Part One

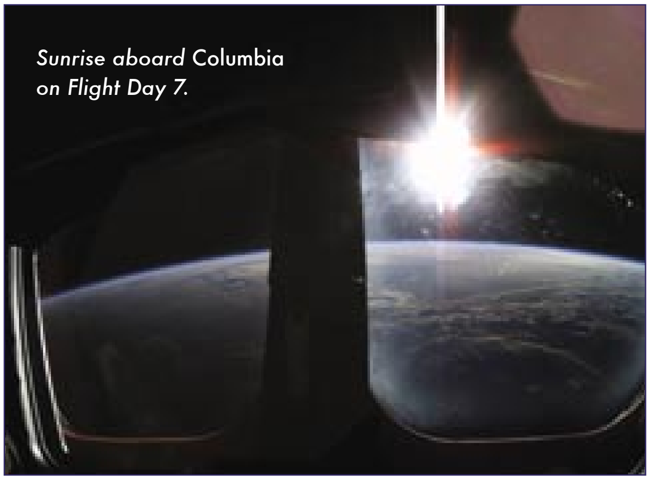
The Accident

"Building rockets is hard." Part of the problem is that space travel is in its infancy. Although humans have been launching orbital vehicles for almost 50 years now – about half the amount of time we have been flying airplanes – contrast the numbers. Since *Sputnik*, humans have launched just over 4,500 rockets towards orbit (not counting suborbital flights and small sounding rockets). During the first 50 years of aviation, there were over one million aircraft built. Almost all of the rockets were used only once; most of the airplanes were used more often.

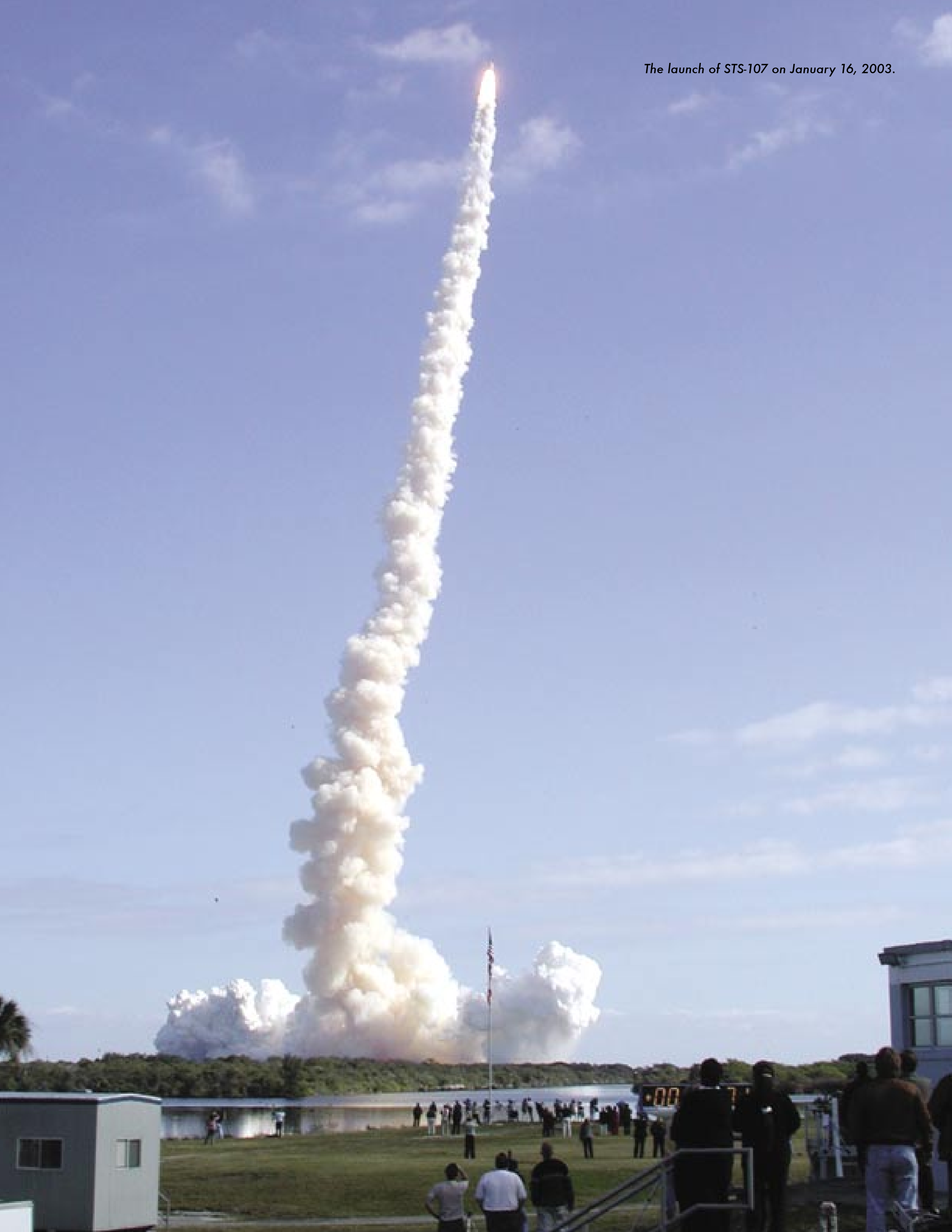
There is also the issue of performance. Airplanes slowly built their performance from the tens of miles per hour the Wright Brothers initially managed to the 4,520 mph that Major William J. Knight flew in the X-15A-2 research airplane during 1967. Aircraft designers and pilots would slightly push the envelope, stop and get comfortable with where they were, then push on. Orbital rockets, by contrast, must have all of their performance on the first (and often, only) flight. Physics dictates this – to reach orbit, without falling back to Earth, you have to exceed about 17,500 mph. If you cannot vary performance, then the only thing left to change is the amount of payload – the rocket designers began with small payloads and worked their way up.

Rockets, by their very nature, are complex and unforgiving vehicles. They must be as light as possible, yet attain outstanding performance to get to orbit. Mankind is, however, getting better at building them. In the early days as often as not the vehicle exploded on or near the launch pad; that seldom happens any longer. It was not that different from early airplanes, which tended to crash about as often as they flew. Aircraft seldom crash these days, but rockets still fail between two-and-five percent of the time. This is true of just about any launch vehicle – Atlas, Delta, Soyuz, Shuttle – regardless of what nation builds it or what basic configuration is used; they all fail about the same amount of the time. Building and launching rockets is still a very dangerous business, and will continue to be so for the foreseeable future while we gain experience at it. It is unlikely that launching a space vehicle will ever be as routine an undertaking as commercial air travel – certainly not in the lifetime of anybody who reads this. The scientists and engineers continually work on better ways, but if we want to continue going into outer space, we must continue to accept the risks.

Part One of the report of the Columbia Accident Investigation Board is organized into four chapters. In order to set the background for further discussion, Chapter 1 relates the history of the Space Shuttle Program before the *Challenger* accident. The events leading to the original approval of the Space Shuttle Program are recounted, as well as an examination of some of the promises made in order to gain that approval. In retrospect, many of these promises could never have been achieved. Chapter 2 documents the final flight of *Columbia*. As a straightforward record of the event, it contains no findings or recommendations. Chapter 3 reviews five analytical paths – aerodynamic, thermodynamic, sensor data timeline, debris reconstruction, and imaging evidence – to show that all five independently arrive at the same conclusion. Chapter 4 describes the investigation into other possible physical factors that might have contributed to the accident, but were subsequently dismissed as possible causes.



Sunrise aboard Columbia *on Flight Day 7.*



The launch of STS-107 on January 16, 2003.

Chapter 1

The Evolution of the Space Shuttle Program

More than two decades after its first flight, the Space Shuttle remains the only reusable spacecraft in the world capable of simultaneously putting multiple-person crews and heavy cargo into orbit, of deploying, servicing, and retrieving satellites, and of returning the products of on-orbit research to Earth. These capabilities are an important asset for the United States and its international partners in space. Current plans call for the Space Shuttle to play a central role in the U.S. human space flight program for years to come.

The Space Shuttle Program's remarkable successes, however, come with high costs and tremendous risks. The February 1 disintegration of *Columbia* during re-entry, 17 years after *Challenger* was destroyed on ascent, is the most recent reminder that sending people into orbit and returning them safely to Earth remains a difficult and perilous endeavor.

It is the view of the Columbia Accident Investigation Board that the *Columbia* accident is not a random event, but rather a product of the Space Shuttle Program's history and current management processes. Fully understanding how it happened requires an exploration of that history and management. This chapter charts how the Shuttle emerged from a series of political compromises that produced unreasonable expectations – even myths – about its performance, how the *Challenger* accident shattered those myths several years after NASA began acting upon them as fact, and how, in retrospect, the Shuttle's technically ambitious design resulted in an inherently vulnerable vehicle, the safe operation of which exceeded NASA's organizational capabilities as they existed at the time of the *Columbia* accident. The Board's investigation of what caused the *Columbia* accident thus begins in the fields of East Texas but reaches more than 30 years into the past, to a series of economically and politically driven decisions that cast the Shuttle program in a role that its nascent technology could not support. To understand the cause of the *Columbia* accident is to understand how a program promising reliability and cost efficiency resulted instead in a developmental vehicle that never achieved the fully operational status NASA and the nation accorded it.

1.1 Genesis of the Space Transportation System

The origins of the Space Shuttle Program date to discussions on what should follow Project Apollo, the dramatic U.S. missions to the moon.[1] NASA centered its post-Apollo plans on developing increasingly larger outposts in Earth orbit that would be launched atop Apollo's immense Saturn V booster. The space agency hoped to construct a 12-person space station by 1975; subsequent stations would support 50, then 100 people. Other stations would be placed in orbit around the moon and then be constructed on the lunar surface. In parallel, NASA would develop the capability for the manned exploration of Mars. The concept of a vehicle – or Space Shuttle – to take crews and supplies to and from low-Earth orbit arose as part of this grand vision (see Figure 1.1-1). To keep the costs of these trips to a minimum, NASA intended to develop a fully reusable vehicle.[2]

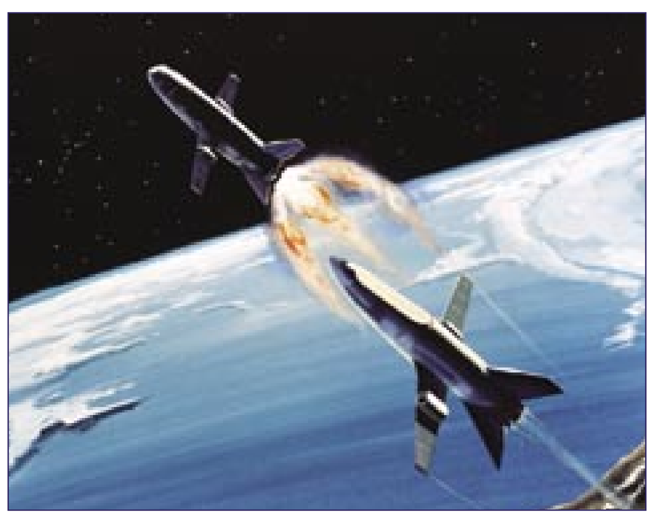


Figure 1.1-1. Early concepts for the Space Shuttle envisioned a reusable two-stage vehicle with the reliability and versatility of a commercial airliner.

NASA's vision of a constellation of space stations and journeying to Mars had little connection with political realities of the time. In his final year in office, President Lyndon Johnson gave highest priority to his Great Society programs and to dealing with the costs and domestic turmoil associated with the Vietnam war. Johnson's successor, President Richard Nixon, also had no appetite for another large, expensive, Apollo-like space commitment. Nixon rejected NASA's ambitions with little hesitation and directed that the agency's budget be cut as much as was politically feasible. With NASA's space station plans deferred and further production of the Saturn V launch vehicle cancelled, the Space Shuttle was the only manned space flight program that the space agency could hope to undertake. But without space stations to service, NASA needed a new rationale for the Shuttle. That rationale emerged from an intense three-year process of technical studies and political and budgetary negotiations that attempted to reconcile the conflicting interests of NASA, the Department of Defense, and the White House.[3]

1.2 Merging Conflicting Interests

During 1970, NASA's leaders hoped to secure White House approval for developing a fully reusable vehicle to provide routine and low cost manned access to space. However, the staff of the White House Office of Management and Budget, charged by Nixon with reducing NASA's budget, was skeptical of the value of manned space flight, especially given its high costs. To overcome these objections, NASA turned to justifying the Space Shuttle on economic grounds. If the same vehicle, NASA argued, launched all government and private sector payloads and if that vehicle were reusable, then the total costs of launching and maintaining satellites could be dramatically reduced. Such an economic argument, however, hinged on the willingness of the Department of Defense to use the Shuttle to place national security payloads in orbit. When combined, commercial, scientific, and national security payloads would require 50 Space Shuttle missions per year. This was enough to justify – at least on paper – investing in the Shuttle.

Meeting the military's perceived needs while also keeping the cost of missions low posed tremendous technological hurdles. The Department of Defense wanted the Shuttle to carry a 40,000-pound payload in a 60-foot-long payload bay and, on some missions, launch and return to a West Coast launch site after a single polar orbit. Since the Earth's surface – including the runway on which the Shuttle was to land – would rotate during that orbit, the Shuttle would need to maneuver 1,100 miles to the east during re-entry. This "cross-range" requirement meant the Orbiter required large delta-shaped wings and a more robust thermal protection system to shield it from the heat of re-entry.

Developing a vehicle that could conduct a wide variety of missions, and do so cost-effectively, demanded a revolution in space technology. The Space Shuttle would be the first reusable spacecraft, the first to have wings, and the first with a reusable thermal protection system. Further, the Shuttle would be the first to fly with reusable, high-pressure hydrogen/oxygen engines, and the first winged vehicle to transition from orbital speed to a hypersonic glide during re-entry.

Even as the design grew in technical complexity, the Office of Management and Budget forced NASA to keep – or at least promise to keep – the Shuttle's development and operating costs low. In May 1971, NASA was told that it could count on a maximum of $5 billion spread over five years for any new development program. This budget ceiling forced NASA to give up its hope of building a fully reusable two-stage vehicle and kicked off an intense six-month search for an alternate design. In the course of selling the Space Shuttle Program within these budget limitations, and therefore guaranteeing itself a viable post-Apollo future, NASA made bold claims about the expected savings to be derived from revolutionary technologies not yet developed. At the start of 1972, NASA leaders told the White House that for $5.15 billion they could develop a Space Shuttle that would meet all performance requirements, have a lifetime of 100 missions per vehicle, and cost $7.7 million per flight.[4] All the while, many people, particularly those at the White House Office of Management and Budget, knew NASA's in-house and external economic studies were overly optimistic.[5]

Those in favor of the Shuttle program eventually won the day. On January 5, 1972, President Nixon announced that the Shuttle would be "designed to help transform the space frontier of the 1970s into familiar territory, easily accessible for human endeavor in the 1980s and 90s. This system will center on a space vehicle that can shuttle repeatedly from Earth to orbit and back. *It will revolutionize transportation into near space, by routinizing it*. [emphasis added]"[6] Somewhat ironically, the President based his decision on grounds very different from those vigorously debated by NASA and the White House budget and science offices. Rather than focusing on the intricacies of cost/benefit projections, Nixon was swayed by the political benefits of increasing employment in key states by initiating a major new aerospace program in the 1972 election year, and by a geopolitical calculation articulated most clearly by NASA Administrator James Fletcher. One month before the decision, Fletcher wrote a memo to the White House stating, "For the U.S. not to be in space, while others do have men in space, is unthinkable, and a position which America cannot accept."[7]

The cost projections Nixon had ignored were not forgotten by his budget aides, or by Congress. A $5.5 billion ceiling imposed by the Office of Management and Budget led NASA to make a number of tradeoffs that achieved savings in the short term but produced a vehicle that had higher operational costs and greater risks than promised. One example was the question of whether the "strap-on" boosters would use liquid or solid propellants. Even though they had higher projected operational costs, solid-rocket boosters were chosen largely because they were less expensive to develop, making the Shuttle the first piloted spacecraft to use solid boosters. And since NASA believed that the Space Shuttle would be far safer than any other spacecraft, the agency accepted a design with no crew escape system (see Chapter 10.)

The commitments NASA made during the policy process drove a design aimed at satisfying conflicting requirements: large payloads and cross-range capability, but also low development costs and the even lower operating costs of a "routine" system. Over the past 22 years, the resulting vehicle has proved difficult and costly to operate, riskier than expected, and, on two occasions, deadly.

It is the Board's view that, in retrospect, the increased complexity of a Shuttle designed to be all things to all people created inherently greater risks than if more realistic technical goals had been set at the start. Designing a reusable spacecraft that is also cost-effective is a daunting engineering challenge; doing so on a tightly constrained budget is even more difficult. Nevertheless, the remarkable system we have today is a reflection of the tremendous engineering expertise and dedication of the workforce that designed and built the Space Shuttle within the constraints it was given.

In the end, the greatest compromise NASA made was not so much with any particular element of the technical design, but rather with the premise of the vehicle itself. NASA promised it could develop a Shuttle that would be launched almost on demand and would fly many missions each year. Throughout the history of the program, a gap has persisted between the rhetoric NASA has used to market the Space Shuttle and operational reality, leading to an enduring image of the Shuttle as capable of safely and routinely carrying out missions with little risk.

1.3 Shuttle Development, Testing, and Qualification

The Space Shuttle was subjected to a variety of tests before its first flight. However, NASA conducted these tests somewhat differently than it had for previous spacecraft.[8] The Space Shuttle Program philosophy was to ground-test key hardware elements such as the main engines, Solid Rocket Boosters, External Tank, and Orbiter separately and to use analytical models, not flight testing, to certify the integrated Space Shuttle system. During the Approach and Landing Tests (see Figure 1.3-1), crews verified that the Orbiter could successfully fly at low speeds and land safely; however, the Space Shuttle was not flown on an unmanned orbital test flight prior to its first mission – a significant change in philosophy compared to that of earlier American spacecraft.

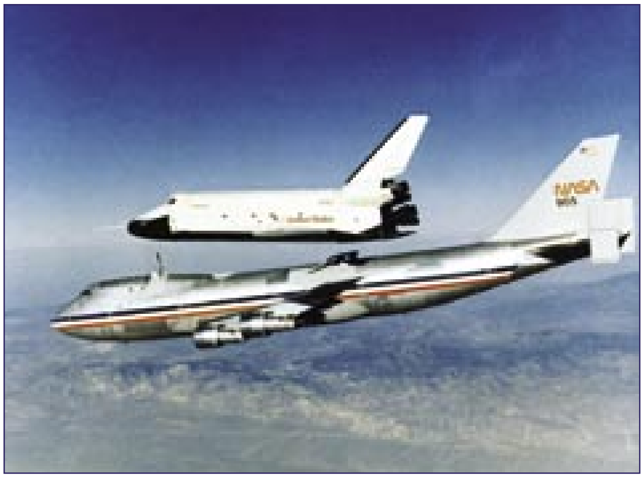


Figure 1.3-1. The first Orbiter was Enterprise, *shown here being released from the Boeing 747 Shuttle Carrier Aircraft during the Approach and Landing Tests at Edwards Air Force Base.*

The significant advances in technology that the Shuttle's design depended on led its development to run behind schedule. The date for the first Space Shuttle launch slipped from March 1978 to 1979, then to 1980, and finally to the spring of 1981. One historian has attributed one year of this delay "to budget cuts, a second year to problems with the main engines, and a third year to problems with the thermal protection tiles."[9] Because of these difficulties, in 1979 the program underwent an exhaustive White House review. The program was thought to be a billion dollars over budget, and President Jimmy Carter wanted to make sure that it was worth continuing. A key factor in the White House's final assessment was that the Shuttle was needed to launch the intelligence satellites required for verification of the SALT II arms control treaty, a top Carter Administration priority. The review reaffirmed the need for the Space Shuttle, and with continued White House and Congressional support, the path was clear for its transition from development to flight. NASA ultimately completed Shuttle development for only 15 percent more than its projected cost, a comparatively small cost overrun for so complex a program.[10]

The Orbiter that was destined to be the first to fly into space was *Columbia*. In early 1979, NASA was beginning to feel the pressure of being behind schedule. Despite the fact that only 24,000 of the 30,000 Thermal Protection System tiles had been installed, NASA decided to fly *Columbia* from the manufacturing plant in Palmdale, California, to the Kennedy Space Center in March 1979. The rest of the tiles would be installed in Florida, thus allowing NASA to maintain the appearance of *Columbia*'s scheduled launch date. Problems with the main engines and the tiles were to leave *Columbia* grounded for two more years.

1.4 The Shuttle Becomes "Operational"

On the first Space Shuttle mission, STS-1,[11] *Columbia* carried John W. Young and Robert L. Crippen to orbit on April 12, 1981, and returned them safely two days later to Edwards Air Force Base in California (see Figure 1.4-1). After three years of policy debate and nine years of development, the Shuttle returned U.S. astronauts to space for the first time since the Apollo-Soyuz Test Project flew in July 1975. Post-flight inspection showed that *Columbia* suffered slight damage from excess Solid Rocket Booster ignition pressure and lost 16 tiles, with 148 others sustaining some damage. Over the following 15 months, *Columbia* was launched three more times. At the end of its fourth mission, on July 4, 1982, *Columbia* landed at Edwards where President Ronald Reagan declared to a nation celebrating Independence Day that "beginning with the next flight, the *Columbia* and her sister ships will be *fully operational*, ready to provide *economical and routine access to space* for scientific exploration, commercial ventures, and for tasks related to the national security" [emphasis added].[12]

There were two reasons for declaring the Space Shuttle "operational" so early in its flight program. One was NASA's hope for quick Presidential approval of its next manned space flight program, a space station, which would not move forward while the Shuttle was still considered developmental. The second reason was that the nation was sud-

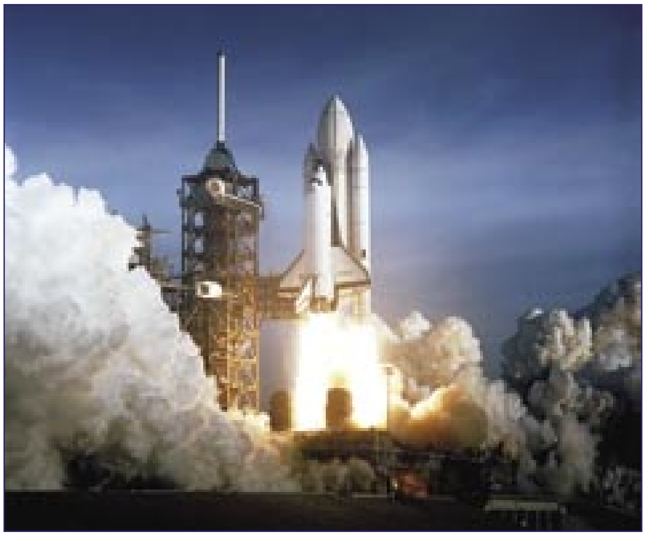


Figure 1.4-1. The April 12, 1981, launch of STS-1, just seconds past 7 a.m., carried astronauts John Young and Robert Crippen into an Earth orbital mission that lasted 54 hours.

denly facing a foreign challenger in launching commercial satellites. The European Space Agency decided in 1973 to develop Ariane, an expendable launch vehicle. Ariane first flew in December 1979 and by 1982 was actively competing with the Space Shuttle for commercial launch contracts. At this point, NASA still hoped that revenue from commercial launches would offset some or all of the Shuttle's operating costs. In an effort to attract commercial launch contracts, NASA heavily subsidized commercial launches by offering services for $42 million per launch, when actual costs were more than triple that figure.[13] A 1983 NASA brochure titled *We Deliver* touted the Shuttle as "the most reliable, flexible, and cost-effective launch system in the world."[14]

Figure 1.4-2. The crew of STS-5 successfully deployed two commercial communications satellites during the first "operational" mission of the Space Shuttle.

Between 1982 and early 1986, the Shuttle demonstrated its capabilities for space operations, retrieving two communications satellites that had suffered upper-stage misfires after launch, repairing another communications satellite on-orbit, and flying science missions with the pressurized European-built Spacelab module in its payload bay. The Shuttle took into space not only U.S. astronauts, but also citizens of Germany, Mexico, Canada, Saudi Arabia, France, the Netherlands, two payload specialists from commercial enterprises, and two U.S. legislators, Senator Jake Garn and Representative Bill Nelson. In 1985, when four Orbiters were in operation, the vehicles flew nine missions, the most launched in a single calendar year. By the end of 1985, the Shuttle had launched 24 communications satellites (see Figure 1.4-2) and had a backlog of 44 orders for future commercial launches.

On the surface, the program seemed to be progressing well. But those close to it realized that there were numerous problems. The system was proving difficult to operate, with more maintenance required between flights than had been expected. Rather than needing the 10 working days projected in 1975 to process a returned Orbiter for its next flight, by the end of 1985 an average of 67 days elapsed before the Shuttle was ready for launch.[15]

Though assigned an operational role by NASA, during this period the Shuttle was in reality still in its early flight-test stage. As with any other first-generation technology, operators were learning more about its strengths and weaknesses from each flight, and making what changes they could, while still attempting to ramp up to the ambitious flight schedule NASA set forth years earlier. Already, the goal of launching 50 flights a year had given way to a goal of 24 flights per year by 1989. The per-mission cost was more than $140 million, a figure that when adjusted for inflation was seven times greater than what NASA projected over a decade earlier.[16] More troubling, the pressure of maintaining the flight schedule created a management atmosphere that increasingly accepted less-than-specification performance of various components and systems, on the grounds that such deviations had not interfered with the success of previous flights.[17]

1.5 The *Challenger* Accident

The illusion that the Space Shuttle was an operational system, safe enough to carry legislators and a high-school teacher into orbit, was abruptly and tragically shattered on the morning of January 28, 1986, when *Challenger* was destroyed 73 seconds after launch during the 25th mission (see Figure 1.5-1). The seven-member crew perished.

To investigate, President Reagan appointed the 13-member Presidential Commission on the Space Shuttle Challenger Accident, which soon became known as the Rogers Commission, after its chairman, former Secretary of State William P. Rogers.[18] Early in its investigation, the Commission identified the mechanical cause of the accident to be the failure of the joint of one of the Solid Rocket Boosters. The Commission found that the design was not well understood by the engineers that operated it and that it had not been adequately tested.

Figure 1.5-1. the Space Shuttle Challenger *was lost during ascent on January 28, 1986, when an O-ring and seal in the right Solid Rocket Booster failed.*

When the Rogers Commission discovered that, on the eve of the launch, NASA and a contractor had vigorously debated the wisdom of operating the Shuttle in the cold temperatures predicted for the next day, and that more senior NASA managers were unaware of this debate, the Commission shifted the focus of its investigation to "NASA management practices, Center-Headquarters relationships, and the chain of command for launch commit decisions."[19] As the investigation continued, it revealed a NASA culture that had gradually begun to accept escalating risk, and a NASA safety program that was largely silent and ineffective.

The Rogers Commission report, issued on June 6, 1986, recommended a redesign and recertification of the Solid Rocket Motor joint and seal and urged that an independent body oversee its qualification and testing. The report concluded that the drive to declare the Shuttle operational had put enormous pressures on the system and stretched its resources to the limit. Faulting NASA safety practices, the Commission also called for the creation of an independent NASA Office of Safety, Reliability, and Quality Assurance, reporting directly to the NASA Administrator, as well as structural changes in program management.[20] (The Rogers Commission findings and recommendations are discussed in more detail in Chapter 5.) It would take NASA 32 months before the next Space Shuttle mission was launched. During this time, NASA initiated a series of longer-term vehicle upgrades, began the construction of the Orbiter *Endeavour* to replace *Challenger*, made significant organizational changes, and revised the Shuttle manifest to reflect a more realistic flight rate.

The *Challenger* accident also prompted policy changes. On August 15, 1986, President Reagan announced that the Shuttle would no longer launch commercial satellites. As a result of the accident, the Department of Defense made a decision to launch all future military payloads on expendable launch vehicles, except the few remaining satellites that required the Shuttle's unique capabilities.

In the seventeen years between the *Challenger* and *Columbia* accidents, the Space Shuttle Program achieved significant successes and also underwent organizational and managerial changes. The program had successfully launched several important research satellites and was providing most of the "heavy lifting" of components necessary to build the International Space Station (see Figure 1.5-2). But as the Board subsequently learned, things were not necessarily as they appeared. (The post-*Challenger* history of the Space Shuttle Program is the topic of Chapter 5.)

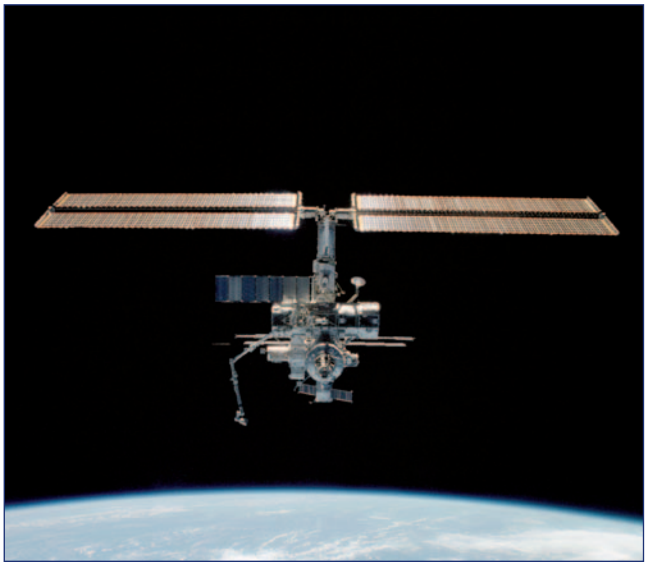


Figure 1.5-2. The International Space Station as seen from an approaching Space Shuttle.

1.6 Concluding Thoughts

The Orbiter that carried the STS-107 crew to orbit 22 years after its first flight reflects the history of the Space Shuttle Program. When *Columbia* lifted off from Launch Complex 39-A at Kennedy Space Center on January 16, 2003, it superficially resembled the Orbiter that had first flown in 1981, and indeed many elements of its airframe dated back to its first flight. More than 44 percent of its tiles, and 41 of the 44 wing leading edge Reinforced Carbon-Carbon (RCC) panels were original equipment. But there were also many new systems in *Columbia*, from a modern "glass" cockpit to second-generation main engines.

Although an engineering marvel that enables a wide-variety of on-orbit operations, including the assembly of the International Space Station, the Shuttle has few of the mission capabilities that NASA originally promised. It cannot be launched on demand, does not recoup its costs, no longer carries national security payloads, and is not cost-effective enough, nor allowed by law, to carry commercial satellites. Despite efforts to improve its safety, the Shuttle remains a complex and risky system that remains central to U.S. ambitions in space. *Columbia*'s failure to return home is a harsh reminder that the Space Shuttle is a developmental vehicle that operates not in routine flight but in the realm of dangerous exploration.

ENDNOTES FOR CHAPTER 1

The citations that contain a reference to "CAIB document" with CAB or CTF followed by seven to eleven digits, such as CAB001-0010, refer to a document in the Columbia Accident Investigation Board database maintained by the Department of Justice and archived at the National Archives.

1 George Mueller, Associate Administrator for Manned Space Flight, NASA, "Honorary Fellowship Acceptance," address delivered to the British Interplanetary Society, University College, London, England, August 10, 1968, contained in John M. Logsdon, Ray A. Williamson, Roger D. Launius, Russell J. Acker, Stephen J. Garber, and Jonathan L. Friedman, editors, Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program Volume IV: Accessing Space, NASA SP-4407 (Washington: Government Printing Office, 1999), pp. 202-205.

2 For detailed discussions of the origins of the Space Shuttle, see Dennis R. Jenkins, Space Shuttle: The History of the National Space Transportation System – The First 100 Missions (Cape Canaveral, FL: Specialty Press, 2001); T. A. Heppenheimer, The Space Shuttle Decision: NASA's Search for a Reusable Space Vehicle, NASA SP-4221 (Washington: Government Printing Office, 1999; also published by the Smithsonian Institution Press, 2002); and T. A. Heppenheimer, Development of the Space Shuttle, 1972-1981 (Washington: Smithsonian Institution Press, 2002). Much of the discussion in this section is based on these studies.

3 See John M. Logsdon, "The Space Shuttle Program: A Policy Failure?" *Science*, May 30, 1986 (Vol. 232), pp. 1099-1105 for an account of this decision process. Most of the information and quotes in this section are taken from this article.

4 See also comments by Robert F. Thompson, Columbia Accident Investigation Board Public Hearing, April 23, 2003, in Appendix G.

5 Heppenheimer, *The Space Shuttle Decision*, pp. 278-289, and Roger A. Pielke, Jr., "The Space Shuttle Program: 'Performance vs. Promise,'" Center for Space and Geosciences Policy, University of Colorado, August 31, 1991; Logsdon, "The Space Shuttle Program: A Policy Failure?" pp. 1099-1105.

6 Quoted in Jenkins, *Space Shuttle*, p. 171.

7 Memorandum from J. Fletcher to J. Rose, Special Assistant to the President, November 22, 1971; Logsdon, John, "The Space Shuttle Program: A Policy Failure?" *Science*, May 30, 1986, Volume 232, pp. 1099-1105.

8 The only actual flight tests conducted of the Orbiter were a series of Approach and Landing Tests where *Enterprise* (OV-101) was dropped from its Boeing 747 Shuttle Carrier Aircraft while flying at 25,000 feet. These tests – with crews aboard – demonstrated the low-speed handling capabilities of the Orbiter and allowed an evaluation of the vehicle's landing characteristics. See Jenkins, *Space Shuttle*, pp. 205-212 for more information.

9 Heppenheimer, *Development of the Space Shuttle,* p. 355.

10 As Howard McCurdy, a historian of NASA, has noted: "With the now-familiar Shuttle configuration, NASA officials came close to meeting their cost estimate of $5.15 billion for phase one of the Shuttle program. NASA actually spent $9.9 billion in real year dollars to take the Shuttle through design, development and initial testing. This sum, when converted to fixed year 1971 dollars using the aerospace price deflator, equals $5.9 billion, or a 15 percent cost overrun on the original estimate for phase one. Compared to other complex development programs, this was not a large cost overrun." See Howard McCurdy, "The Cost of Space Flight," *Space Policy* 10 (4) p. 280. For a program budget summary, see Jenkins, *Space Shuttle*, p. 256.

11 STS stands for Space Transportation System. Although in the years just before the 1986 *Challenger* accident NASA adopted an alternate Space Shuttle mission numbering scheme, this report uses the original STS flight designations.

12 President Reagan's quote is contained in President Ronald Reagan, "Remarks on the Completion of the Fourth Mission of the Space Shuttle *Columbia*," July 4, 1982, p. 870, in *Public Papers of the Presidents of the United States: Ronald Reagan* (Washington: Government Printing Office, 1982-1991). The emphasis noted is the Board's.

13 "Pricing Options for the Space Shuttle," Congressional Budget Office Report, 1985.

14 The quote is from page 2 of the *We Deliver* brochure, reproduced in *Exploring the Unknown Volume IV*, p. 423.

15 NASA Johnson Space Center, "Technology Influences on the Space Shuttle Development," June 8, 1986, p. 1-7.

16 The 1971 cost-per-flight estimate was $7.7 million; $140.5 million dollars in 1985 when adjusted for inflation becomes $52.9 million in 1971 dollars or nearly seven times the 1971 estimate. "Pricing Options for the Space Shuttle."

17 See Diane Vaughan, *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA* (Chicago: The University of Chicago Press, 1996).

18 See John M. Logsdon, "Return to Flight: Richard H. Truly and the Recovery from the Challenger Accident," in Pamela E. Mack, editor, *From Engineering to Big Science: The NACA and NASA Collier Trophy Research Project Winners*, NASA SP-4219 (Washington: Government Printing Office, 1998) for an account of the aftermath of the accident. Much of the account in this section is drawn from this source.

19 Logsdon, "Return to Flight," p. 348.

20 *Presidential Commission on the Space Shuttle Challenger Accident* (Washington: Government Printing Office, June 6, 1986).