This shift sometimes imposed substantial additional costs.

75. Normally, Congress is reluctant to fund an entire project in one appropriation because of the impact on the budget of any one year. However, proponents of the fifth orbiter successfully argued that full funding would result in lower overall costs. In fact, the funds for the fifth orbiter were taken from excess Air Force appropriations.

76. This first flight of OV-105 was used to rescue the Intelsat VI satellite, which had been left stranded in LEO.

Kennedy Space Center Director Forrest McCartney, who observed that "[it] was a great day for America . . . today we stand tall."[77]

The second and last Shuttle flight of 1988 (STS-27) took place nine weeks later on December 2, during which the orbiter *Atlantis* carried a classified DOD satellite into high-inclination orbit.[78] The success of this flight added to NASA's (and DOD's) confidence in the revised launch procedures.

The loss of *Challenger* had forced NASA to reexamine the risks of human spaceflight, to examine more closely the methods used to evaluate and reduce such risks, and to be more forthcoming with the American public about them. Some NASA officials had inadvertently slipped into thinking that the Space Shuttle was nearly as reliable as a commercial aircraft. However, aircraft typically have empirically derived reliabilities (successful flights divided by attempts) approaching 99.9999 percent, based on many thousands of flights of essentially identical vehicles. Prior to the Shuttle's first launch, NASA had faced the difficulty of estimating flight risks based on detailed estimates of previous experience with subsystems, extensive testing of new subsystems, and the amount of redundancy built into critical systems. Based on such considerations, NASA designed each orbiter to have a 97-percent probability of lasting 100 flights, which leads to a requirement that each individual Shuttle flight have a reliability of at least 99.97 percent. Actual Shuttle reliability was uncertain, but one NASA-funded study estimated that it lies between 97 and 99 percent.[79]

After operations begin, estimations of reliability can also be based on statistical analysis of observed successes and failures, although with most launch vehicles such analysis involves the statistics of small numbers.[80] For example, using a simple statistical analysis, the congressional Office of Technology Assessment estimated for illustrative purposes that if STS reliability were assumed to be 98 percent, NASA would face a fifty-fifty chance of losing an orbiter within thirty-four flights.[81] [II-45] Whatever the actual reliability, this analysis led to the conclusion that reducing, rather than enhancing, the flight rate would be a prudent way to reduce Shuttle losses over time. The 1986 policy that encouraged federal agencies to launch on commercial ELVs when possible helped reduce the pressure on Space Shuttle launches. It also increased the resilience of the launch fleet because it made it possible to recover from a launch failure of a single vehicle more quickly than was true prior to January 1986—a concern of great importance to military planners who must have the greatest possible access to space.[82] However, too few Shuttle flights might increase flight risks, because the skill level of Shuttle launch crews might degrade between launches. Since 1988, NASA has kept the rate of Shuttle flights relatively low (five to seven per

77. "Back to Space!," *Aviation Week & Space Technology*, October 3, 1988, p. 7.

78. According to news sources, *Atlantis* carried a Lacrosse imaging radar satellite, a supposition that is strengthened by the fact that *Atlantis* entered a 57-degree orbit. See Craig Covault, "Atlantis' Radar Satellite Payload Opens New Reconnaissance Era," *Aviation Week & Space Technology*, December 12, 1988, pp. 26–28.

79. L-Systems, Inc., *Shuttle/Shuttle—Cooperations, Risks, and Cost Analyses*, LSYS-88-008 (El Segundo, CA: L-Systems, Inc., 1988).

80. Most statistical analyses of launch system reliability are further hampered by the changes that are made in the system after a failure to improve it; this introduces new unknowns into the analysis. Furthermore, for the STS, each of the four orbiters are somewhat different, and many upgrades and other changes are made in the subsystems between flights. Therefore, each launch can in many respects be considered as nearly the first of its kind. Nevertheless, one can obtain a rough statistical estimate of reliability by assuming that all Shuttle launches are roughly identical.

81. U.S. Congress, Office of Technology Assessment, *Round Trip to Orbit: Human Spaceflight Alternatives* (Washington, DC: U.S. Government Printing Office, August 1989), pp. 6, 25.

82. Resilience is a measure of the ability to recover from a launch failure. High resilience can be accomplished by repairing the failure quickly and employing a launch surge strategy to catch up on waiting launches or by using other launch vehicles (assuming launch vehicles are relatively interchangeable). Before the development of the Titan IV, heavy payloads could only be launched on the Shuttle.

year) and improved its on-time launch performance, suggesting that such a rate provides a good balance between safety and costs.

The Soviet Shuttle

Before NASA officials were able to savor fully the return of the Space Shuttle to flight status, the Soviet Union demonstrated its capacity to build and launch its own shuttle. In a move that mirrored the increasing openness of Soviet society during the regime of General Secretary Mikhail Gorbachev, early in 1988, Soviet officials released drawings and descriptions of their space shuttle.[83] Later in the year, on November 15, rocket engineers successfully launched the shuttle *Buran* (meaning "snowstorm") into orbit, attached to the all-liquid Energiya heavy-lift launch vehicle.[84] The flight was automated; no crew members were aboard (Figure 2–7). After two orbits, flight controllers landed *Buran* on a runway about ten kilometers from the Baikonur Cosmodrome launch pad.

Although *Buran* superficially resembled the U.S. Shuttle orbiter, in detail its concept was rather different. For one thing, in keeping with the Russian approach to new human spaceflight undertakings, the first flight was fully automatic—no cosmonauts were aboard, although the orbiter was reportedly capable of carrying ten crew members. Second, *Buran* carried no rocket engines. Finally, unlike the integrated SRBs, external tank, and SSMEs of the U.S. Shuttle, Energia was a stand-alone vehicle capable of launching up to 220,000 pounds to LEO, including the *Buran* orbiter. Although it lasted only two orbits, the flight was an impressive achievement, but one that was not followed up either with additional flights or the crafting of other orbiters. While the weakness of the Soviet space program had not yet become fully apparent in the United States, the program was past its zenith. By 1991, the Soviet Union and its economy had collapsed, taking with them the will to continue to invest large sums in space achievements. In a few years, *Buran* became an exhibit in a Moscow park, and the Energiya launcher was never used again to lift payloads into orbit.

Figure 2–7. The former Soviet Union's unmanned shuttle, Buran, *stood ready on the launch pad with the Energiya launcher in late 1988. It would make only one flight.*

83. "Soviet Union Developing Range of Manned, Unmanned Launchers," *Aviation Week & Space Technology,* March 28, 1988, pp. 52, 53, 58.

84. Craig Covault, "Soviet Shuttle Launched on Energia Booster," *Aviation Week & Space Technology,* November 21, 1988, pp. 18–21.

Variations on the Shuttle Theme

Beginning well before the Space Shuttle actually flew, engineers considered a wide variety of technical options for improving or extending the Shuttle's basic capabilities. These included adding to its lift capacity, carrying civilian passengers, and extending the stay time on orbit. The impetus for such studies derived from the firm belief among some observers that once the Shuttle became operational, the demand for launch services would grow quickly, making it attractive to add significantly to overall launch capacity. Among the ideas driving such thinking was the photovoltaic solar power satellite, which if built would have required lofting millions of kilograms of materials into geosynchronous orbit and space workers into LEO.[85] Concepts developed during the mid-1970s ranged from simply adding additional smaller solid rockets to the SRBs, to substituting large liquid rocket boosters for the SRBs, to building a fly-back booster.[86] Concepts also included ideas as diverse as a passenger-carrying orbiter capable of taking several tens of passengers to and from orbit and a strictly-cargo vehicle based on using the SRBs, the external tank, the SSMEs, and a cargo canister to substitute for the orbiter.

In general, these ideas never got beyond the concept stage. Yet, by the late 1980s, as space station planners struggled with the realities of lofting a station into orbit and resupplying it, some experts began to revive such concepts. Among other options, they considered building a heavy-lift launch vehicle that would be capable of launching large station payloads to orbit. The specter of losing an orbiter in the course of station construction, and the large number of Shuttle flights (more than twenty) required for the station then under consideration, led to studies of an alternative, larger cargo vehicle to reduce the number of orbiter flights. The Advanced Launch System (ALS) then under consideration (see Chapter 4) might have served such a purpose, but some NASA engineers argued for a cargo vehicle based on the Space Shuttle.

Initially, this was called the Shuttle-Derived Vehicle; later, the concept became known as the Shuttle-C, for cargo.[87] [II-46] Because the design of the Shuttle puts the SSMEs necessary for part of the propulsion on the orbiter itself, the Shuttle-C cargo carrier would also need to carry liquid engines to reach orbit. NASA considered the option of using the reusable SSMEs in a boat-tail configuration and dropping them off to be recovered in the ocean, but the agency found recovery and refurbishment too costly.[88] NASA engineers decided instead to employ SSMEs that had flown enough times that they were no longer sufficiently reliable for human flight, then letting them burn up in the atmosphere after use. As the concept was developed, the Shuttle-C would have been capable of lofting about 178,000 pounds to orbit from Kennedy Space Center. Ultimately, after nearly four years of study, NASA dropped its Shuttle-C efforts, in large part because OMB deemed the vehicle too costly. Furthermore, the move away from using the Shuttle launch for science payloads that could fly on ELVs removed most of the non–space station launch pressure on the Shuttle.

---

85. Peter E. Glaser, "Power from the Sun: Its Future," *Science* 162 (November 22, 1968): 857–86. For a description and assessment of solar power satellite concepts of the late 1970s, see U.S. Congress, Office of Technology Assessment, *Solar Power Satellites*, OTA-E-144 (Washington, DC: U.S. Government Printing Office, August 1981).

86. M.W. Jack Bell, "Space Shuttle Vehicle Growth Options," paper presented at the American Institute of Aeronautics Conference on Large Space Platforms: Future Needs and Capabilities, Los Angeles, CA, September 27–29, 1978.

87. Theresa M. Foley, "NASA May Seek Proposals for Shuttle-Derived Booster," *Aviation Week & Space Technology*, June 29, 1987, pp. 24–25.

88. Craig Covault, "Shuttle-C Unmanned Heavy Booster Could Simplify Space Station Launch," *Aviation Week & Space Technology*, August 15, 1988, pp. 87–88.

The Advanced Solid Rocket Motor

The failure of the Space Shuttle's solid rocket motor had repercussions for NASA's Shuttle program that extended far beyond the redesign of the motor. Proponents of both liquid boosters (pump-fed and pressure-fed) and more advanced solid rocket designs argued within NASA and before Congress that a major overhaul was needed. In addition to providing additional safety, the proposed designs would have improved the payload capacity of the Shuttle, which fell far short of the expected 65,000 pounds placed in the standard twenty-eight-degree LEO 110 nautical miles above Earth's surface. As a result of weight growth during manufacture and early operations, the Shuttle was capable of carrying a maximum payload to this orbit of only 48,000 pounds. However, some payloads, particularly space station components, were expected to weigh more.

During the period after the Shuttle returned to flight, NASA engineers explored two new solid rocket designs—the Advanced Solid Rocket Motor (ASRM) and an improved Redesigned Solid Rocket Motor (RSRM). The ASRM was a totally new design that would use a new manufacturing process, allowing the entire motor to be poured at one time. It would therefore not have joints that might fail. Proponents argued that the ASRM would provide greater safety than segmented boosters. After conducting detailed engineering studies of both liquid- and solid-fuel designs and comparing costs and safety, NASA decided in early 1989 to proceed with the ASRM on the basis that it would result in lower overall costs with comparable flight safety.[89] In March 1989, NASA's Aerospace Safety Advisory Panel noted that "on the basis of safety and reliability alone it is questionable whether the ASRM would be superior to the RSRM . . . until the ASRM has a similar background of testing and flight experience."[90]

Yet, NASA's own analysis disagreed with these findings, and in late April 1989, the agency awarded two contracts for the ASRM to a partnership formed between Aerojet and Lockheed. One contract supported the design and development of the ASRM; the second contract was for the design, construction, and operation of an automated solid rocket motor production facility. NASA designated Yellow Creek, Mississippi, as its preferred government-owned/contractor-operated ASRM production site and the Stennis Space Center in Mississippi as the motor test location. NASA estimated that ASRMs could be ready for a first launch in 1994 or 1995. Agency officials also expected that the ASRM program would help promote a competitive solid rocket motor industry.[91]

The ASRM was never built. After NASA built the plant in Yellow Creek, Mississippi, and began to outfit it, Congress began to have second thoughts about the increasing costs of the ASRM program. In October 1993, Congress voted to shut down the ASRM program as a cost-saving move. NASA then decided to put greater emphasis on improving the RSRM.

Space Shuttle in the 1990s

Once NASA was assured that the redesigned solid rocket motors worked safely, that the operation of the SSME improved, and that other safety-related issues were addressed, the space agency began to operate the Space Shuttle on a more regular basis, and launches had fewer delays. In fact, by the late 1990s, NASA felt that it could hand over the day-to-day

89. Proponents of solid rocket motors argued that such motors, if properly designed, are nearly as safe as liquid rocket motors that are by their very nature much more complicated and suffer from a greater number of possible failure modes.

90. Aerospace Safety Advisory Panel, *Annual Report for 1988* (Washington, DC: NASA Headquarters, Code Q-1, March 1989), p. 3.

91. NASA, "Space Shuttle Advanced Solid Rocket Motor—Acquisition Plan," March 31, 1988, p. 3, NASA Historical Reference Collection.

operations of the Shuttle to a private contractor, United Space Alliance. [II-47] The reusability of the orbiter also made it possible for NASA to demonstrate the Shuttle's ability to return payloads from orbit. For example, in 1990, STS-32 returned from the Long Duration Exposure Facility, which had been in orbit since 1984, when it was deployed by STS 41-C. After the communications satellite Intelsat VI was placed in an unusable orbit by a Titan III rocket in March 1990, NASA astronauts aboard STS-49 in May 1992 captured the satellite and redeployed it after attaching a new perigee kick motor to place it in geosynchronous orbit. In December 1993, the Shuttle rendezvoused with the Hubble Space Telescope, which had been launched with a misshapen primary mirror; the Shuttle crew was able to install equipment on the telescope to correct this mistake and perform other servicing tasks. Such feats, while demonstrating the utility and flexibility of the Space Shuttle, were generally overshadowed by the Shuttle's high operating costs, and NASA began gradually to focus more on the use of the Space Shuttle for use in constructing and operating the International Space Station.

The 1993 agreement between the Russian Federation and the United States to include Russia as a partner in the International Space Station had a major effect on Space Shuttle's operation during the 1990s.[92] On one hand, Russia agreed to launch part of the station and to assist in resupply, reducing the burden on the Shuttle. On the other hand, the United States agreed to place the station in a 51.6-degree orbit, which reduces the payload the Shuttle can carry to an orbit with that high of an inclination. Furthermore, Russia and the United States agreed to a combined Shuttle-*Mir* program as a precursor to International Space Station's construction. As NASA argued before Congress, this program would not only give NASA and the Russian Space Agency valuable experience in working together before the launch and assembly of the International Space Station, it would also test the Shuttle system's ability to reach a high orbit reliably with a tightly constrained launch window.

The first Shuttle launch to the Russian space station *Mir* took place during June 1995 on STS-71 (Figures 2–8, 2–9, and 2–10). On June 29, the Shuttle *Atlantis* docked with *Mir* to deliver two Russian cosmonauts and to return NASA astronaut Norman Thagard to Earth after 115 days aboard the Russian station. The Shuttle-*Mir* program was completed with STS-91 in June 1998 after nine successful dockings with *Mir.* On December 4, 1999, the Shuttle *Endeavour* (STS-88) launched the first component of the International Space Station into orbit, marking 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.

Conclusion

As the documents following this essay illustrate, the design of the Space Shuttle was a compromise among many technical and political considerations. During its conception, right on through to its development and use, virtually every element of the Shuttle's design and use was criticized by someone—sometimes for technical reasons, sometimes for its high costs, and sometimes for questionable NASA decisions. In retrospect, perhaps the most serious of the criticisms was that leveled at the set of policies that led to the attempt to require the use of the Space Shuttle for all U.S. space transportation needs.[93] Nevertheless, this compromise design, while expensive and complicated to operate, is today the world's most advanced and versatile launch system. Although NASA and its contractors have explored numerous alternatives to launching human crews to and from space (see Chapter 4), none are likely to replace the Space Shuttle for at least another decade.

---

92. U.S. Congress, Office of Technology Assessment, *U.S.-Russian Cooperation in Space,* OTA-ISS-618 (Washington, DC: U.S. Government Printing Office, April 1995).

93. Logsdon, "The Space Shuttle Program: A Policy Failure?"

Figure 2–8. A member of the crew on the Russian space station Mir *took this photo of the orbiter* Atlantis *over the southern Aral Sea prior to rendezvous. With the payload doors open, the Spacelab science module and the docking mechanism can be seen on June 28, 1995. (NASA photo)*

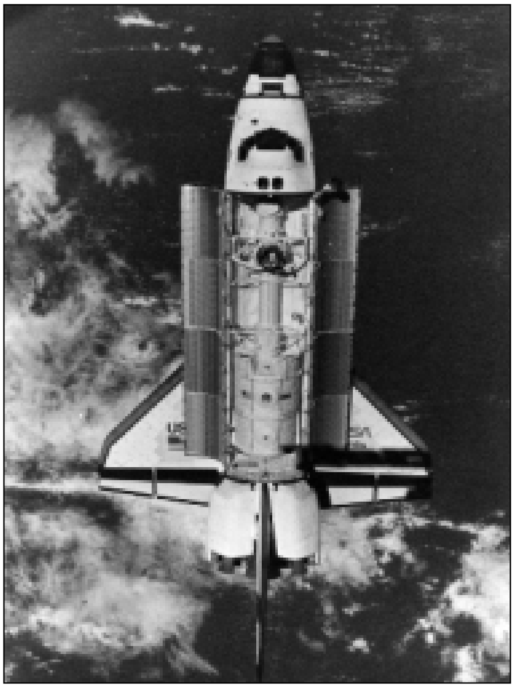

Figure 2–9. Taken the same day, this photo shows Atlantis *approaching the docking node on the Kristall module of the* Mir *space station. (NASA photo)*