CHAPTER THREE

SPACE TRANSPORTATION/ HUMAN SPACEFLIGHT

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Introduction

In April 1981, after a hiatus of six years, American astronauts returned to space when they left the launch pad aboard the Space Shuttle orbiter *Columbia*. This chapter describes the major technology used by the Space Shuttle; each Space Shuttle mission through 1988, their payloads, and the operations surrounding the missions; the events surrounding the 1986 *Challenger* accident and the changes that occurred as a result of the accident; and the development of the Space Station program through 1988, one of NASA's major initiatives of the decade. It also describes the budget for human spaceflight at NASA and the management of human spaceflight activities.

The Last Decade Reviewed (1969–1978)

The successful culmination of three major spaceflight programs and steady progress in the Space Shuttle program highlighted NASA's second decade. The Apollo program concluded with its lunar landings; Skylab demonstrated the possibility of a space-based platform that could support human life over an extended period of time; and the Apollo-Soyuz Test Project showed that international cooperation in the space program was possible in the face of political differences. Steady progress in the human spaceflight program encouraged NASA to commit major resources to the Shuttle program.

The successful Apollo lunar expeditions caught the imagination of the American public. The first lunar landing took place on July 20, 1969, and was followed by the lunar landings of Apollo 12, 14, 15, 16, and 17. (Apollo 13 experienced a major anomaly, and the mission was aborted before a lunar landing could take place.) However, by the later missions, enthusiasm over the scientific and technological advances gave way to budget concerns, which ended the program with Apollo 17.

Skylab was the first American experimental space station to be built and could be considered a predecessor of the space station efforts of the 1980s. Skylab was an orbital workshop constructed from a Saturn IVB stage. It was launched in May 1973 and visited by three crews over the next nine months, each remaining at the orbiting laboratory for increasingly extended periods of time. The mission confirmed that humans could productively function in a space environment. It also provided solar observations, Earth resource studies, and tests of space manufacturing techniques.

The 1975 Apollo-Soyuz Test Project involved the docking of an American Apollo vehicle and a Soviet Soyuz vehicle. Joined by a docking module, the two crews conducted joint activities on their docked vehicles for two days before separating. Even though many hoped that this program would be the first of ongoing cooperative ventures between the two superpowers, the political situation prevented further efforts during this decade.

Although a six-year period interrupted human spaceflights between the 1975 Apollo-Soyuz mission and the first Shuttle flight in 1981, development of the new Space Shuttle moved slowly but steadily toward its inaugural launch in 1981. The major component of the Space Transportation System (STS), the Shuttle would perform a variety of tasks in orbit, including conducting scientific and technological experiments as well as serving as NASA's primary launch vehicle. NASA received presidential approval to proceed with the program in August 1972, and Rockwell International, the prime Shuttle contractor, rolled out *Enterprise*, the first test orbiter, in September 1976, setting off a series of system and flight tests. The production of *Columbia*, the first orbiter that would actually circle the Earth, already under way, continued during this time. Even though qualifying *Columbia* for spaceflight took longer than anticipated, as the decade closed, NASA was eagerly awaiting its first orbital flight test scheduled for the spring of 1981.

Overview of Space Transportation/Human Spaceflight (1979–1988)

The inauguration of Space Shuttle flights dominated the decade from 1979 through 1988. Twenty-seven Shuttle flights took place, and twenty-six of them were successful. However, from January 28, 1986, the memory of STS 51-L dominated the thoughts of many Americans and effectively overshadowed NASA's considerable achievements. The loss of life and, in particular, the loss of individuals who were not career astronauts haunted both the public and the agency. The agency conducted a far-reaching examination of the accident and used the findings of the independent Rogers Commission and the NASA STS 51-L Data and Design Analysis Task Force to implement a series of recommendations that improved the human spaceflight program from both a technical and management perspective. Two successful Shuttle missions followed at the end of the decade, demonstrating that NASA was able to recover from its worst accident ever.

The first twenty-four Shuttle missions and the two following the *Challenger* accident deployed an assortment of government and commercial satellites and performed an array of scientific and engineering experiments. The three Spacelab missions highlighted NASA's investigations aboard the Shuttle, studying everything from plant life and monkey nutrition to x-ray emissions from clusters of galaxies.

The 1980s also included a push toward the development of a permanently occupied space station. Announced by President Ronald Reagan in his 1984 State of the Union address, which directed NASA to have a permanently manned space station in place within ten years, NASA invested considerable time and money toward bringing it about. The European Space Agency (ESA), Canada, and Japan signed on as major participants in both the financial and technical areas of the Space Station program, and by the end of 1988, Space Station Freedom had completed the Definition and Preliminary Design Phase of the project and had moved into the Design and Development Phase.

Management of the Space Transportation/Human Spaceflight Program

The organizational elements of the space transportation program have been addressed in Chapter 2, "Launch Systems." Briefly, Code M, at different times called the Office of Space Transportation, Office of Space Transportation Systems (Acquisition), and Office of Space Flight, managed space transportation activities for the decade from 1979 through 1988. From November 1979 to August 1982, Code M split off the operations function of the spaceflight program into Code O, Office of Space Operations. Also, in 1984, the Office of Space Station, Code S, superseded the Code M Space Station Task Force, in response to President Reagan's directive to develop and build an occupied space station within the next ten years. Space Station program management is addressed later in this section.

The Space Shuttle program was the major segment of NASA's National Space Transportation System (NSTS), managed by the Office of Space Flight at NASA Headquarters. (The Space Shuttle Program Office was renamed the National Space Transportation System Program Office in March 1983.) The office was headed by an associate administrator who reported directly to the NASA administrator and was charged with providing executive leadership, overall direction, and effective accomplishment of the Space Shuttle and associated programs, including expendable launch vehicles.

The associate administrator for spaceflight exercised institutional management authority over the activities of the NASA field organizations whose primary functions were related to the NSTS program. These were the Johnson Space Center in Houston, the Kennedy Space Center at Cape Canaveral, Florida, the Marshall Space Flight Center in Huntsville, Alabama, and the Stennis Space Center (formerly National Space Technology Laboratories) in Bay St. Louis, Mississippi. Organizational elements of the NSTS office were located at NASA Headquarters, Johnson, Kennedy, Marshall, and at the Vandenberg Launch Site in California.

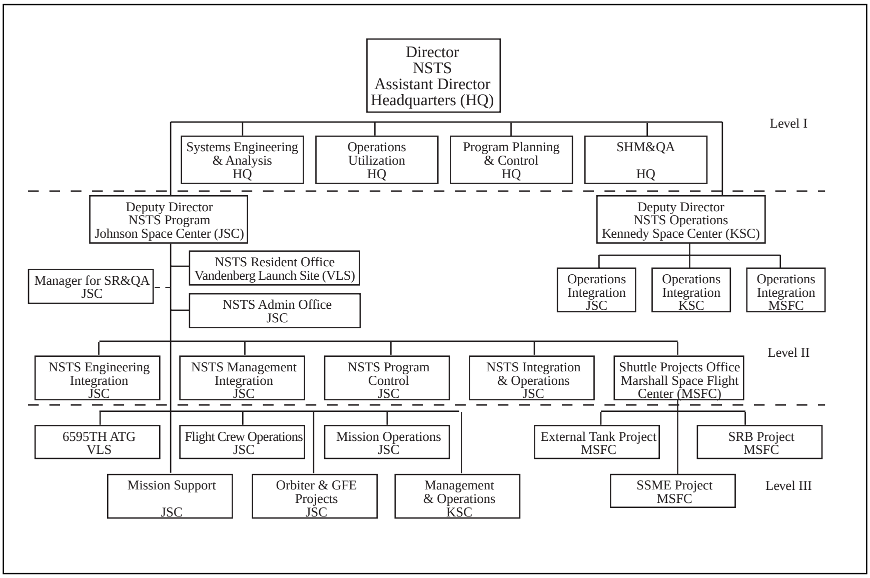

Figure 3–1. NSTS Organization

The organization of the NSTS was divided into four levels (Figure 3–1). The NSTS director served as the Level I manager and was responsible for the overall program requirements, budgets, and schedules. The NSTS deputy directors were Level II managers and were responsible for the management and integration of all program elements, including integrated flight and ground system requirements, schedules, and budgets. NSTS project managers located at Johnson, Kennedy, and Marshall were classified as Level III managers and were responsible for managing the design, qualification, and manufacturing of Space Shuttle components, as well as all launch and landing operations. NSTS design authority personnel and contractors were Level IV managers (not shown in Figure 3–1) and were responsible for the design, development, manufacturing, test, and qualification of Shuttle systems.

Initially, the NSTS was based at Johnson Space Center, which was designated as the lead center for the Space Shuttle program. Johnson had management responsibility for program control and overall systems engineering and systems integration. Johnson was also responsible for the development, production, and delivery of the Shuttle orbiter and managed the contract of the orbiter manufacturer.

Kennedy Space Center was responsible for the design of the launch and recovery facilities. Kennedy served as the launch and landing site for the Shuttle development flights and for most operational missions. Marshall Space Flight Center was responsible for the development, production, and delivery of the Space Shuttle main engines, solid rocket boosters, and external tank.

Robert F. Thompson served as manager of the Space Shuttle Program Office until 1981, when Glynn S. Lunney assumed the position of NSTS program manager. He had been with NASA since 1959 and involved in the Shuttle program since 1975. Lunney held the position of manager until his retirement in April 1985. He was replaced by Arnold D. Aldrich in July 1985, a twenty-six-year NASA veteran and head of the Space Shuttle Projects Office at Johnson Space Center. Aldrich's appointment was part of a general streamlining of the NSTS that took effect in August of that year, which reflected the maturation of the Shuttle program. In that realignment, the Level II NSTS organization at Johnson was renamed the NSTS Office and assimilated the Projects Office, consolidating all program elements under Aldrich's direction. Richard H. Kohrs, who had been acting program manager, and Lt. Col. Thomas W. Redmond, U.S. Air Force, were named deputy managers.

Aldrich took charge of the integration of all Space Shuttle program elements, including flight software, orbiter, external tank, solid rocket boosters, main engines, payloads, payload carriers, and Shuttle facilities. His responsibilities also included directing the planning for NSTS operations and managing orbiter and government-furnished equipment projects.

Post-**Challenger** ***Restructuring***

The *Challenger* accident brought about major changes in the management and operation of the NSTS. The Rogers Commission concluded that flaws in the management structure and in communication at all levels were elements that needed to be addressed and rectified. Two of the recommendations (Recommendations II and V, respectively) addressed the management structure and program communication. In line with these recommendations, NASA announced in November 1986 a new Space Shuttle management structure for the NSTS. These changes aimed at clarifying the focal points of authority and responsibility in the Space Shuttle program and to establish clear lines of communication in the information-transfer and decision-making processes.

Associate Administrator for Space Flight Admiral Richard Truly issued a detailed description of the restructured NSTS organization and operation in a memorandum released on November 5, 1986. As part of the restructuring, the position of director, NSTS, was established, with Arnold Aldrich, who had been manager, NSTS, at the Johnson Space Center since July 1985, assuming that position in Washington, D.C. He had full responsibility and authority for the operation and conduct of the NSTS program. This included total program control, with full responsibility for budget, schedule, and balancing program content. He was responsible for overall program requirements and performance and had the approval authority for top-level program requirements, critical hardware waivers, and budget authorization adjustments that exceeded a predetermined level. He reported directly to the associate administrator for spaceflight and had two deputies, one for the program and one for operations.

NASA appointed Richard H. Kohrs, who had been deputy manager, NSTS, at the Johnson Space Center, to the position of deputy director, NSTS program. He was responsible for the day-to-day management and execution of the Space Shuttle program, including detailed program planning, direction, scheduling, and STS systems configuration management. Other responsibilities encompassed systems engineering and integration for the STS vehicle, ground facilities, and cargoes. The NSTS Engineering Integration Office, reporting to the deputy director, NSTS program, was established and directly participated with each NSTS project element (main engine, solid rocket booster, external tank, orbiter, and launch and landing system). Kohrs was located at Johnson, but he reported directly to the NSTS director.

Five organizational elements under the deputy director, NSTS program, were charged with accomplishing the management responsibilities of the program. The first four was located at Johnson, and the last was at the Marshall Space Flight Center.

- NSTS Engineering Integration
- NSTS Management Integration
- NSTS Program Control
- NSTS Integration and Operations
- Shuttle Projects Office

The Shuttle Projects Office had overall management and coordination responsibility for the Marshall elements involved in the Shuttle program: the solid rocket boosters, external tank, and main engines.

NASA named Captain Robert L. Crippen to the position of deputy director, NSTS operations, reporting directly to the NSTS director and responsible for all operational aspects of STS missions. This included such functions as final vehicle preparation, mission execution, and return of the vehicle for processing for its next flight. In addition, the deputy director, NSTS operations, presented the Flight Readiness Review, which was chaired by the associate administrator for spaceflight, managed the final launch decision process, and chaired the Mission Management Team.

Three operations integration offices located at Johnson, the Kennedy Space Center, and Marshall carried out the duties of the NSTS deputy director. In addition to the duties of the director and deputy directors described above, Admiral Truly's memorandum addressed the role of the centers and project managers in the programmatic chain and budget procedures and control. In the programmatic chain, the managers of the project elements located at the various field centers reported to the deputy director, NSTS program. Depending on the individual center organization, this chain was either direct (such as the Orbiter Project Office at Johnson) or via an intermediate office (such as the Shuttle Projects Office at Marshall).

The NSTS program budget continued to be submitted through the center directors to the director, NSTS, who had total funding authority for the program. The deputy directors, NSTS program and NSTS operations, each provided an assessment of the budget submittal to the director, NSTS, as an integral part of the decision process.

The restructuring also revitalized the Office of Space Flight Management Council. The council consisted of the associate administrator for spaceflight and the directors of Marshall, Kennedy, Johnson, and the NSTS. This group met regularly to review Space Shuttle program progress and to provide an independent and objective assessment of the status of the overall program.

Management relationships in the centralized NSTS organization were configured into four basic management levels, which were designed to reduce the potential for conflict between the program organizations and the NASA institutional organizations.

Office of Safety, Reliability, and Quality Assurance

Although not part of the Office of Space Flight, the Office of Safety, Reliability, and Quality Assurance (Code Q) resulted from the findings of the Rogers Commission, which recommended that NASA establish such an office with direct authority throughout the agency. NASA established this office in July 1986, with George A. Rodney, formerly of Martin Marietta, named as its first associate administrator (Figure 3–2). The objectives of the office were to ensure that a NASA Safety, Reliability, and Quality Assurance program monitored equipment status, design validation problem analysis, and system acceptability in agencywide plans and programs.

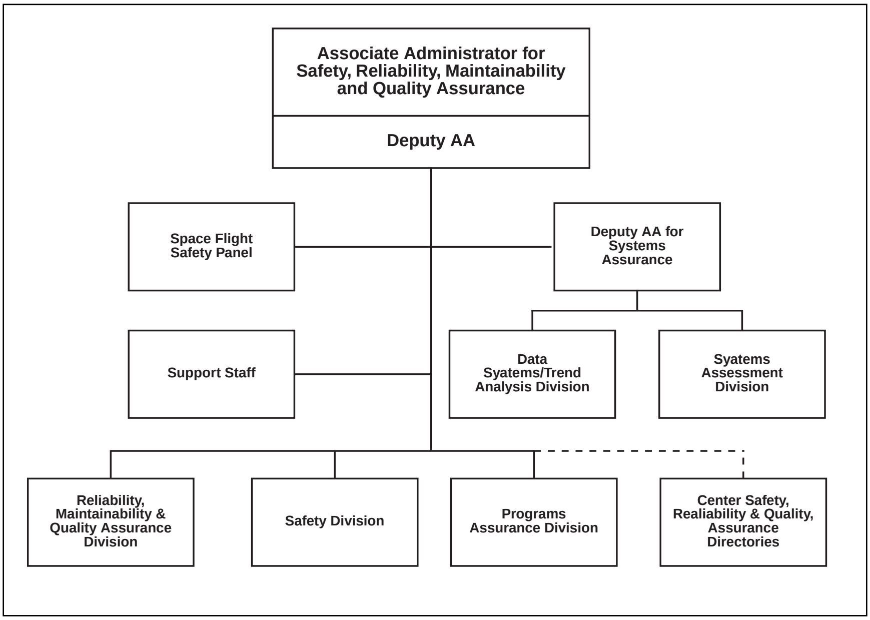

Figure 3–2. Safety, Reliability, and Quality Assurance Office Organization

The responsibilities of the associate administrator included the oversight of safety, reliability, and quality assurance functions related to all NASA activities and programs. In addition, he was responsible for the direction of reporting and documentation of problems, problem resolution, and trends associated with safety.

Management of the Space Station Program

NASA first officially committed to a space station on May 20, 1982, when it established the Space Station Task Force under the direction of John D. Hodge, assistant for space station planning and analysis, Office of the Associate Deputy Administrator in the Office of Space Flight (Code M). Hodge reported to Philip E. Culbertson, associate deputy administrator, and drew from space station-related activities of each of the NASA program offices and field centers.

The task force was responsible for the development of the programmatic aspects of a space station as they evolved, including mission analysis, requirements definition, and program management. It initiated industry participation with Phase A (conceptual analysis) studies that focused on user requirements and their implications for design. The task force developed the space station concept that formed the basis for President Reagan’s decision to commit to a space station.

The task force remained in existence until April 6, 1984, when, in response to Reagan’s January 1984 State of the Union address, NASA established an interim Space Station Program Office. Culbertson, in addition to his duties as associate deputy administrator, assumed the role of acting director of the interim office, with Hodge (former director of the Space Station Task Force) as his acting deputy. The interim office was responsible for the direction of the Space Station program and for the planning of the organizational structure of a permanent program office.

Also during the first half of 1984, NASA formulated the Space Station program management structure. Associate administrators and center directors agreed to use a “work package” concept and a three-level management structure consisting of a Headquarters office, a program office at the Johnson Space Center, and project offices located at the various NASA centers.

The interim office became permanent on August 1, 1984, when NASA established Code S, Office of Space Station. Culbertson became the Associate Administrator for Space Station, and Hodge served as the deputy associate administrator. Culbertson served until December 1985, when he was succeeded by Hodge, who became acting associate administrator.

The Office of Space Station was responsible for developing the station and conducting advanced development and technology activities, advanced planning, and other activities required to carry out Reagan’s direction to NASA to develop a permanently manned space station within a decade. The program continued using the three-tiered management structure developed earlier in the year. The Headquarters Level A office encompassed the Office of the Associate Administrator for the Office of Space Station and provided overall policy and program direction for the Space Station program. The Level B Space Station Program Office at Johnson in Houston reported to the Headquarters office. Space Station Level C project offices at other NASA centers also were responsible to the Office of Space Station through the Johnson program office. Johnson had been named lead center for the Space Station program in February 1984. The associate administrator was supported by a chief scientist, policy and plans and program support offices, and business management, engineering, utilization and performance requirements, and operations divisions.

On June 30, 1986, Andrew J. Stofan, who had been director of NASA's Lewis Research Center in Cleveland, was appointed Associate Administrator for Space Station. Along with this appointment, NASA Administrator James C. Fletcher announced several management structural actions that were designed to strengthen technical and management capabilities in preparation for moving into the development phase of the Space Station program.

The decision to create the new structure resulted from recommendations made by a committee headed by former Apollo program manager General Samuel C. Phillips. General Phillips had conducted a review of space station management as part of a long-range assessment of NASA's overall capabilities and requirements, including relationships between the various space centers and NASA Headquarters. His report reflected discussions with representatives from all the NASA centers and the contractors involved in the definition and preliminary design of the space station, as well as officials from other offices within NASA. His report recommended the formation of a program office, which was implemented in October 1986 when NASA Administrator Fletcher named Thomas L. Moser director of the Space Station Program Office, reporting to Associate Administrator Stofan.

Fletcher stated that the new space station management structure was consistent with recommendations of the Rogers Commission, which investigated the Space Shuttle *Challenger* accident. The commission had recommended that NASA reconsider management structures, lines of communication, and decision-making processes to ensure the flow of important information to proper decision levels. As part of the reconfiguration of the management structure, the Johnson Space Center was no longer designated as Level B. Instead, a Level A' was substituted, located in the Washington metropolitan area, assuming the same functions Johnson previously held (Figure 3–3).

Fletcher said the program would use the services of a top-level, nonhardware support contractor. In addition to the systems engineering role, the program office would contain a strong operations function to ensure that the program adequately addressed the intensive needs of a permanent facility in space.

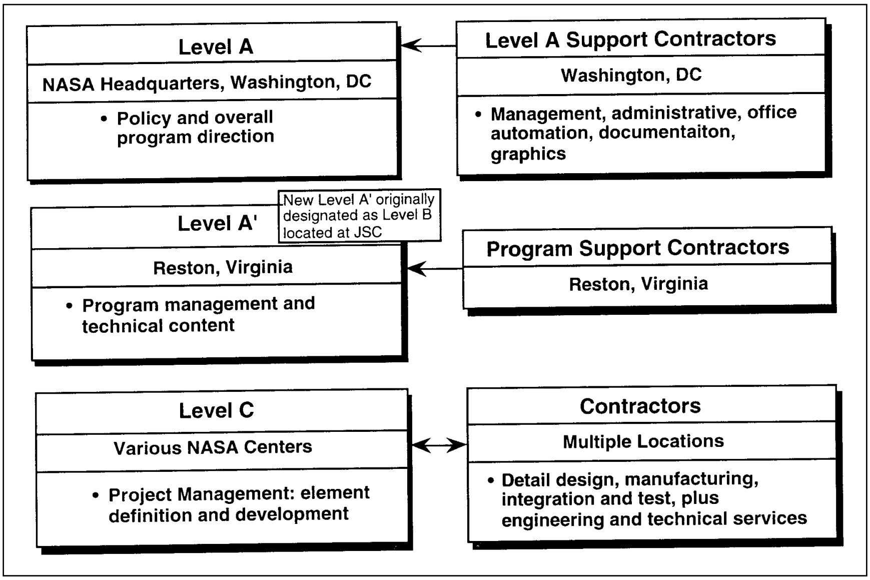

Figure 3–3. Space Station Program Management Approach

NASA established a systems integration field office in Houston as part of the program office organization. Project managers at the Goddard Space Flight Center, Johnson, Kennedy, Lewis, and Marshall reported functionally to the associate administrator. They coordinated with their respective center directors to keep them informed of significant program matters.

NASA assigned John Hodge the job of streamlining and clarifying NASA's procurement and management approach for the Space Station program and issuing instructions related to work package assignments, the procurement of hardware and services, and the selection of contractors for the development phase of the program. In addition, NASA tasked Hodge with developing a program overview document that would define the role automation and robotics would play in the Space Station program and with conducting further studies in the areas of international involvement, long-term operations, user accommodations, and servicing.

At the same time, Fletcher authorized NASA to procure a Technical and Management Information System (TMIS), a computer-based information network. It would link NASA and contractor facilities together and provide engineering services, such as computer-aided design, as well as management support on items such as schedules, budgets, labor, and facilities. TMIS was implemented in 1988.

The Space Station Program Office was responsible for the overall technical direction and content of the Space Station program, including systems engineering and analysis, configuration management, and the integration of all elements into an operating system that was responsive to customer needs. NASA approved a further reorganization of the Office of Space Station in December 1986.

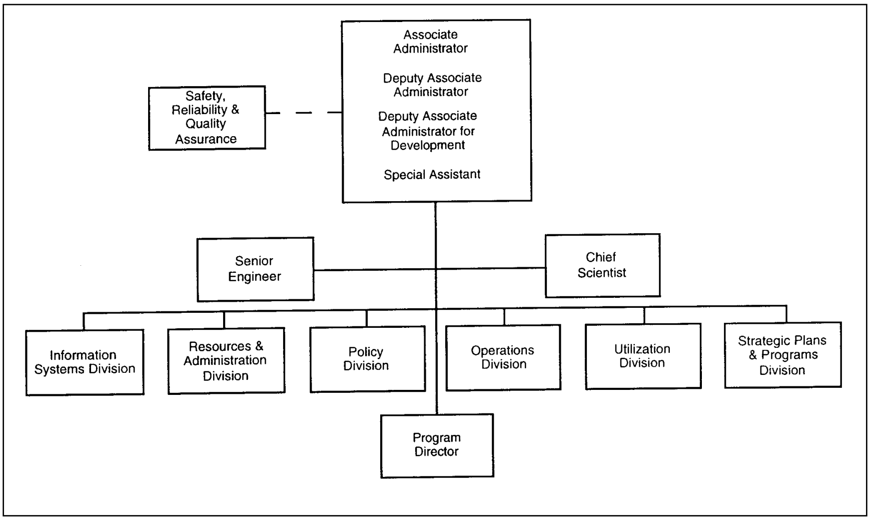

Figure 3–4. Office of Space Station Organization (December 1986)

In addition to the associate administrator and two deputies, the approved Space Station program organization included a chief scientist, a senior engineer, and six division directors responsible for resources and administration, policy, utilization, operations, strategic plans and programs, and information systems. There was also a position of special assistant to the associate administrator (Figure 3–4).

Andrew Stofan continued in the position of associate administrator. Franklin D. Martin continued as the deputy associate administrator for space station. Previously director of space and Earth sciences at the Goddard Space Flight Center, Martin had been named to the post in September 1986.

Thomas L. Moser became the deputy associate administrator for development in October 1986, a new position established by the reorganization. In this position, Moser also served as the program director for the Office of Space Station, directing the Washington area office that was responsible for overall technical direction and content of the Space Station program, including systems engineering and analysis, program planning and control, configuration management, and the integration of all the elements into an operating system. The creation of the program director position was the central element of program restructuring in response to recommendations of the committee headed by General Phillips. The Phillips Committee conducted an extensive examination of the Space Station organization.

As a result of this restructuring, NASA centers performed a major portion of the systems integration through Space Station field offices that were established at Goddard, Johnson, Kennedy, Lewis, and Marshall. The space station project manager at each of the five centers headed the field office and reported directly to the program manager in Washington.

A program support contractor assisted the program office and field offices in systems engineering, analysis, and integration activities.

Also as part of this reorganization, NASA named Daniel H. Herman senior engineer, a new staff position. The senior engineer advised the associate administrator on the policy, schedule, cost, and user implications of technical decisions. Previously, Herman was director of the engineering division, whose functions and responsibilities were absorbed by Moser's organization, and was on the original Space Station Task Force, which defined the basic architecture of the space station system.

David C. Black continued to serve as chief scientist for the space station. Black, chief scientist of the Space Research Directorate at the Ames Research Center, had served as chief scientist for the space station since the post was created in 1984.

Paul G. Anderson acted as the director of the Resources and Administration Division, which combined the former business management and program support organizations. Anderson previously served as comptroller at the Lewis Research Center.

Margaret Finarelli, director of the Policy Division, had functional responsibility for the former policy and plans organization. This element of the reorganization reflected the strong policy coordination role required of the Space Station Program Office in working with other elements of NASA, the international partners, and other external organizations. Prior to this assignment, Finarelli was chief of the International Planning and Programs Office in the International Affairs Division at NASA Headquarters.

Richard E. Halpern became the director of the Utilization Division, which had responsibility for developing user requirements for the space station, including science and applications, technology development, commercial users, and the assurance that those requirements could be efficiently and economically accommodated on the space station. Halpern was the director of the Microgravity Science and Applications Division in the Office of Space Science and Applications prior to accepting this position.

The Operations Division had the responsibility for developing an overall philosophy and management approach for space station system operations, including user support, prelaunch and postlanding activities, logistics support, and financial management. Granville Paules served as acting director of the Operations Division.

Under the new organization, NASA formed two new divisions, Strategic Plans and Programs and Information Systems. The Information Systems Division provided a management focus for the total end-to-end information system complex for Space Station.

Alphonso V. Diaz assumed the position of director of strategic plans and programs and had responsibility for ensuring that the evolution of the space station infrastructure was well planned and coordinated with other NASA offices and external elements. As part of its responsibility, this division managed and acted as the single focus for space station automation and robotics activities and program-focused technology and advanced development work.

The Strategic Plans and Program Division under Mr. Diaz became responsible for determining requirements and managing the Transition Definition program at Level A. The division maintained the Space Station Evolution Technical and Management Plan, which detailed evolution planning for the long-term use of the space station. The Level A' Space Station Program Office in Reston, Virginia, managed the program, including provision for the "hooks and scars," which were design features for the addition or update of computer software (hooks) or hardware (scars). The Langley Evolution Definition Office chaired the agencywide Evolution Working Group, which provided interagency communication and coordination of station evolution, planning, and interfaces with the baseline Work Packages (Level C). (Work Packages are addressed later in this chapter.)

William P. Raney, who had served as director of the Utilization and Performance Requirements Division, served as special assistant to the associate administrator. Stofan served as Associate Administrator for Space Station until his retirement from NASA in April 1988, when he was replaced by James B. Odom.

Money for Human Spaceflight

As with money for launch systems, Congress funded human spaceflight entirely from the Research and Development (R&D) appropriation through FY 1983. Beginning with FY 1984, the majority of funds for human spaceflight came from the Space Flight, Control, and Data Communications (SFC&DC) appropriation. Only funds for the Space Station and Spacelab programs remained with R&D. In FY 1985, Space Station became a program office with its own budget. Spacelab remained in the Office of Space Flight.

As seen in Table 3–1, appropriated funding levels for human spaceflight for most years met NASA's budget requests as submitted to Congress. The last column in the table shows the actual amounts that were programmed for the major budget items.

Program funding generally increased during 1979–1988 (Table 3–2). However, the reader must note that these figures are all current year money—that is, the dollar amounts do not take into account the reduced buying power caused by inflation. In addition, the items that are included in a major budget category change from one year to the next, depending on the current goals and resources of the agency and of Congress. Thus, it is difficult to compare dollar amounts because the products or services that those dollars are intended to buy may differ from year to year.

Tables 3–3 through 3–10 show funding levels for individual programs within the human spaceflight category.

Space Station

NASA's initial estimate of the U.S. investment in the Space Station program was $8 billion in 1984 dollars. By March 1988, this estimate had grown to $14.5 billion, even though, in 1987, the National Research Council had priced the Space Station program at $31.8 billion.[1]

President Reagan strongly endorsed the program and persuaded an ambivalent Congress of its importance. Program funding reflected both his persuasive powers and the uncertainty in which members of Congress looked at the space station, who took the view that it had little real scientific or technological purpose. The congressional Office of Technology Assessment reported that Congress should not commit to building a space station until space goals were more clear and that the potential uses of the proposed station did not justify the $8 billion price tag.

Congress passed the FY 1985 appropriation of $155.5 million for starting the design and development work on the space station based on NASA's initial $8 billion figure. The FY 1986 appropriation reduced the Administration's request from $230 million to $205 million.

President Reagan's FY 1987 budget asked for $410 million for the Space Station program, doubling the station funds from the previous year. Congress approved this increase in August 1986, which would move space station into the development phase toward planned operation by the mid-1990s. However, Congress placed limitations on the appropriation; it stipulated that NASA funds could not be spent to reorganize the program without congressional approval. In addition, $150 million was to be held back until NASA met several design and assembly requirements set by the House Appropriations Committee. About $260 million of the $410 million were to be spent for Phase B activities, and the other $150 million was reserved for initial hardware development. NASA must comply with the following conditions: a minimum of thirty-seven and a half kilowatts of power for initial operating capability, rather than the twenty-five kilowatts envisioned by NASA; a fully equipped materials processing laboratory by the sixth Space Shuttle flight and before crew habitat was launched; early launch of scientific payloads; and deployment of U.S. core elements before foreign station elements.[2]

During the next month, NASA Administrator James Fletcher stated that the $8 billion estimated for the Space Station program was now seen to be insufficient and that the station must either receive additional funds or be scaled down. The Reagan Administration submitted a request in

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[1] National Research Council, *Report of the Committee on the Space Station of the National Research Council* (Washington, DC: National Academy Press, September 1987).

[2] Report to accompany Department of Housing and Urban Development–Independent Agencies Appropriations Budget, 1987, House of Representatives.

January 1987 for $767 million for the Space Station program. However, after much debate, which raised the possibility of freezing the entire program, Congress appropriated only $425 million, but again, conditions were attached. In the FY 1988 Continuing Resolution that funded the program, Congress ordered NASA to provide a rescoping plan for the space station. In addition, only $200 million of the $425 million was to be available before June 1, 1988, while the rescoping was under discussion. By the time the rescoping plan had gone to Congress, the cost of the Station was up to $14.5 billion. Further talks in Congress later during the year proposed reducing funding for FY 1989 to an even lower level.

The Space Transportation System

This section focuses on the structure and operation of the equipment and systems used in the Space Transportation System (STS) and describes the mission and flight operations. The overview provides a brief chronology of the system's development. The next section looks at the orbiter as the prime component of STS. (The launch-related elements—that is, the external tank, solid rocket boosters, main engines, and the propulsion system in general—have been addressed previously in Chapter 2, "Launch Systems.") The last part of this section addresses STS mission operations and support.

A vast quantity of data exists on the Space Shuttle, and this document presents only a subset of the available material. It is hoped that the primary subject areas have been treated adequately and that the reader will get a useful overview of this complex system. It is highly recommended that readers who wish to acquire more detailed information consult the *NSTS Shuttle Reference Manual* (1988).[3]

Overview

The history of NASA's STS began early in the 1970s when President Richard Nixon proposed the development of a reusable space transportation system. The *NASA Historical Data Book, Volume III, 1969–1978,* presents an excellent account of events that took place during those early days of the program.[4]

By 1979, all major STS elements were proceeding in test and manufacture, and major ground test programs were approaching completion. NASA completed the design certification review of the overall Space Shuttle configuration in April 1979. Development testing throughout the

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[3] *NSTS Shuttle Reference Manual* (1988), available both through the NASA History Office and on-line through the NASA Kennedy Space Center Home Page.

[4] Linda Neuman Ezell, *NASA Historical Data Book, Volume III: Programs and Projects, 1969–1978* (Washington, DC: NASA SP-4012, 1988).

program was substantially complete, and the program was qualifying flight-configured systems.

The orbiter's structural test article was under subcontract for structural testing and would ultimately be converted to become the second orbital vehicle, *Challenger.* The development of *Columbia* was proceeding more slowly than anticipated, with much work remaining to be completed before the first flight, then scheduled for late 1980. The main engine had accumulated more than 50,000 seconds of test time toward its goal of 80,000 seconds before the first orbital flight, and the first external tank that would be used during flight had been delivered as well as three test tanks. Three flight tanks were also being manufactured for flight in the orbital flight test program. By the end of 1979, Morton Thiokol, the solid rocket booster contractor, had completed four development firings of the solid rocket boosters, and the qualification firing program had started. Two qualification motor firings had been made, and one more was scheduled before the first flight. Most of the rocket segments for the first flight boosters had been delivered to Kennedy Space Center.

All launch and landing facilities at Kennedy were complete and in place for the first orbital flight. Ground support equipment and the computerized launch-processing installations were almost complete, and software validation was progressing. All hardware for the launch processing system had been delivered, simulation support was continuing for the development of checkout procedures, and checkout software was being developed and validated.

By the end of 1979, nine commercial and foreign users had reserved space on Space Shuttle flights. Together with NASA's own payloads and firm commitments from the Department of Defense (DOD) and other U.S. government agencies, the first few years of STS operations were fully booked.

During 1980, testing and manufacture of all major system continued, and by the end of 1980, major ground-test programs neared completion. The first flight-configuration Space Shuttle stood on the launch pad. Additional testing of the vehicle was under way; qualification testing of flight-configured elements continued toward a rescheduled launch in the spring of 1981.

In December 1980, *Columbia* was in final processing at the Kennedy Space Center. The main engines had surpassed their goal of 80,000 seconds of engine test time, with more than 90,000 seconds completed. Technicians had mated the orbiter with the solid rocket boosters and external tank in November and rolled it out onto the launch pad in December. Contractors had delivered the final flight hardware, which was in use for vehicle checkout. Hardware and thermal protection system certifications were nearly complete. Further manufacture and testing of the external tanks and solid rocket boosters had also been completed.

The Kennedy launch site facilities were completed during 1980 in anticipation of the first launch. The computerized launch processing system had been used extensively for Space Shuttle testing and facility activation. The high-energy fuel systems had been checked out, and the integrated test of the Shuttle was complete.

The mission control center and Shuttle mission simulator facilities at the Johnson Space Center were ready to support the first Shuttle flight. Both the flight crew and ground flight controllers had used these facilities extensively for training and procedure development and verification. Seven full-duration (fifty-four-hour) integrated simulations had been successfully conducted, with numerous ascent, orbit, entry, and landing runs completed. The mission flight rules and launch-commit criteria had also been completed.

Follow-on orbiter production was in progress, leading to the four-orbiter fleet for the STS's future needs. The structural test article was being modified to a flight-configured orbiter, *Challenger.* Secondary and primary structural installations were under way, and thermal protection installations had begun for vehicle delivery in June 1982.

The Space Shuttle program made its orbital debut with its first two flights in 1981. All major mission objectives were met on both flights. Details of these missions and other STS missions through 1988 appear in later sections of this chapter.

The following pages describe the orbiter's structure, major systems, and operations, including crew training. Because this volume concentrates on the period from 1979 through 1988, the wording reflects configurations and activities as they existed during that decade. However, most of the Space Shuttle's physical characteristics and operations have continued beyond 1988 and are still valid.

Orbiter Structure

NASA designed the Space Shuttle orbiter as a space transport vehicle that could be reused for approximately 100 missions. The orbiter was about the same length and weight as a commercial DC-9 airplane. Its structure consisted of the forward fuselage (upper and lower forward fuselage and the crew module, which could accommodate up to seven crew members in normal operations and up to ten during emergency operations), the wings, the mid-fuselage, the payload bay doors, the aft fuselage, and the vertical stabilizer. Its appearance, however, differed markedly from a conventional airplane. High-performance double-delta (or triangular) wings and a large cargo bay gave the Shuttle its squat appearance (Figure 3–5 and Table 3–11).

A cluster of three Space Shuttle Main Engines (SSMEs) in the aft fuselage provided the main propulsion for the orbiter vehicle. The external tank carried fuel for the orbiter's main engines. Both the solid rocket boosters and the external tank were jettisoned prior to orbital insertion. In orbit, the orbital maneuvering system (OMS), contained in two pods on the aft fuselage, maneuvered the orbiter. The OMS provided the thrust for orbit insertion, orbit circularization, orbit transfer, rendezvous, deorbit, abort-to-orbit, and abort-once-around and could provide up to 453.6 kilograms of

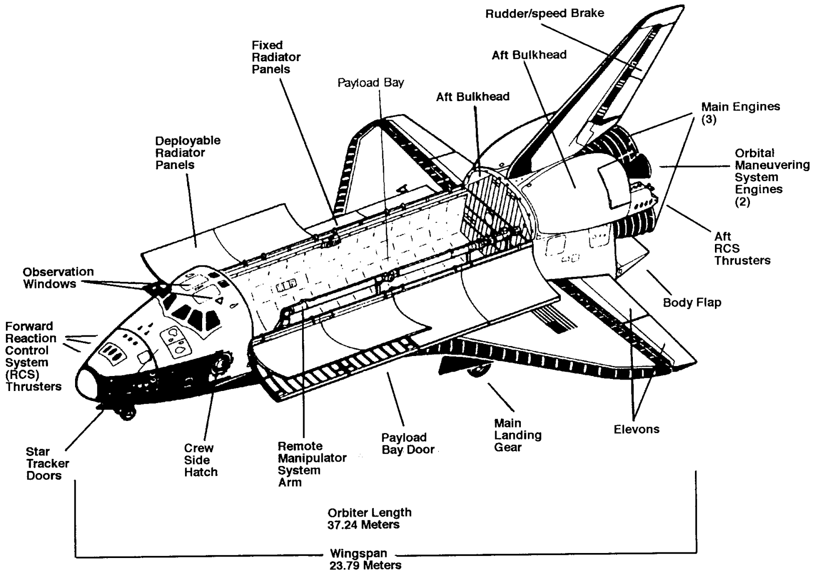

Figure 3–5. Space Shuttle Orbiter

propellant to the aft reaction control system (RCS). The RCS, contained in the two OMS pods and in a module in the nose section of the forward fuselage, provided attitude control in space and during reentry and was used during rendezvous and docking maneuvers. When it completed its orbital activities, the orbiter landed horizontally, as a glider, at a speed of about ninety-five meters per second and at a glide angle of between eighteen and twenty-two degrees.

The liquid hydrogen–liquid oxygen engine was a reusable high-performance rocket engine capable of various thrust levels. Ignited on the ground prior to launch, the cluster of three main engines operated in parallel with the solid rocket boosters during the initial ascent. After the boosters separated, the main engines continued to operate for approximately eight and a half minutes. The SSMEs developed thrust by using high-energy propellants in a staged combustion cycle. The propellants were partially combusted in dual preburners to produce high-pressure hot gas to drive the turbopumps. Combustion was completed in the main combustion chamber. The SSME could be throttled over a thrust range of 65 to 109 percent, which provided for a high thrust level during liftoff and the initial ascent phase but allowed thrust to be reduced to limit acceleration to three g’s during the final ascent phase.

The orbiter was constructed primarily of aluminum and was protected from reentry heat by a thermal protection system. Rigid silica tiles or some other heat-resistant material shielded every part of the Space Shuttle’s external shell. Tiles covering the upper and forward fuselage sections and the tops of the wings could absorb heat as high as

650 degrees Centigrade. Tiles on the underside absorbed temperatures up to 1,260 degrees Centigrade. Areas that had to withstand temperatures greater than 1,260 degrees Centigrade, such as the nose and leading edges of the wings on reentry, were covered with black panels made of reinforced carbon-carbon.

A five-computer network configured in a redundant operating group (four operate at all times and one is a backup) monitored all Space Shuttle subsystems. They simultaneously processed data from every area of the Shuttle, each interacting with the others and comparing data.

During ascent, acceleration was limited to less than three g's. During reentry, acceleration was less than two and a half g's. By comparison, Apollo crews had to withstand as much as eight g's during reentry into the Earth's atmosphere. The Space Shuttle's relatively comfortable ride allowed crew other than specially trained astronauts to travel on the Shuttle. While in orbit, crew members inhabited a "shirtsleeve" environment—no spacesuits or breathing apparatus were required. The microgravity atmosphere remained virtually the only non-Earth-like condition that crew members had to encounter.

NASA named the first four orbiter spacecraft after famous exploration sailing ships:

- *Columbia* (OV-102), the first operational orbiter, was named after a sailing frigate launched in 1836, one of the first Navy ships to circumnavigate the globe. *Columbia* also was the name of the Apollo 11 command module that carried Neil Armstrong, Michael Collins, and Edwin "Buzz" Aldrin on the first lunar landing mission in July 1969. *Columbia* was delivered to Rockwell's Palmdale assembly facility for modifications on January 30, 1984, and was returned to the Kennedy Space Center on July 14, 1985, for return to flight.

- *Challenger* (OV-099) was also the name of a Navy ship, one that explored the Atlantic and Pacific Oceans from 1872 to 1876. The name also was used in the Apollo program for the Apollo 17 lunar module. *Challenger* was delivered to Kennedy on July 5, 1982.

- *Discovery* (OV-103) was named after two ships. One was the vessel in which Henry Hudson in 1610–11 attempted to search for a northwest passage between the Atlantic and Pacific Oceans and instead discovered the Hudson Bay. The other was the ship in which Captain Cook discovered the Hawaiian Islands and explored southern Alaska and western Canada. *Discovery* was delivered to Kennedy on November 9, 1983.

- *Atlantis* (OV-104) was named after a two-masted ketch operated for the Woods Hole Oceanographic Institute from 1930 to 1966 that traveled more than half a million miles conducting ocean research. *Atlantis* was delivered to Kennedy on April 3, 1985.

A fifth orbiter, *Endeavour* (OV-105), was named by Mississippi school children in a contest held by NASA. It was the ship of Lieutenant James Cook in 1769–71, on a voyage to Tahiti to observe the planet Venus passing between the Earth and the Sun. This orbiter was delivered to NASA by Rockwell International in 1991.

Major Systems

Avionics Systems

The Space Shuttle avionics system controlled, or assisted in controlling, most of the Shuttle systems. Its functions included automatic determination of the vehicle's status and operational readiness; implementation sequencing and control for the solid rocket boosters and external tank during launch and ascent; performance monitoring; digital data processing; communications and tracking; payload and system management; guidance, navigation, and control; and electrical power distribution for the orbiter, external tank, and solid rocket boosters.

Thermal Protection System

A passive thermal protection system helped maintain the temperature of the orbiter spacecraft, systems, and components within their temperature limits primarily during the entry phase of the mission. It consisted of various materials applied externally to the outer structural skin of the orbiter.

Orbiter Purge, Vent, and Drain System

The purge, vent, and drain system on the orbiter provided unpressurized compartments with gas purge for thermal conditioning and prevented the accumulation of hazardous gases, vented the unpressurized compartments during ascent and entry, drained trapped fluids (water and hydraulic fluid), and conditioned window cavities to maintain visibility.

Orbiter Communications System

The Space Shuttle orbiter communications system transferred (1) telemetry information about orbiter operating conditions and configurations, systems, and payloads; (2) commands to the orbiter systems to make them perform some function or configuration change; (3) documentation from the ground that was printed on the orbiter's teleprinter or text and graphics system; and (4) voice communications among the flight crew members and between the fight crew and ground. This information was transferred through hardline and radio frequency links.

Direct communication took place through Air Force Satellite Control Facility remote tracking station sites, also known as the Spaceflight Tracking and Data Network ground stations for NASA missions or space-ground link system ground stations for military missions. Direct signals from the ground to the orbiter were referred to as uplinks, and signals from the orbiter to the ground were called downlinks.

Tracking and Data Relay Satellite (TDRS) communication took place through the White Sands Ground Terminal. These indirect signals from TDRS to the orbiter were called forward links, and the signal from the orbiter to the TDRS was called the return link. Communication with a detached payload from the orbiter was also referred to as a forward link, and the signal from the payload to the orbiter was the return link. Refer to Chapter 4, “Tracking and Data Acquisition Systems,” in Volume VI of the *NASA Historical Databook* for a more detailed description of Shuttle tracking and communications systems.

Data Processing System

The data processing system, through the use of various hardware components and its self-contained computer programming (software), provided the vehicle with computerized monitoring and control. This system supported the guidance, navigation, and control of the vehicle, including calculations of trajectories, SSME thrusting data, and vehicle attitude control data; processed vehicle data for the flight crew and for transmission to the ground and allowed ground control of some vehicle systems via transmitted commands; checked data transmission errors and crew control input errors; supported the annunciation of vehicle system failures and out-of-tolerance system conditions; supported payloads with flight crew/software interface for activation, deployment, deactivation, and retrieval; processed rendezvous, tracking, and data transmissions between payloads and the ground; and monitored and controlled vehicle subsystems.

Guidance, Navigation, and Control

Guidance, navigation, and control software commanded the guidance, navigation, and control system to effect vehicle control and to provide the sensor and controller data needed to compute these commands. The process involved three steps: (1) guidance equipment and software computed the orbiter location required to satisfy mission requirements; (2) navigation tracked the vehicle’s actual location; and (3) flight control transported the orbiter to the required location. A redundant set of four orbiter general purpose computers (GPCs) formed the primary avionics software system; a fifth GPC was used as the backup flight system.

The guidance, navigation, and control system operated in two modes: auto and manual (control stick steering). In the automatic mode, the primary avionics software system essentially allowed the GPCs to fly the vehicle; the flight crew simply selected the various operational sequences. In the manual mode, the flight crew could control the vehicle using hand controls, such as the rotational hand controller, translational hand controller, speed brake/thrust controller, and rudder pedals. In this mode, flight crew commands still passed through and were issued by the GPCs. There were no direct mechanical links between the flight crew and the orbiter's various propulsion systems or aerodynamic surfaces; the orbiter was an entirely digitally controlled, fly-by-wire vehicle.

Dedicated Display System

The dedicated displays provided the flight crew with information required to fly the vehicle manually or to monitor automatic flight control system performance. The dedicated displays were the attitude director indicators, horizontal situation indicators, alpha Mach indicators, altitude/vertical velocity indicators, a surface position indicator, RCS activity lights, a g-meter, and a heads-up display.

Main Propulsion System

The Space Shuttle's main propulsion system is addressed in Chapter 2, "Launch Systems."

Crew Escape System

The in-flight crew escape system was provided for use only when the orbiter would be in controlled gliding flight and unable to reach a runway. This condition would normally lead to ditching. The crew escape system provided the flight crew with an alternative to water ditching or to landing on terrain other than a landing site. The probability of the flight crew surviving a ditching was very slim.

The hardware changes required to the orbiters following the STS 51-L (*Challenger*) accident enabled the flight crew to equalize the pressurized crew compartment with the outside pressure via the depressurization valve opened by pyrotechnics in the crew compartment aft bulkhead that a crew member would manually activate in the mid-deck of the crew compartment. The crew could also pyrotechnically jettison the crew ingress/egress side hatch manually in the mid-deck of the crew compartment and bail out from the mid-deck through the ingress/egress side hatch opening after manually deploying the escape pole through, outside, and down from the side hatch opening.

Emergency Egress Slide. The emergency egress slide replaced the emergency egress side hatch bar. It provided the orbiter flight crew members with a rapid and safe emergency egress through the orbiter mid-deck ingress/egress side hatch after a normal opening of the side hatch or after jettisoning of the side hatch at the nominal end-of-mission landing site or at a remote or emergency landing site. The emergency egress slide supported return-to-launch-site, transatlantic-landing, abort-once-around, and normal end-of-mission landings.

Secondary Emergency Egress. The lefthand flight deck overhead window provided the flight crew with a secondary emergency egress route.

Side Hatch Jettison. The mid-deck ingress/egress side hatch was modified to provide the capability of pyrotechnically jettisoning the side hatch for emergency egress on the ground. In addition, a crew compartment pressure equalization valve provided at the crew compartment aft bulkhead was also pyrotechnically activated to equalize cabin/outside pressure before the jettisoning of the side hatch.

Crew Equipment

Food System and Dining. The mid-deck of the orbiter was equipped with facilities for food stowage, preparation, and dining for each crew member. Three one-hour meal periods were scheduled for each day of the mission. This hour included time for eating and cleanup. Breakfast, lunch, and dinner were scheduled as close to the usual hours as possible. Dinner was scheduled at least two to three hours before crew members began preparations for their sleep period.

Shuttle Orbiter Medical System. The Shuttle orbiter medical system provided medical care in flight for minor illnesses and injuries. It also provided support for stabilizing severely injured or ill crew members until they were returned to Earth. The medical system consisted of the medications and bandage kit and the emergency medical kit.

Operational Bioinstrumentation System. The operational bioinstrumentation system provided an amplified electrocardiograph analog signal from either of two designated flight crew members to the orbiter avionics system, where it was converted to digital tape and transmitted to the ground in real time or stored on tape for dump at a later time. On-orbit use was limited to contingency situations.

Radiation Equipment. The harmful biological effects of radiation must be minimized through mission planning based on calculated predictions and monitoring of dosage exposures. Preflight requirements included a projection of mission radiation dosage, an assessment of the probability of solar flares during the mission, and a radiation exposure history of flight crew members. In-flight requirements included the carrying of passive dosimeters by the flight crew members and, in the event of solar flares or other radiation contingencies, the readout and reporting of the active dosimeters.

Crew Apparel. During launch and entry, crew members wore the crew altitude protection system consisting of a helmet, a communications cap, a pressure garment, an anti-exposure, anti-gravity suit, gloves, and boots. During launch and reentry, the crew wore escape equipment over the crew altitude protection system, consisting of an emergency oxygen system; parachute harness, parachute pack with automatic opener, pilot chute, drogue chute, and main canopy; a life raft; two liters of drinking water; flotation devices; and survival vest pockets containing a radio/beacon, signal mirror, shroud cutter, pen gun flare kit, sea dye marker, smoke flare, and beacon.

Sleeping Provisions. Sleeping provisions consisted of sleeping bags, sleep restraints, or rigid sleep stations. During a mission with one shift, all crew members slept simultaneously and at least one crew member would wear a communication headset to ensure the reception of ground calls and orbiter caution and warning alarms.

Personal Hygiene Provisions. Personal hygiene and grooming provisions were furnished for both male and female flight crew members. A water dispensing system provided water.

Housekeeping. In addition to time scheduled for sleep periods and meals, each crew member had housekeeping tasks that required from five to fifteen minutes at intervals throughout the day. These included cleaning the waste management compartment, the dining area and equipment, floors and walls (as required), the cabin air filters, trash collection and disposal, and change-out of the crew compartment carbon dioxide (lithium hydroxide) absorber canisters.

Sighting Aids. Sighting aids included all items used to aid the flight crew within and outside the crew compartment. They included the crewman optical alignment sight, binoculars, adjustable mirrors, spotlights, and eyeglasses.

Microcassette Recorder. The microcassette recorder was used primarily for voice recording of data but could also be used to play prerecorded tapes.

Photographic Equipment. The flight crew used three camera systems—16mm, 35mm, and 70mm—to document activities inside and outside the orbiter.

Wicket Tabs. Wicket tabs helped the crew members activate controls when vision was degraded. The tabs provided the crew members with tactile cues to the location of controls to be activated as well as a memory aid to their function, sequence of activation, and other pertinent information. Controls that were difficult to see during the ascent and entry flight phases had wicket tabs.

Reach Aid. The reach aid, sometimes known as the '“swizzle stick,” was a short adjustable bar with a multipurpose end effector that was used to actuate controls that were out of the reach of seated crew members. It could be used during any phase of flight, but was not recommended for use during ascent because of the attenuation and switch-cueing difficulties resulting from acceleration forces.

Restraints and Mobility Aids. Restraints and mobility aids enabled the flight crew to perform all tasks safely and efficiently during ingress, egress, and orbital flight. Restraints consisted of foot loop restraints, the airlock foot restraint platform, and the work/dining table as well as temporary stowage bags, Velcro, tape, snaps, cable restraints, clips, bungees, and tethers. Mobility aids and devices consisted of handholds for ingress and egress to and from crew seats in the launch and landing configuration, handholds in the primary interdeck access opening for ingress and egress in the launch and landing configuration, a platform in the mid-deck for ingress and egress to and from the mid-deck when the orbiter is in the launch configuration, and an interdeck access ladder to enter the flight deck from the mid-deck in the launch configuration and go from the flight deck to the mid-deck in the launch and landing configuration.

Crew Equipment Stowage. Crew equipment aboard the orbiter was stowed in lockers with two sizes of insertable trays. The trays could be adapted to accommodate a wide variety of soft goods, loose equipment, and food. The lockers were interchangeable and attached to the orbiter with crew fittings. The lockers could be removed or installed in flight by the crew members.

Exercise Equipment. The only exercise equipment on the Shuttle was a treadmill.

Sound Level Meter. The sound level meter determined on-orbit acoustical noise levels in the cabin. Depending on the requirements for each flight, the flight crew took meter readings at specified crew compartment and equipment locations. The data obtained by the flight crew were logged and/or voice recorded.

Air Sampling System. The air sampling system consisted of air bottles that were stowed in a modular locker. They were removed for sampling and restowed for entry.

On-Board Instrumentation. Orbiter operational instrumentation collected, routed, and processed information from transducers and sensors on the orbiter and its payloads. This system also interacted with the solid rocket boosters, external tank, and ground support equipment. More than 2,000 data points were monitored, and the data were routed to operational instrumentation multiplexers/demultiplexers. The instrumentation system consisted of transducers, signal conditioners, two pulse code modulation master units, encoding equipment, two operational recorders, one payload recorder, master timing equipment, and on-board checkout equipment.

Payload Accommodations

The Space Shuttle had three basic payload accommodation categories: dedicated, standard, and mid-deck accommodations:

- **Dedicated payloads** took up the entire cargo-carrying capacity and services of the orbiter, such as the Spacelab and some DOD payloads.

- **Standard payloads**—usually geosynchronous communications satellites—were the primary type of cargo carried by the Space Shuttle. Normally, the payload bay could accommodate up to four standard payloads per flight. Power, command, and data services for standard payloads were provided by the avionics system through a standard mixed cargo harness.

- **Mid-deck payloads**—small, usually self-contained packages—were stored in compartments on the mid-deck. These were often manufacturing-in-space or small life sciences experiments.

Structural attach points for payloads were located at 9.9-centimeter intervals along the tops of the two orbiter mid-fuselage main longerons. Some payloads were not attached directly to the orbiter but to payload carriers that were attached to the orbiter. The inertial upper stage, Spacelab and Spacelab pallet, and any specialized cradle for holding a payload were typical carriers.

Small payloads mounted in the payload bay required a smaller range of accommodations. These payloads received a reduced level of electric power, command, and data services, and their thermal conditions were those in the payload bay thermal environment. Small payloads could be mounted in either a side-mounted or an across-the-bay configuration.

The Space Shuttle could also accommodate small payloads in the mid-deck of the crew compartment. This location was ideal for payloads that required a pressurized crew cabin environment or needed to be operated directly by the crew. Payloads located in the mid-deck could also be stowed on board shortly before launch and removed quickly after landing.

Space Shuttle Operations

Although each Space Shuttle mission was unique, Space Shuttle missions followed a prescribed sequence of activities that was common to all flights. The following sections describe the typical activities preceding launch, the launch and ascent activities, on-orbit events, and events surrounding descent and landing. Figure 3–6 shows the typical sequence of mission events.

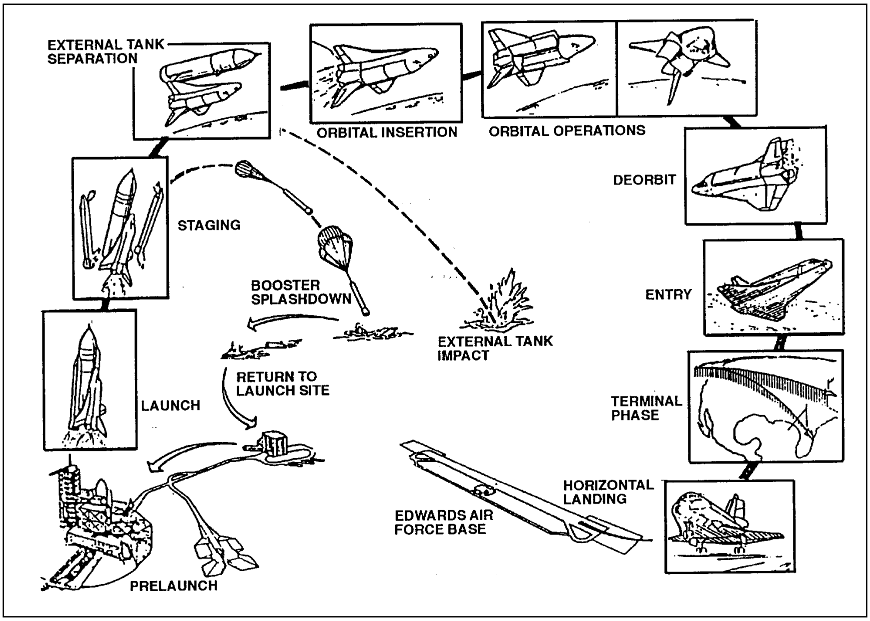

Figure 3–6. Typical STS Flight Profile

Prelaunch Activities

Space Shuttle components were gathered from various locations throughout the country and brought to Launch Complex 39 facilities at the Kennedy Space Center. There, technicians assembled the components—the orbiter, solid rocket booster, and external tank—into an integrated Space Shuttle vehicle, tested the vehicle, rolled it out to the launch pad, and ultimately launched it into space.

Each of the components that comprised the Shuttle system underwent processing prior to launch. NASA used similar processing procedures for new and reused Shuttle flight hardware. In general, new orbiters underwent more checkouts before being installed. In addition, the main engines underwent test firing on the launch pad. Called the Flight Readiness Firing, the test verified that the main propulsion system worked properly. For orbiters that had already flown, turnaround processing procedures included various postflight deservicing and maintenance functions, which were carried out in parallel with payload removal and the installation of equipment needed for the next mission.

If changes are made in external tank design, the tank usually required a tanking test in which it was loaded with liquid oxygen and hydrogen just as it was before launch. This confidence check verified the tank's ability to withstand the high pressures and super cold temperatures of the cryogenics.

The processing of each major flight component consisted of independent hardware checks and servicing in an operation called standalone processing. Actual Shuttle vehicle integration started with the stacking of the solid rocket boosters on a Mobile Launcher Platform in one of the high bays of the Vehicle Assembly Building. Next, the external tank was moved from its Vehicle Assembly Building location to the Mobile Launcher Platform and was mated with the solid rocket boosters. The orbiter, having completed its prelaunch processing and after horizontally integrated payloads had been installed, was towed from the Orbiter Processing Facility to the Vehicle Assembly Building and hoisted into position alongside the solid rocket boosters and the external tank. It was then mated to the external tank/solid rocket booster assembly. After mating was completed, the erection slings and load beams that had been holding the orbiter in place were removed, and the platforms and stands were positioned for orbiter/external tank/solid rocket booster access.

After the orbiter had been mated to the external tank/solid rocket booster assembly and all umbilicals were connected, technicians performed an electrical and mechanical verification of the mated interfaces to verify all critical vehicle connections. The orbiter underwent a Space Shuttle interface test using the launch processing system to verify Shuttle vehicle interfaces and Shuttle vehicle-to-ground interfaces. After completion of interface testing, ordnance devices were installed, but not electrically connected. Final ordnance connection and flight close-out were completed at the pad.

When the Vehicle Assembly Building prelaunch preparations were completed, the crawler transporter, an enormous tracked vehicle that NASA originally used during the Apollo and Skylab programs, lifted the assembled Space Shuttle and the Mobile Launcher Platform and rolled them slowly down a crawlerway to the launch pad at Launch Complex 39. Loaded, the vehicle moved at a speed of one mile an hour. The move took about six hours. At the pad, vertically integrated payloads were loaded into the payload bay. Then, technicians performed propellant servicing and needed ordnance tasks.

After the Space Shuttle had been rolled out to the launch pad on the Mobile Launcher Platform, all prelaunch activities were controlled from the Launch Control Center using the Launch Processing System. On the launch pad, the Rotating Service Structure was placed around the Shuttle and power for the vehicle was activated. The Mobile Launcher Platform and the Shuttle were then electronically and mechanically mated with support launch pad facilities and ground support equipment. An extensive series of validation checks verified that the numerous interfaces were functioning properly. Meanwhile, in parallel with prelaunch pad activities, cargo operations began in the Rotating Service Structure’s Payload Changeout Room.

Vertically integrated payloads were delivered to the launch pad before the Space Shuttle was rolled out and stored in the Payload Changeout Room until the Shuttle was ready for cargo loading. Once the Rotating Service Structure was in place around the orbiter, the payload bay doors were opened and the cargo installed. Final cargo and payload bay closeouts were completed in the Payload Changeout Room, and the payload bay doors were closed for flight.

Propellant Loading. Initial Shuttle propellant loading involved pumping hypergolic propellants into the orbiter’s aft and forward OMS and RCS storage tanks, the orbiter’s hydraulic Auxiliary Power Units, and the solid rocket booster hydraulic power units. These were hazardous operations, and while they were under way, work on the launch pad was suspended. Because these propellants were hypergolic—they ignite on contact with one another—oxidizer and fuel loading operations were carried out serially, never in parallel.

Dewar tanks on the Fixed Service Structure were filled with liquid oxygen and liquid hydrogen, which would be loaded into the orbiter’s Power Reactant and Storage Distribution tanks during the launch countdown. Before the formal Space Shuttle launch countdown began, the vehicle was powered down while pyrotechnic devices were installed or hooked up. The extravehicular mobility units—spacesuits—were stored on board along with other items of flight crew equipment.

Launch Processing System. The Launch Processing System made Space Shuttle processing, checkout, and countdown procedures more automated and streamlined than those of earlier human spaceflight programs. The countdown for the Space Shuttle took only about forty hours, compared with more than eighty hours usually needed for a

Saturn/Apollo countdown. Moreover, the Launch Processing System called for only about ninety people to work in the firing room during launch operations, compared with about 450 needed for earlier human missions. This system automatically controlled and performed much of the Shuttle processing from the arrival of individual components and their integration to launch pad operations and, ultimately, the launch itself. The system consisted of three basic subsystems: the Central Data Subsystem located on the second floor of the Launch Control Center, the Checkout, Control and Monitor Subsystem located in the firing rooms, and the Record and Playback Subsystem.

Complex 39 Launch Pad Facilities. The Kennedy Space Center's Launch Complex 39 had two identical launch pads, which were originally designed and built for the Apollo lunar landing program. The pads, built in the 1960s, were used for all of the Apollo/Saturn V missions and the Skylab space station program. Between 1967 and 1975, twelve Apollo/Saturn V vehicles, one Skylab/Saturn V workshop, three Apollo/Saturn 1B vehicles for Skylab crews, and one Apollo/Saturn 1B for the joint U.S.-Soviet Apollo Soyuz Test Project were launched from these pads.

The pads underwent major modifications to accommodate the Space Shuttle vehicle. Initially, Pad A modifications were completed in mid-1978, while Pad B was finished in 1985 and first used for the ill-fated STS 51-L mission in January 1986. The modifications included the construction of new hypergolic fuel and oxidizer support areas at the southwest and southeast corners of the pads, the construction of new Fixed Service Structures, the addition of a Rotating Service Structure, the addition of 1,135,620-liter water towers and associated plumbing, and the replacement of the original flame deflectors with Shuttle-compatible deflectors.

Following the flight schedule delays resulting from the STS 51-L accident, NASA made an additional 105 pad modifications. These included the installation of a sophisticated laser parking system on the Mobile Launcher Platform to facilitate mounting the Shuttle on the pad and emergency escape system modifications to provide emergency egress for up to twenty-one people. The emergency shelter bunker also was modified to allow easier access from the slidewire baskets.

Systems, facilities, and functions at the complex included:

- Fixed Service Structure
- Orbiter Access Arm
- External Tank Hydrogen Vent Line and Access Arm
- External Tank Gaseous Oxygen Vent Arm
- Emergency Exit System
- Lightning Mast
- Rotating Service Structure
- Payload Changeout Room

- Orbiter Midbody Umbilical Unit
- Hypergolic Umbilical System
- Orbital Maneuvering System Pod Heaters
- Sound Suppression Water System
- Solid Rocket Booster Overpressure Suppression System
- Main Engine Hydrogen Burnoff System
- Pad Surface Flame Detectors
- Pad-Propellant Storage and Distribution

Launch Sites. NASA used the Kennedy Space Center in Florida for launches that placed the orbiter in equatorial orbits (around the equator). The Vandenberg Air Force Base launch site in California was intended for launches that placed the orbiter in polar orbit missions, but it was never used and has been inactive since 1987.

NASA's prime landing site was at Kennedy. Additional landing sites were provided at Edwards Air Force Base in California and White Sands, New Mexico. Contingency landing sites were also provided in the event the orbiter must return to Earth in an emergency.

Kennedy Space Center launches had an allowable path no less than thirty-five degrees northeast and no greater than 120 degrees southeast. These were azimuth degree readings based on due east from Kennedy as ninety degrees. These two azimuths—thirty-five and 120 degrees—represented the launch limits from Kennedy. Any azimuth angles farther north or south would launch a spacecraft over a habitable land mass, adversely affect safety provisions for abort or vehicle separation conditions, or present the undesirable possibility that the solid rocket booster or external tank could land on foreign land or sea space.

Launch and Ascent

At launch, the three SSMEs were ignited first. When the proper engine thrust level was verified, a signal was sent to ignite the solid rocket boosters. At the proper thrust-to-weight ratio, initiators (small explosives) at eight hold-down bolts on the solid rocket boosters were fired to release the Space Shuttle for liftoff. All this took only a few seconds.

Maximum dynamic pressure was reached early in the ascent, approximately sixty seconds after liftoff. Approximately a minute later (two minutes into the ascent phase), the two solid rocket boosters had consumed their propellant and were jettisoned from the external tank at an altitude of 48.27 kilometers. This was triggered by a separation signal from the orbiter.

The boosters briefly continued to ascend to an altitude of 75.6 kilometers, while small motors fired to carry them away from the Space Shuttle. The boosters then turned and descended, and at a predetermined altitude, parachutes were deployed to decelerate them for a safe splashdown in the ocean. Splashdown occurred approximately 261 kilometers from the launch site.

When a free-falling booster descended to an altitude of about 4.8 kilometers, its nose cap was jettisoned and the solid rocket booster pilot parachute popped open. The pilot parachute then pulled out the 16.5-meter diameter, 499-kilogram drogue parachute. The drogue parachute stabilized and slowed the descent to the ocean.

At an altitude of 1,902 meters, the frustum, a truncated cone at the top of the solid rocket booster where it joined the nose cap, separated from the forward skirt, causing the three main parachutes to pop out. These parachutes were thirty-five meters in diameter and had a dry weight of about 680 kilograms each. When wet with sea water, they weighed about 1,361 kilograms.

At six minutes and forty-four seconds after liftoff, the spent solid rocket boosters, weighing about 7,484 kilograms, had slowed their descent speed to about 100 kilometers per hour, and splashdown took place in the predetermined area. There, a crew aboard a specially designed recovery vessel recovered the boosters and parachutes and returned them to the Kennedy Space Center for refurbishment. The parachutes remained attached to the boosters until they were detached by recovery personnel.

Meanwhile, the orbiter and external tank continued to climb, using the thrust of the three SSMEs. Approximately eight minutes after launch and just short of orbital velocity, the three engines were shut down (main engine cutoff, or MECO), and the external tank was jettisoned on command from the orbiter.

The forward and aft RCS engines provided attitude (pitch, yaw, and roll) and the translation of the orbiter away from the external tank at separation and return to attitude hold prior to the OMS thrusting maneuver. The external tank continued on a ballistic trajectory and entered the atmosphere, where it disintegrated. Its projected impact was in the Indian Ocean (except for fifty-seven-degree inclinations) for equatorial orbits.

Aborts. An ascent abort might become necessary if a failure that affects vehicle performance, such as the failure of an SSME or an OMS. Other failures requiring early termination of a flight, such as a cabin leak, might also require an abort.

Space Shuttle missions had two basic types of ascent abort modes: intact aborts and contingency aborts. Intact aborts were designed to provide a safe return of the orbiter to a planned landing site. Contingency aborts were designed to permit flight crew survival following more severe failures when an intact abort was not possible. A contingency abort would generally result in a ditch operation.

Intact Aborts. There were four types of intact aborts: abort-to-orbit, abort-once-around, transatlantic landing, and return-to-launch-site (Figure 3–7):

- The **abort-to-orbit** (ATO) mode was designed to allow the vehicle to achieve a temporary orbit that was lower than the nominal orbit. This mode required less performance and allowed time to evaluate problems and then choose either an early deorbit maneuver or an OMS thrusting maneuver to raise the orbit and continue the mission.

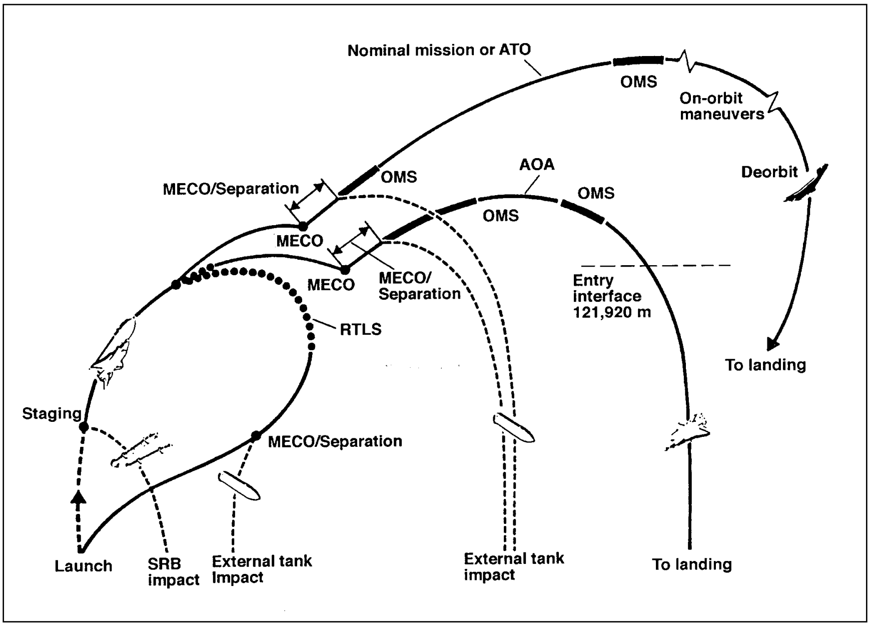

Figure 3–7. Types of Intact Aborts

- The **abort-once-around** (AOA) mode was designed to allow the vehicle to fly once around the Earth and make a normal entry and landing. This mode generally involved two OMS thrusting sequences, with the second sequence being a deorbit maneuver. The entry sequence would be similar to a normal entry. This abort mode was used on STS 51-F and was the only abort that took place.

- The **transatlantic landing** mode was designed to permit an intact landing on the other side of the Atlantic Ocean. This mode resulted in a ballistic trajectory, which did not require an OMS maneuver.

- The **return-to-launch-site** (RTLS) mode involved flying downrange to dissipate propellant and then turning around under power to return directly to a landing at or near the launch site.

A definite order of preference existed for the various abort modes. The type of failure and the time of the failure determined which type of abort is selected. In cases where performance loss was the only factor, the preferred modes would be abort-to-orbit, abort-once-around, transatlantic landing, and return-to-launch-site, in that order. The mode chosen was the highest one that could be completed with the remaining vehicle performance. In the case of some support system failures, such as cabin leaks or vehicle cooling problems, the preferred mode might be the one that would end the mission most quickly. In those cases, transatlantic landing or return-to-launch-site might be preferable to abort-once-around or abort-to-orbit. A contingency abort was never chosen if another abort option existed.

The Mission Control Center in Houston was “prime” for calling these aborts because it had a more precise knowledge of the orbiter’s position than the crew could obtain from on-board systems. Before MECO, Mission Control made periodic calls to the crew to tell them which abort mode was (or was not) available. If ground communications were lost, the flight crew had on-board methods, such as cue cards, dedicated displays, and display information, to determine the current abort region.

Contingency Aborts. Contingency aborts would occur when there was a loss of more than one main engine or other systems fail. Loss of one main engine while another was stuck at a low thrust setting might also require a contingency abort. Such an abort would maintain orbiter integrity for in-flight crew escape if a landing could not be achieved at a suitable landing field.

Contingency aborts caused by system failures other than those involving the main engines would normally result in an intact recovery of vehicle and crew. Loss of more than one main engine might, depending on engine failure times, result in a safe runway landing. However, in most three-engine-out cases during ascent, the orbiter would have to be ditched. The in-flight crew escape system would be used before ditching the orbiter.

Orbit Insertion. An orbit could be accomplished in two ways: the conventional OMS insertion method called “standard” (which was last used with STS-35 in December 1990) and the direct insertion method. The standard insertion method involved a brief burn of the OMS engines shortly after MECO, placing the orbiter into an elliptical orbit. A second OMS burn was initiated when the orbiter reached apogee in its elliptical orbit. This brought the orbiter into a near circular orbit. If required during a mission, the orbit could be raised or lowered by additional firings of the OMS thrusters.

The direct insertion technique used the main engines to achieve the desired orbital apogee, or high point, thus saving OMS propellant. Only one OMS burn was required to circularize the orbit, and the remaining OMS fuel could then be used for frequent changes in the operational orbit, as called for in the flight plan. The first direct insertion orbit took place during the STS 41-C mission in April 1984, when *Challenger* was placed in a 463-kilometer-high circular orbit where its flight crew successfully captured, repaired, and redeployed the Solar Maximum Satellite (Solar Max).

The optimal orbital altitude of a Space Shuttle depended on the mission objectives and was determined before launch. The nominal altitude varied between 185 to 402 kilometers. During flight, however, problems, such as main engine and solid rocket booster performance loss and OMS propellant leaks or certain electrical power system failures, might prevent the vehicle from achieving the optimal orbit. In these cases, the OMS burns would be changed to compensate for the failure by selecting a delayed OMS burn, abort-once-around, or abort-to-orbit option.

Tables 3–12 and 3–13 show the events leading up to a typical launch and the events immediately following launch.[5]

On-Orbit Events. Once the orbiter achieved orbit, the major guidance, navigation, and control tasks included achieving the proper position, velocity, and attitude necessary to accomplish the mission objectives. To do this, the guidance, navigation, and control computer maintained an accurate state vector, targeted and initiated maneuvers to specified attitudes and positions, and pointed a specified orbiter body vector at a target. These activities were planned with fuel consumption, vehicle thermal limits, payload requirements, and rendezvous/proximity operations considerations in mind. The Mission Control Center, usually referred to as "Houston," controlled Space Shuttle flights.

Maneuvering in Orbit. Once the Shuttle orbiter went into orbit, it operated in the near gravity-free vacuum of space. However, to maintain proper orbital attitude and to perform a variety of maneuvers, the Shuttle used an array of forty-six large and small rocket thrusters—the OMS and RCS that was used to place the Shuttle in orbit. Each of these thrusters burned a mixture of nitrogen tetroxide and monoethylhydrazine, a combination of fuels that ignited on contact with each other.

Descent and Landing Activities

On-Orbit Checkout. The crew usually performed on-orbit checkout of the orbiter systems that were used during reentry the day before deorbit. System checkout had two parts. The first part used one auxiliary power unit/hydraulic system. It repositioned the left and right main engine nozzles for entry and cycled the aerosurfaces, hydraulic motors, and hydraulic switching valves. After the checkout was completed, the auxiliary power unit was deactivated. The second part checked all the crew-dedicated displays; self-tested the microwave scan beam landing system, tactical air navigation, accelerometer assemblies, radar altimeter, rate gyro assemblies, and air data transducer assemblies; and checked the hand controllers, rudder pedal transducer assemblies, speed brake, panel trim switches, RHC trim switches, speed brake takeover push button, and mode/sequence push button light indicators.

Shuttle Landing Operations. When a mission accomplished its planned in-orbit operations, the crew began preparing the vehicle for its return to Earth. Usually, the crew devoted the last full day in orbit to activities, such as stowing equipment, cleaning up the living areas, and

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[5] The terms "terminal count," "first stage," and "second stage" are commonly used when describing prelaunch, launch, and ascent events. The terminal phase extends from T minus twenty minutes where "T" refers to liftoff time. First-stage ascent extends from solid rocket booster ignition through solid rocket booster separation. Second-stage ascent begins at solid rocket booster separation and extends through MECO and external tank separation.

making final systems configurations that would facilitate postlanding processing.

The crew schedule was designed so that crew members were awake and into their “work day” six to eight hours before landing. About four hours before deorbit maneuvers were scheduled, the crew and flight controllers finished with the Crew Activity Plan for the mission. They then worked from the mission’s *Deorbit Prep Handbook,* which covered the major deorbit events leading to touchdown. Major events included the “go” from Mission Control Center to close the payload bay doors and final permission to perform the deorbit burn, which would return the orbiter to Earth.

Before the deorbit burn took place, the orbiter was turned to a tail-first attitude—that is, the aft end of the orbiter faced the direction of travel. At a predesignated time, the OMS engines were fired to slow the orbiter and to permit deorbit. The RCS thrusters were then used to return the orbiter into a nose-first attitude. These thrusters were used during much of the reentry pitch, roll, and yaw maneuvering until the orbiter’s aerodynamic, aircraft-like control surfaces encountered enough atmospheric drag to control the landing. This was called Entry Interface and usually occurred thirty minutes before touchdown at about 122 kilometers altitude. At this time, a communications blackout occurred as the orbiter was enveloped in a sheath of plasma caused by electromagnetic forces generated from the high heat experienced during entry into the atmosphere.

Guidance, navigation, and control software guided and controlled the orbiter from this state (in which aerodynamic forces were not yet felt) through the atmosphere to a precise landing on the designated runway. All of this must be accomplished without exceeding the thermal or structural limits of the orbiter. Flight control during the deorbit phase was similar to that used during orbit insertion.

Orbiter Ground Turnaround. Approximately 160 Space Shuttle Launch Operations team members supported spacecraft recovery operations at the nominal end-of-mission landing site. Beginning as soon as the spacecraft stopped rolling, the ground team took sensor measurements to ensure that the atmosphere in the vicinity of the spacecraft was not explosive. In the event of propellant leaks, a wind machine truck carrying a large fan moved into the area to create a turbulent airflow that broke up gas concentrations and reduced the potential for an explosion.

A ground support equipment air-conditioning purge unit was attached to the righthand orbiter T-0 umbilical so cool air could be directed through the orbiter to dissipate the heat of entry. A second ground support equipment ground cooling unit was connected to the lefthand orbiter T-0 umbilical spacecraft Freon coolant loops to provide cooling for the flight crew and avionics during the postlanding and system checks. The flight crew then left the spacecraft, and a ground crew powered down the spacecraft.

Meanwhile, at the Kennedy Space Center, the orbiter and ground support equipment convoy moved from the runway to the Orbiter Processing

Facility. If the spacecraft landed at Edwards Air Force Base, the same procedures and ground support equipment applied as at Kennedy after the orbiter had stopped on the runway. The orbiter and ground support equipment convoy moved from the runway to the orbiter mate and demate facility. After detailed inspection, the spacecraft was prepared to be ferried atop the Shuttle carrier aircraft from Edwards to Kennedy.

Upon its return to the Orbiter Processing Facility at Kennedy, a ground crew safed the orbiter, removed its payload, and reconfigured the orbiter payload bay for the next mission. The orbiter also underwent any required maintenance and inspections while in the Orbiter Processing Facility. The spacecraft was then towed to the Vehicle Assembly Building and mated to the new external tank, beginning the cycle again.

Mission Control

The Mission Control Center at Johnson Space Center in Houston controlled all Shuttle flights. It has controlled more than sixty NASA human spaceflights since becoming operational in June 1965 for the Gemini IV mission. Two flight control rooms contained the equipment needed to monitor and control the missions.

The Mission Control Center assumed mission control functions when the Space Shuttle cleared the service tower at Kennedy's Launch Complex 39. Shuttle systems data, voice communications, and television traveled almost instantaneously to the Mission Control Center through the NASA Ground and Space Networks, the latter using the orbiting TDRS. The Mission Control Center retained its mission control function until the end of a mission, when the orbiter landed and rolled to a stop. At that point, Kennedy again assumed control.

Normally, sixteen major flight control consoles operated during a Space Shuttle mission. Each console was identified by a title or "call sign," which was used when communicating with other controllers or the astronaut flight crew. Teams of up to thirty flight controllers sat at the consoles directing and monitoring all aspects of each flight twenty-four hours a day, seven days a week. A flight director headed each team, which typically worked an eight-hour shift. Table 3–14 lists the mission command and control positions and responsibilities.

During Spacelab missions, an additional position, the command and data management systems officer, had primary responsibility for the data processing of the Spacelab's two main computers. To support Spacelab missions, the electrical, environmental, and consumables systems engineer and the data processing systems engineer both worked closely with the command and data management systems officer because the missions required monitoring additional displays involving almost 300 items and coordinating their activities with the Marshall Space Flight Center's Payload Operations Control Center (POCC).

The Mission Control Center's display/control system was one of the most unusual support facilities. It consisted of a series of projected screen displays that showed the orbiter's real-time location, live television pictures of crew activities, Earth views, and extravehicular activities. Other displays included mission elapsed time as well as time remaining before a maneuver or other major mission event. Many decisions or recommendations made by the flight controllers were based on information shown on the display/control system displays

Eventually, it was planned that modern state-of-the-art workstations with more capability to monitor and analyze vast amounts of data would replace the Apollo-era consoles. Moreover, instead of driving the consoles with a single main computer, each console would eventually have its own smaller computer, which could monitor a specific system and be linked into a network capable of sharing the data.

The POCCs operated in conjunction with the Flight Control Rooms. They housed principal investigators and commercial users who monitored and controlled payloads being carried aboard the Space Shuttle. One of the most extensive POCCs was at the Marshall Space Flight Center in Huntsville, Alabama, where Spacelab missions were coordinated with the Mission Control Center. It was the command post, communications hub, and data relay station for the principal investigators, mission managers, and support teams. Here, decisions on payload operations were made, coordinated with the Mission Control Center flight director, and sent to the Spacelab or Shuttle.

The POCC at the Goddard Space Flight Center controlled free-flying spacecraft that were deployed, retrieved, or serviced by the Space Shuttle. Planetary mission spacecraft were controlled from the POCC at NASA's Jet Propulsion Laboratory in Pasadena, California. Finally, private sector payload operators and foreign governments maintained their own POCCs at various locations for the control of spacecraft systems under their control.

NASA Centers and Responsibilities

Several NASA centers had responsibility for particular areas of the Space Shuttle program. NASA's Kennedy Space Center in Florida was responsible for all launch, landing, and turnaround operations for STS missions requiring equatorial orbits. Kennedy had primary responsibility for prelaunch checkout, launch, ground turnaround operations, and support operations for the Shuttle and its payloads. Kennedy's Launch Operations had responsibility for all mating, prelaunch testing, and launch control ground activities until the Shuttle vehicle cleared the launch pad tower.

Responsibility was then turned over to NASA's Mission Control Center at the Johnson Space Center in Houston. The Mission Control Center's responsibility included ascent, on-orbit operations, entry, approach, and landing until landing runout completion, at which time the orbiter was handed over to the postlanding operations at the landing site for turnaround and relaunch. At the launch site, the solid rocket boosters and external tank were processed for launch and the solid rocket boosters were recycled for reuse. The Johnson Space Center was responsible for the integration of the complete Shuttle vehicle and was the central control point for Shuttle missions.

NASA's Marshall Space Flight Center in Huntsville, Alabama, was responsible for the SSMEs, external tanks, and solid rocket boosters. NASA's National Space Technology Laboratories at Bay St. Louis, Mississippi, was responsible for testing the SSMEs. NASA's Goddard Space Flight Center in Greenbelt, Maryland, operated a worldwide tracking station network.

Crew Selection, Training, and Related Services

Crew Selection

NASA selected the first group of astronauts—known as the Mercury seven—in 1959. Since then, NASA has selected eleven other groups of astronaut candidates. Through the end of 1987, 172 individuals have graduated from the astronaut program.

NASA selected the first thirty-five astronaut candidates for the Space Shuttle program in January 1978. They began training at the Johnson Space Center the following June. The group consisted of twenty mission specialists and fifteen pilots and included six women and four members of minority groups. They completed their one-year basic training program in August 1979.

NASA accepted applications from qualified individuals—both civilian and military—on a continuing basis. Upon completing the course, successful candidates became regular members of the astronaut corps. Usually, they were eligible for a flight assignment about one year after completing the basic training program.

Pilot Astronauts. Pilot astronauts served as either commanders or pilots on Shuttle flights. During flights, commanders were responsible for the vehicle, the crew, mission success, and safety. The pilots were second in command; their primary responsibility was to assist the Shuttle commander. During flights, commanders and pilots usually assisted in spacecraft deployment and retrieval operations using the Remote Manipulator System (RMS) arm or other payload-unique equipment aboard the Shuttle.

To be selected as a pilot astronaut candidate, an applicant must have a bachelor's degree in engineering, biological science, physical science, or mathematics. A graduate degree was desired, although not essential. The applicant must have had at least 1,000 hours flying time in jet aircraft. Experience as a test pilot was desirable, but not required. All pilots and missions specialists must be citizens of the United States.

Mission Specialist Astronauts. Mission specialist astronauts, working closely with the commander and pilot, were responsible for coordinating on-board operations involving crew activity planning, use, and monitoring of the Shuttle's consumables (fuel, water, food, and so on), as well as conducting experiment and payload activities. They must have a detailed knowledge of Shuttle systems and the operational characteristics, mission requirements and objectives, and supporting systems for each of the experiments to be conducted on the assigned missions. Mission specialists performed on-board experiments, spacewalks, and payload-handling functions involving the RMS arm.

Academically, applicants must have a bachelor's degree in engineering, biological science, physical science, or mathematics, plus at least three years of related and progressively responsible professional experience. An advanced degree could substitute for part or all of the experience requirement—one year for a master's degree and three years for a doctoral degree.

Payload Specialists. This newest category of Shuttle crew member, the payload specialist, was a professional in the physical or life sciences or a technician skilled in operating Shuttle-unique equipment. The payload sponsor or customer selected a payload specialist for a particular mission. For NASA-sponsored spacecraft or experiments requiring a payload specialist, the investigator nominated the specialist who was approved by NASA.

Payload specialists did not have to be U.S. citizens. However, they must meet strict NASA health and physical fitness standards. In addition to intensive training for a specific mission assignment at a company plant, a university, or government agency, the payload specialist also must take a comprehensive flight training course to become familiar with Shuttle systems, payload support equipment, crew operations, housekeeping techniques, and emergency procedures. This training was conducted at the Johnson Space Center and other locations. Payload specialist training might begin as much as two years before a flight.

Astronaut Training

Astronaut training was conducted under the auspices of Johnson's Mission Operations Directorate. Initial training for new candidates consisted of a series of short courses in aircraft safety, including instruction in ejection, parachute, and survival to prepare them in the event their aircraft is disabled and they have to eject or make an emergency landing. Pilot and mission specialist astronauts were trained to fly T-38 high-performance jet aircraft, which were based at Ellington Field near Johnson. Flying these aircraft, pilot astronauts could maintain their flying skills and mission specialists could become familiar with high-performance jets. They also took formal science and technical courses

Candidates obtained basic knowledge of the Shuttle system, including payloads, through lectures, briefings, textbooks, mockups, and flight operations manuals. They also gained one-on-one experience in the single systems trainers, which contained computer databases with software allowing students to interact with controls and displays similar to those of a Shuttle crew station. Candidates learned to function in a weightless or environment using the KC-135 four-engine jet transport and in an enormous neutral buoyancy water tank called the Weightless Environment Training Facility at Johnson.

Because the orbiter landed on a runway much like a high-performance aircraft, pilot astronauts used conventional and modified T-38 trainers and the KC-135 aircraft to simulate actual landings. They also used a modified Grumman Gulfstream II, known as the Shuttle Training Aircraft, which was configured to simulate the handling characteristics of the orbiter for landing practice.

Advanced training included sixteen different course curricula covering all Shuttle-related crew training requirements. The courses ranged from guidance, navigation, and control systems to payload deployment and retrieval systems. This advanced training was related to systems and phases. Systems training provided instruction in orbiter systems and was not related to a specific mission or its cargo. It was designed to familiarize the trainee with a feel for what it was like to work and live in space. Generally, systems training was completed before an astronaut is assigned to a mission. Phase-related training concentrated on the specific skills an astronaut needed to perform successfully in space. This training was conducted in the Shuttle Mission Simulator. Phase-related training continued after a crew was assigned to a specific mission, normally about seven months to one year before the scheduled launch date.

At that time, crew training became more structured and was directed by a training management team that was assigned to a specific Shuttle flight. The training involved carefully developed scripts and scenarios for the mission and was designed to permit the crew to operate as a closely integrated team, performing normal flight operations according to a flight timeline.

About 10 weeks before a scheduled launch, the crew began “flight-specific integrated simulations, designed to provide a dynamic testing ground for mission rules and flight procedures.” Simulating a real mission, the crew worked at designated stations interacting with the flight control team members, who staffed their positions in the operationally configured Mission Control Center.

These final prelaunch segments of training were called integrated and joint integrated simulations and normally included the payload users’ operations control centers. Everything from extravehicular activity (EVA) operations to interaction with the tracking networks could be simulated during these training sessions.

Shuttle Mission Simulator. The Shuttle Mission Simulator was the primary system for training Space Shuttle crews. It was the only high-fidelity simulator capable of training crews for all phases of a mission beginning at T-minus thirty minutes, including such simulated events as launch, ascent, abort, orbit, rendezvous, docking, payload handling, undocking, deorbit, entry, approach, landing, and rollout.

The unique simulator system could duplicate main engine and solid rocket booster performance, external tank and support equipment, and interface with the Mission Control Center. The Shuttle Mission Simulator’s construction was completed in 1977 at a cost of about $100 million.

Crew-Related Services

In support of payload missions, crew members provided unique ancillary services in three specific areas: EVA, intravehicular activity (IVA), and in-flight maintenance. EVAs, also called spacewalks, referred to activities in which crew members put on pressurized spacesuits and life support systems (spacepaks), left the orbiter cabin, and performed various payload-related activities in the vacuum of space, frequently outside the payload bay. (Each mission allowed for at least two crew members to be training for EVA.) EVA was an operational requirement when satellite repair or equipment testing was called for on a mission. However, during any mission, two crew members must be ready to perform a contingency EVA if, for example, the payload bay doors failed to close properly and must be closed manually, or equipment must be jettisoned from the payload bay.

The first Space Shuttle program contingency EVA occurred in April 1985, during STS 51-D, a *Discovery* mission, following deployment of the Syncom IV-3 (Leasat 3) communications satellite. The satellite's sequencer lever failed, and initiation of the antenna deployment and spin-up and perigee kick motor start sequences did not take place. The flight was extended two days to give mission specialists Jeffrey Hoffman and David Griggs an opportunity to try to activate the lever during EVA operations, which involved using the RMS. The effort was not successful, but was accomplished on a later mission. Table 3–15 lists all of the operational and contingency EVAs that have taken place through 1988.

IVA included all activities during which crew members dressed in spacesuits and using life support systems performed hands-on operations inside a customer-supplied crew module. (IVAs performed in the Spacelab did not require crew members to dress in spacesuits with life support systems.)

Finally, in-flight maintenance was any off-normal, on-orbit maintenance or repair action conducted to repair a malfunctioning payload. In-flight maintenance procedures for planned payload maintenance or repair were developed before a flight and often involved EVA.

Space Shuttle Payloads

Space Shuttle payloads were classified as either "attached" or "free-flying." Attached payloads such as Spacelab remained in the cargo bay or elsewhere on the orbiter throughout the mission. Free-flying payloads were released to fly alone. Some free-flyers were meant to be serviced or retrieved by the Shuttle. Others were boosted into orbits beyond the Shuttle's reach.

Attached Payloads

Spacelab

Spacelab was an orbiting laboratory built by the ESA for use with the STS. It provided the scientific community with easy, economical access to space and an opportunity for scientists worldwide to conduct experiments in space concerning astronomy, solar physics, space plasma physics, atmospheric physics, Earth observations, life sciences, and materials sciences.

Spacelab was constructed from self-contained segments or modules. It had two major subsections: cylindrical, pressurized crew modules and U-shaped unpressurized instrument-carrying pallets. The crew modules provided a "shirtsleeve" environment where payload specials worked as they would in a ground-based laboratory. Pallets accommodated experiments for direct exposure to space. They could be combined with another small structure called an igloo.

Crew modules and pallets were completely reusable; they were designed for multi-use applications and could be stacked or fitted together in a variety of configurations to provide for completely enclosed, completely exposed, or a combination of both enclosed-exposed facilities. The Spacelab components got all their electric, cooling, and other service requirements from the orbiter. An instrument pointing system, also part of the Spacelab, provided pointing for the various Spacelab experiment telescopes and cameras.

The crew module maintained an oxygen-nitrogen atmosphere identical to that in the orbiter crew compartment. Depending on mission requirements, crew modules consisted of either one segment (short module) or two segments (long module). The short module was four and two-tenths meters long; the long module measured seven meters. All crew modules were four meters in diameter. Most of the equipment housed in the short module controlled the pallet-mounted experiments. Spacelab missions used the long module when more room was needed for laboratory-type investigations. Equipment inside the crew modules was mounted in fifty-centimeter-wide racks. These racks were easily removed between flights so module-mounted experiments could be changed quickly.

The U-shaped pallet structure accommodated experiment equipment for direct exposure to the space environment when the payload bay doors were opened. It provided hardpoints for mounting heavy experiments and inserts for supporting light payloads. Individual payload segments were three meters long and four meters wide. The orbiter keel attachment fitting provided lateral restraint for the pallet when installed in the orbiter (Figure 3–8).

The igloo was a pressurized cylindrical canister 1,120 millimeters in diameter and 2,384 millimeters in height and with a volume of two and two-tenths cubic meters (Figure 3–9). It consisted of a primary structure, a secondary structure, a removable cover, and an igloo mounting structure and housed the following components:

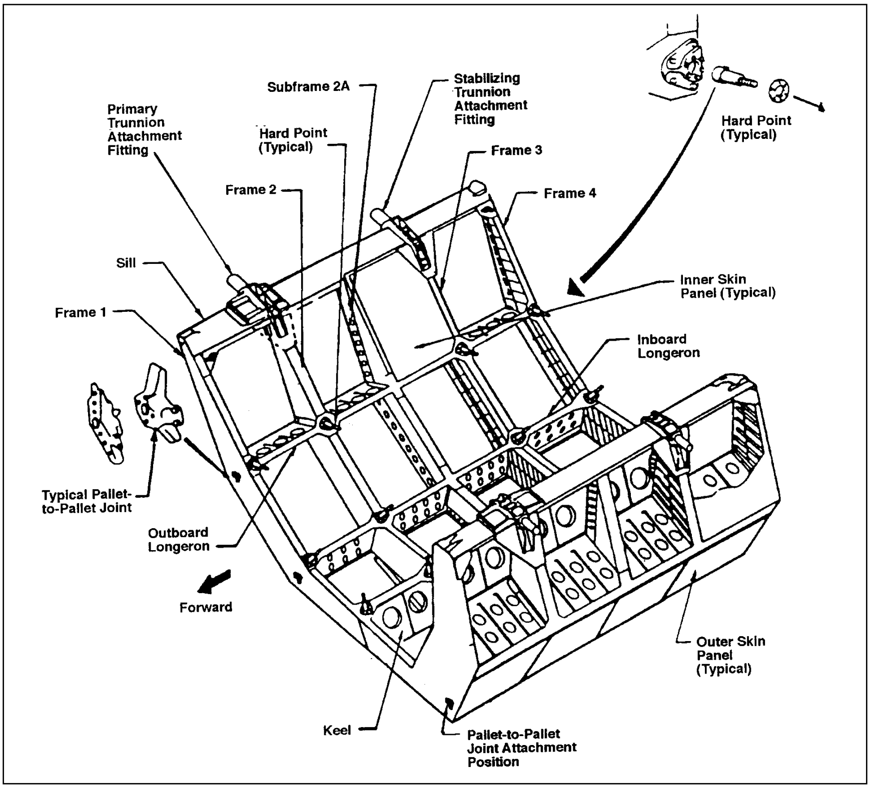

Figure 3–8. Pallet Structure and Panels

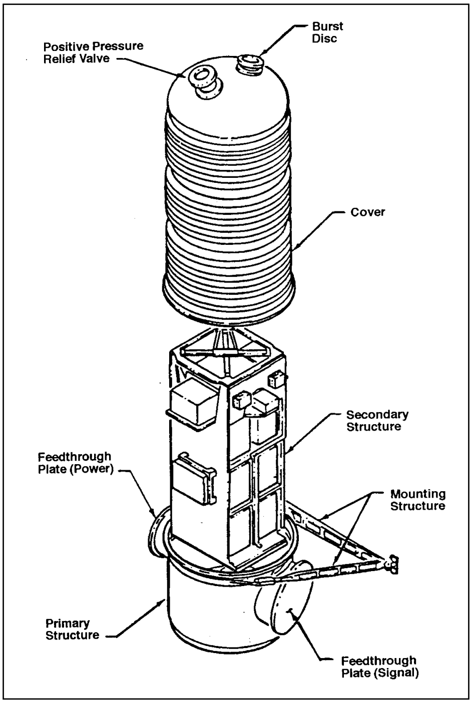

Figure 3–9. Spacelab Igloo Structure

- Three computers (subsystem, experiment, and backup)
- Two input-output units (subsystem and experiment)
- One mass memory unit
- Two subsystem remote acquisition units
- Eleven interconnect stations
- One emergency box
- One power control box
- One subsystem power distribution box
- One remote amplification and advisory box
- One high-rate multiplexer

An international agreement between the United States and Austria, Belgium, Denmark, France, Germany, Italy, The Netherlands, Spain, Switzerland, and the United Kingdom formally established the Spacelab program. Ten European nations, of which nine were members of ESA, participated in the program. NASA and ESA each bore their respective program costs. ESA responsibilities included the design, development, production, and delivery of the first Spacelab and associated ground support equipment to NASA, as well as the capability to produce additional Spacelabs. NASA responsibilities included the development of flight and ground support equipment not provided by ESA, the development of Spacelab operational capability, and the procurement of additional hardware needed to support NASA's missions.

ESA designed, developed, produced, and delivered the first Spacelab. It consisted of a pressurized module and unpressurized pallet segments, command and data management, environmental control, power distribution systems, an instrument pointing system, and much of the ground support equipment and software for both flight and ground operations.

NASA provided the remaining hardware, including the crew transfer tunnel, verification flight instrumentation, certain ground support equipment, and a training simulator. Support software and procedures development, testing, and training activities not provided by ESA, which were needed to demonstrate the operational capability of Spacelab, were also NASA's responsibility. NASA also developed two principal versions of the Spacelab pallet system. One supported missions requiring the igloo and pallet in a mixed cargo configuration; the other version supported missions that did not require the igloo.

Scientific Experiments

In addition to the dedicated Spacelab missions, nearly all STS missions had some scientific experiments on board. They used the unique microgravity environment found on the Space Shuttle or the environment surrounding the Shuttle. These experiments were in diverse disciplines and required varying degrees of crew involvement. Details of the scientific experiments performed on the various Shuttle missions are found in the "mission characteristics" tables for each mission.

Get-Away Specials

The Get-Away Specials were small self-contained payloads. Fifty-three Get-Away Special payloads had flown on Space Shuttle missions through 1988. The idea for the program arose in the mid-1970s when NASA began assigning major payloads to various Shuttle missions. It soon became apparent that most missions would have a small amount of space available after installing the major payloads. NASA's discussion of how best to use this space led to the Small Self-Contained Payloads program, later known as the Get-Away Special program.

This program gave anyone, including domestic and international organizations, an opportunity to perform a small space experiment. NASA hoped that by opening Get-Away Specials to the broadest community possible, it could further the goals of encouraging the use of space by all, enhancing education with hands-on space research opportunities, inexpensively testing ideas that could later grow into major space experiments, and generating new activities unique to space.

In October 1976, NASA's Associate Administrator for Space Flight, John Yardley, announced the beginning of the Get-Away Special program. Immediately, R. Gilbert Moore purchased the first Get-Away Special payload reservation. Over the next few months, NASA defined the program's boundaries. Only payloads of a scientific research and development nature that met NASA's safety regulations were acceptable. Payloads were to be self-contained, supplying their own power, means of data collection, and event sequencing. Keeping safety in mind and the varying technical expertise of Get-Away Special customers, NASA designed a container that could contain potential hazards. Three payload options evolved:

- A 0.07-cubic-meter container for payloads up to twenty-seven kilograms costing $3,000
- A 0.07-cubic-meter container for payloads weighing twenty-eight to forty-five kilograms for $5,000
- A 0.14-cubic-meter container for payloads up to ninety kilograms costing $10,000

Early in 1977, NASA assigned the Get-Away Special program to the Sounding Rocket Division, later renamed the Special Payloads Division, at the Goddard Space Flight Center. Meanwhile, news of the Get-Away Special program had passed informally throughout the aerospace community. With no publicity since Yardley's initial announcement the previous year, NASA had already issued more than 100 payload reservation numbers.

The Get-Away Special team did not anticipate flying a Get-Away Special payload before STS-5. However, the weight of a Get-Away Special container and its adapter beam was needed as ballast for STS-3's aft cargo bay. Thus, the Get-Away Special program and the Flight Verification Payload received an early go-ahead for the STS-3 flight in

March 1982. The first official Get-Away Special, a group of experiments developed by Utah State University students, flew on STS-4. Details of this Get-Away Special and the other Get-Away Special experiments can be found in the detailed STS mission tables that follow.

Shuttle Student Involvement Program

The Shuttle Student Involvement Program (SSIP) was a joint venture of NASA and the National Science Teachers Association (NSTA). It was designed to stimulate the study of science and technology in the nation's secondary schools. To broaden participation in the program, NASA solicited industrial firms and other groups to sponsor the development of the student experiments. Sponsors were asked to assign a company scientist to work with the student; fund the development of the experiment, including the necessary hardware; provide travel funds to take the student to appropriate NASA installations during experiment development; and provide assistance in analyzing postflight data and preparing a final report. Students proposed and designed the payloads associated with the program.

NASA and the NSTA held contests to determine which student experiments would fly on Space Shuttle missions. Following the mission, NASA returned experiment data to the student for analysis. Most Shuttle missions had at least one SSIP experiment; some missions had several experiments on board. Hardware developed to support the student experiments was located in the mid-deck of the orbiter. As a general rule, no more than one hour of crew time was to be devoted to the student experiment.

The first SSIP project took place during the 1981–82 school year as a joint venture of NASA's Academic Affairs Division and the NSTA. The NSTA announced the program, which resulted in the submission of 1,500 proposals and the selection of 191 winners from ten regions. Ten national winners were selected in May 1991. NASA then matched the finalists with industrial or other non-NASA sponsors who would support the development and postflight analysis of their experiments. Winners who were not matched with a sponsor had their experiments supported by NASA. Details of individual SSIP experiments can be found in the detailed STS mission tables that follow.

Free-Flying Payloads

Free-flying payloads are released from the Space Shuttle. Most have been satellites that were boosted into a particular orbit with the help of a inertial upper stage or payload assist module. Most free-flying payloads had lifetimes of several years, with many performing long past their anticipated life span. Some free-flying payloads sent and received communications data. These communications satellites usually belonged to companies that were involved in the communications industry. Other free-flying payloads contained sensors or other instruments to read atmospheric conditions. The data gathered by the sensors was transmitted to Earth either directly to a ground station or by way of a TDRS. Scientists on Earth interpreted the data gathered by the instruments. Examples of this kind of satellite were meteorological satellites and planetary probes. These satellites frequently were owned and operated by NASA or another government agency, although private industry could participate in this type of venture.

Other free-flying payloads were meant to fly for only a short time period. They were then retrieved by a robot arm and returned to the Shuttle's cargo bay. Individual free-flying payload missions are discussed in Chapter 4, "Space Science," in this volume and Chapter 2, "Space Applications," in Volume VI of the *NASA Historical Data Book.*

Payload Integration Process

The payload integration process began with the submission of a Request for Flight Assignment form by the user organization—a private or governmental organization—to NASA Headquarters. If NASA approved the request, a series of actions began that ultimately led to spaceflight. These actions included signing a launch services agreement, developing a payload integration plan, and preparing engineering designs and analyses, safety analysis, and a flight readiness plan. An important consideration was the weight of the payload.

For orbiters *Discovery* (OV-103), *Atlantis* (OV-104), and *Endeavour* (OV-105), the abort landing weight constraints could not exceed 22,906 kilograms of allowable cargo on the so-called simple satellite deployment missions. For longer duration flights with attached payloads, the allowable cargo weight for end-of-mission or abort situations was limited to 11,340 kilograms. For *Columbia* (OV-102), however, these allowable cargo weights were reduced by 3,810.2 kilograms.

In November 1987, NASA announced that the allowable end-of-mission total landing weight for Space Shuttle orbiters had been increased from the earlier limit of 95,709.6 kilograms to 104,328 kilograms. The higher limit was attributed to an ongoing structural analysis and additional review of forces encountered by the orbiter during maneuvers just before touchdown. This new capability increased the performance capability between lift capacity to orbit and the allowable return weight during reentry and landing. Thus, the Shuttle would be able to carry a cumulative weight in excess of 45,360 kilograms of additional cargo through 1993. This additional capability was expected to be an important factor in delivering materials for construction of the space station. Moreover, the new allowable landing weights were expected to aid in relieving the payload backlog that resulted from the STS 51-L *Challenger* accident.

Space Shuttle Missions

The following sections describe each STS mission beginning with the first four test missions. Information on Space Shuttle missions is extremely well documented. The pre- and postflight Mission Operations Reports (MORs) that NASA was required to submit for each mission provided the majority of data. At a minimum, these reports listed the mission objectives, described mission events and the payload in varying degrees of detail, listed program/project management, and profiled the crew. NASA usually issued the preflight MOR a few weeks prior to the scheduled launch date.

The postflight MOR was issued following the flight. It assessed the mission's success in reaching its objectives and discussed anomalies and unexpected events. It was signed by the individuals who had responsibility for meeting the mission objectives.

NASA also issued press kits prior to launch. These documents included information of special interest to the media, the information from the prelaunch MORs, and significant background of the mission. Other sources included NASA Daily Activity Reports, NASA News, NASA Fact Sheets, and other STS mission summaries issued by NASA. Information was also available on-line through NASA Headquarters and various NASA center home pages.

Mission Objectives

Mission objectives may seem to the reader to be rather general and broad. These objectives usually focused on what the vehicle and its components were to accomplish rather than on what the payload was to accomplish. Because one main use of the Space Shuttle was as a launch vehicle, deployment of any satellites on board was usually a primary mission objective. A description of the satellite's objectives (beyond a top level) and a detailed treatment of its configuration would be found in the MOR for that satellite's mission. For instance, the mission objectives for the Earth Radiation Budget Satellite would be found in the MOR for that mission rather than in the MOR for STS 41-G, the launch vehicle for the satellite. In addition, missions with special attached payloads, such as Spacelab or OSTA-1, issued individual MORs. These described the scientific and other objectives of these payloads and on-board experiments or "firsts" to be accomplished in considerable detail.

The Test Missions: STS-1 Through STS-4

Overview

Until the launch of STS-1 in April 1981, NASA had no proof of the Space Shuttle as an integrated Space Transportation System that could reach Earth orbit, perform useful work there, and return safely to the ground. Thus, the purpose of the Orbital Flight Test (OFT) program was to verify the Shuttle's performance under real spaceflight conditions and to establish its readiness for operational duty. The test program would expand the Shuttle's operational range toward the limits of its design in careful increments. During four flights of *Columbia,* conducted from April 1981 to July 1982, NASA tested the Shuttle in its capacities as a launch vehicle, habitat for crew members, freight handler, instrument platform, and aircraft. NASA also evaluated ground operations before, during, and after each launch. Each flight increased the various structural and thermal stresses on the vehicle, both in space and in the atmosphere, by a planned amount. The OFT phase of the STS program demonstrated the flight system's ability to safely perform launch orbital operations, payload/scientific operations, entry, approach, landing, and turnaround operations. Table 3–16 provides a summary of STS-1 through STS-4.

Following the landing of STS-4 on July 4, 1982, NASA declared the OFT program a success, even though further testing and expansion of the Shuttle's capabilities were planned on operational flights. The OFT program consisted of more than 1,100 tests and data collections. NASA tested many components by having them function as planned—if an engine valve or an insulating tile worked normally, then its design was verified. Other components, such as the RMS arm, went through validation runs to check out their different capabilities. Final documentation of Shuttle performance during OFT considered the reports from astronaut crews, ground observations and measurements, and data from orbiter instruments and special developmental flight instrumentation that collected and recorded temperatures and accelerations at various points around the vehicle and motion from points around the Shuttle.

The first OFT flights were designed to maximize crew and vehicle safety by reducing ascent and entry aerodynamic loads on the vehicle as much as possible. The missions used two-person crews, and the orbiter was equipped with two ejection seats until satisfactory performance, reliability, and safety of the Space Shuttle had been demonstrated. Launch operations were controlled from the Kennedy Space Center and flight operations from the Johnson Space Center.

At the end of OFT, *Columbia*'s main engines had been demonstrated successfully up to 100 percent of their rated power level (upgraded engines throttled to 109 percent of this level on later flights) and down to 65 percent. Designed to provide 1.67 million newtons of thrust each at sea level for an estimated fifty-five missions, the engines were on target to meeting these guidelines at the end of the test program. They met all requirements for start and cutoff timing, thrust direction control, and the flow of propellants.

Launch Phase

NASA tested the Space Shuttle in its launch phase by planning increasingly more demanding ascent conditions for each test flight, and then by comparing predicted flight characteristics with data returned from Aerodynamic Coefficient Identification Package and developmental flight instrumentation instruments and ground tracking. *Columbia* lifted slightly heavier payloads into space on each mission. The altitudes and speeds at which the solid rocket boosters and external tank separated were varied, as was the steepness of the vehicle's climb and main engine throttling times. All of these changes corresponded to a gradual increasing during the test program in the maximum dynamic pressure, or peak aerodynamic stress, inflicted on the vehicle. At no time did *Columbia* experience any significant problems with the aerodynamic or heat stresses of ascent.

A major milestone in the test program was the shift (after STS-2) from using wind tunnel data for computing *Columbia*'s ascent path to using aerodynamic data derived from the first two flights. On STS-1 and STS-2, the Shuttle showed a slight lofting—about 3,000 meters at main engine cutoff—above its planned trajectory. This was caused by the inability of wind tunnel models to simulate the afterburning of hot exhaust gasses in the real atmosphere. Beginning with the third flight, the thrust of the booster rockets was reoriented slightly to reduce this lofting.

On STS-3 and STS-4, however, the trajectory was considered too shallow, in part because of a slower than predicted burn rate for the solid rocket boosters that had also been observed on the first two flights. Engineers continued to use OFT data after STS-4 to refine their predictions of this solid propellant burn rate so that ascent trajectories could be planned as accurately as possible on future missions. In all cases, the combined propulsion of main engines, solid boosters, and OMS engines delivered the Shuttle to its desired orbit.

STS-4 was the first mission to orbit at a twenty-eight-and-a-half-degree inclination to the equator. The first flights flew more steeply inclined orbits (thirty-eight to forty degrees) that took them over more ground tracking stations. The more equatorial STS-4 inclination was favored because it gave the vehicle a greater boost from the rotating Earth at launch. The first two flights also verified that the vehicle had enough energy for an emergency landing in Spain or Senegal, as abort options, should two main engines fail during ascent. After STS-5, the crew ejection seats were removed from *Columbia*, eliminating the option to eject and ending the need for astronauts to wear pressure suits during launch.

Solid Rocket Boosters. On each test flight, the twin solid rocket boosters provided evenly matched thrust, shut off at the same times, and separated as planned from the external tank, then parachuted down to their designated recovery area in the Atlantic Ocean for towing back to the mainland and reloading with solid propellant. Each booster had three main parachutes that inflated fully about twenty seconds before water impact. Prior to the test flights, these parachutes were designed to separate automatically from the boosters by means of explosive bolts when the rockets hit the water, because it was thought that recovery would be easier if the chutes were not still attached.

On the first and third flights, however, some parachutes sank before recovery. Then, on STS-4, the separation bolts fired prematurely because of strong vibrations, the parachutes detached from the rockets before water impact, and the rockets hit the water at too great a speed and sank. They were not recovered. As a result of these problems, NASA changed the recovery hardware and procedures beginning with STS-5. Instead of separating automatically with explosives, the parachutes remained attached to the boosters through water impact, and were detached by the recovery team. Sections of the boosters were also strengthened as a result of water impact damage seen on the test flights.

External Tank. The Space Shuttle's external fuel tank met all performance standards for OFT. Heat sensors showed ascent temperatures to be moderate enough to allow for planned reductions in the thickness and weight of the tank's insulation. Beginning with STS-3, white paint on the outside of the tank was left off to save another 243 kilograms of weight, leaving the tank the brown color of its spray-on foam insulation.

Onboard cameras showed flawless separation of the tank from the orbiter after the main engines cut off on each flight, and Shuttle crews reported that this separation was so smooth that they could not feel it happening. To assist its breakup in the atmosphere, the tank had a pyrotechnic device that set it tumbling after separation rather than skipping along the atmosphere like a stone. This tumble device failed on STS-1, but it worked perfectly on all subsequent missions. On all the test flights, radar tracking of the tank debris showed that the pieces fell well within the planned impact area in the Indian Ocean.

Orbital Maneuvering System. Shortly after it separated from the fuel tank, the orbiter fired its two aft-mounted OMS engines for additional boosts to higher and more circularized orbits. At the end of orbital operations, these engines decelerated the vehicle, beginning the orbiter's fall to Earth. The engines performed these basic functions during OFT with normal levels of fuel consumption and engine wear. Further testing included startups after long periods of idleness in vacuum and low gravity (STS-1 and STS-2), exposure to cold (STS-3), and exposure to the Sun (STS-4). Different methods of distributing the system's propellants were also demonstrated. Fuel from the left tank was fed to the right tank, and vice versa, and from the OMS tanks to the smaller RCS thrusters. On STS-2, the engine cross-feed was performed in the middle of an engine burn to simulate engine failure.

Orbital Operations

Once in space, opening the two large payload bay doors with their attached heat radiators was an early priority. If the doors did not open in orbit, the Shuttle could not deploy payloads or shed its waste heat. If they failed to close at mission's end, reentry through the atmosphere would be impossible.

The STS-1 crew tested the payload bay doors during *Columbia*'s first few hours in space. The crew members first unlatched the doors from the bulkheads and from each other. One at a time, they were opened in the manual drive mode. The movement of the doors was slightly more jerky and hesitant in space than in Earth-gravity simulations, but this was expected and did not affect their successful opening and closing. The crew members closed and reopened the doors again one day into the STS-1 mission as a further test, then closed them for good before reentry. The crew verified normal alignment and latching of the doors, as did the STS-2 crew during their door cycling tests, including one series in the automatic mode.

The crew also tested door cycling after prolonged exposure to heat and cold. The doors were made of a graphite-epoxy composite material, while the orbiter itself was made of aluminum. It was therefore important to understand how they would fit together after the aluminum expanded or contracted in the temperature extremes of space. At the beginning of STS-3 orbital operations, the doors opened as usual. The payload bay was then exposed to cold shadow for a period of twenty-three hours. When the crew closed the port-side door at the end of this “coldsoak,” the door failed to latch properly, as it did after a similar cold exposure on the STS-4 mission. Apparently, the orbiter warped very slightly with nose and tail bent upward toward each other, accounting in part for the doors’ inability to clear the aft bulkhead.

The crew solved the problem by holding the orbiter in a top-to-Sun position for fifteen minutes to warm the cargo bay, then undergoing a short “barbecue roll” to even out vehicle temperatures, allowing the doors to close and latch normally. In addition, hardware changes to the doors and to the aft bulkhead improved their clearance.

Thermal Tests. Thermal tests accounted for hundreds of hours of OFT mission time. The temperatures of spacecraft structures changed dramatically in space, depending on their exposure to the Sun. Temperatures on the surface of payload bay insulation on STS-3, for example, went from a low of –96° C to a peak of 127° C. The Space Shuttle kept its components within their designed temperature limits through its active thermal control system, which included two coolant loops that transported waste heat from the orbiter and payload electronics to the door-mounted radiator panels for dumping into space, and through the use of insulation and heaters. Figure 3–10 shows the insulating materials used on the orbiter.

The OFT program tested the orbiter’s ability to keep cool and keep warm under conditions much more extreme than that of the average mission. STS-3 and STS-4 featured extended thermal “soaks,” where parts of the orbiter were deliberately heated up or cooled down by holding certain attitudes relative to the Sun for extended time periods. These long thermal soaks were separated by shorter periods of “barbecue roll” for even heating. On STS-4, the thermal soak tests continued with long tail-to-Sun and bottom-to-Sun exposures.

Overall, these hot and cold soak tests showed that the Shuttle had a better than predicted thermal stability. STS-3 readings showed that the orbiter’s skin kept considerably warmer during coldsoaks than had been expected and that many critical systems, such as the orbital maneuvering engines, were also warmer. Most vehicle structures also tended to heat up or cool down more slowly than expected. The active thermal control sys-

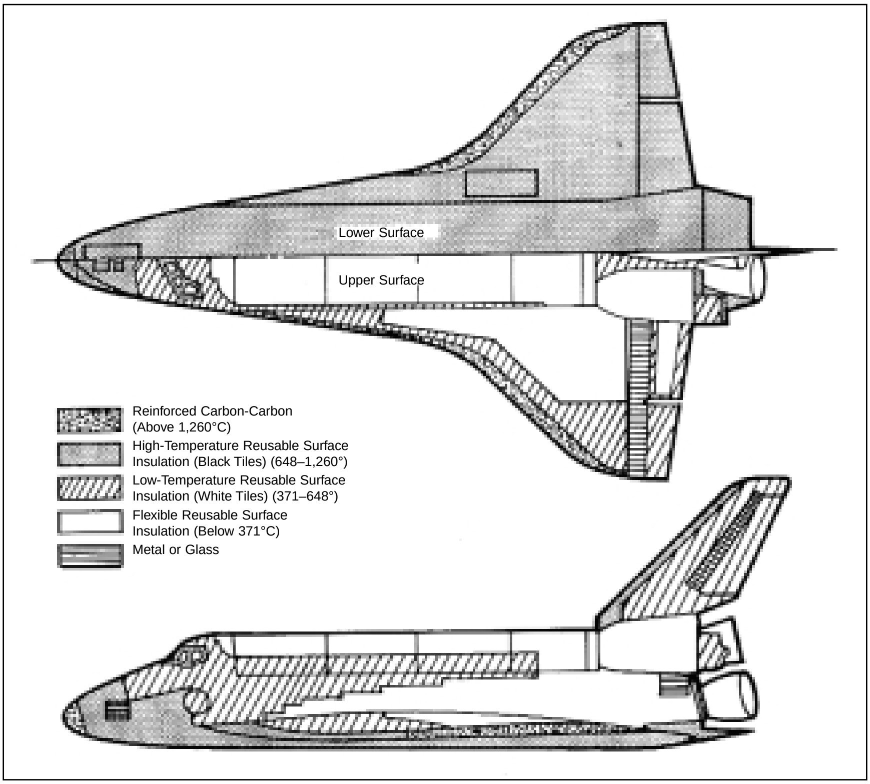

Figure 3–10. Insulating Materials

tem, with its coolant loops and space radiators, proved capable of handling Shuttle heat loads in orbit, even under extreme conditions.

The crew tested the space radiators with all eight panels deployed, and they proved capable of shedding most heat loads with only four panels deployed. During ascent, another part of the thermal control system, the Shuttle's flash evaporators, transferred heat from circulating coolant to water, beginning about two minutes into the ascent when the vehicle first required active cooling. These flash evaporators normally worked until the space radiators were opened in orbit. Then, during reentry, the flash evaporators were reactivated and used down to an altitude of approximately 36,000 meters. From that altitude down to the ground, the Shuttle shed heat by boiling ammonia rather than water. During OFT, the crew members successfully tested these methods of cooling as backups to each other.

Subsystems. All crews for the flight test program tested and retested the Space Shuttle's main subsystems under varying conditions. On the four OFT flights, virtually every system—hydraulic, electrical, navigation and guidance, communications, and environmental control—performed up to design standards or better.

The hydraulic subsystem that controlled the movement of the Shuttle's engine nozzles, its airplane-like control flaps, and its landing gear functioned well during OFT launches and reentries. The crew tested the hydraulic system successfully on STS-2 by cycling the eleven control surfaces while in orbit. On STS-4, the hydraulics were evaluated after a long coldsoak, and the crew found that the circulation pumps needed to operate at only minimal levels to keep the hydraulic fluids above critical temperatures, thus saving on electric power usage.

Although an oil filter clog in the hydraulic system's auxiliary power units delayed the launch of STS-2 by more than a week, the problem did not recur. Tighter seals were used to prevent the oil from being contaminated by the units' hydrazine fuel.

The STS-2 mission was also cut short because of the failure of one of the three Shuttle fuel cells that converted cryogenic hydrogen and oxygen to electricity. A clog in the cell's water flow lines caused the failure, and this problem was remedied during OFT by adding filters to the pipes. This failure allowed an unscheduled test of the vehicle using only two fuel cells instead of three, which were enough to handle all electrical needs. Partly as a result of the Shuttle's thermal stability, electricity consumption by the orbiter proved to be lower than expected, ranging from fourteen to seventeen kilowatts per hour in orbit as opposed to the predicted fifteen to twenty kilowatts.

The Shuttle's computers successfully demonstrated their ability to control virtually every phase of each mission, from final countdown sequencing to reentry, with only minor programming changes needed during the test program. The crew checked out the on-orbit navigation and guidance aids thoroughly. The orbiter "sensed" its position in space by means of three inertial measurement units, whose accuracy was checked and periodically updated by a star tracker located on the same navigation base in the flight deck. The crew tested this star tracker/inertial measurement unit alignment on the first Shuttle mission, including once when the vehicle was rolling. The star tracker could find its guide stars in both darkness and daylight. Its accuracy was better than expected, and the entire navigation instrument base showed stability under extreme thermal conditions.

Radio and television communication was successful on all four flights, with only minimal hardware and signal acquisition problems at ground stations. Specific tests checked different transmission modes, radio voice through the Shuttle's rocket exhaust during ascent, and UHF transmission as a backup to the primary radio link during launch and operations in space. All were successful. Tests on STS-4 also evaluated how different orbiter attitudes affected radio reception in space.

The closed-circuit television system inside the orbiter and out in the cargo bay gave high-quality video images of operations in orbit. In sunlight and in artificial floodlighting of the payload bay, they showed the necessary sensitivity, range of vision, remote control, and video-recording capabilities.

Attitude Control. When in orbit, the Shuttle used its RCS to control its attitude and to make small-scale movements in space. The thrusting power and propellant usage of both types of RCS jets were as expected, with the smaller verniers more fuel-efficient than expected. Two of the four vernier jets in *Columbia*'s tail area had a problem with the downward direction of their thrust. The exhaust hit the aft body flap and eroded some of its protective tiles, which also reduced the power of the jets. One possible solution considered was to reorient these jets slightly on future orbiters.

The orbiter demonstrated its ability to come to rest after a maneuver. At faster rates, it proved nearly impossible to stop the vehicle's motion without overshooting, then coming back to the required "stop" position, particularly with the large primary engines. Both types of thrusters were used to keep the orbiter steady in "attitude hold" postures. The small thrusters were particularly successful and fuel-efficient, holding the vehicle steady down to one-third of a degree of drift at normal rates of fuel use, which was three times their required sensitivity.

Further tests of the RCS assessed how well *Columbia* could hold steady without firing its jets when differential forces of gravity tended to tug the vehicle out of position. The results of these tests looked promising for the use of "passive gravity gradient" attitudes for future missions where steadiness for short periods of time was required without jet firings.

Remote Manipulator System. Ground simulators could not practice three-dimensional maneuvers because the remote manipulator system (RMS) arm was too fragile to support its own weight in Earth gravity. Therefore, one of the most important as well as most time-consuming of all OFT test series involved the fifteen-meter mechanical arm. This Canadian-built device, jointed as a human arm at the shoulder, elbow, and wrist, attached to the orbiter at various cradle points running the length of the inside of the cargo bay. In place of a hand, the arm had a cylindrical end effector that grappled a payload and held it rigid with wire snares. A crew member controlled the arm from inside the orbiter. The arm could be moved freely around the vehicle in a number of modes, with or without help from the Shuttle's computers.

The crew tested all manual and automatic drive modes during OFT. They also tested the arm's ability to grab a payload firmly, remove it from a stowed position, then reberth it precisely and securely. Lighting and television cameras also were verified—the crew relied on sensitive elbow and wrist cameras as well as cameras mounted in the payload bay to monitor operations. For the test program, special data acquisition cameras in the cargo bay documented arm motion.

STS-2 was the first mission to carry the arm. Although the crew did not pick up a payload with the arm, the astronauts performed manual approaches to a grapple fixture in the cargo bay, and they found the arm to control smoothly. The crew also began tests to see how the arm's movement interacted with orbiter motions. The crew reported that firings of the small vernier thrusters did not influence arm position, nor did arm motions necessitate attitude adjustment firings by the orbiter.

STS-3 tests evaluated the arm with a payload. The end effector grappled the 186-kilogram Plasma Diagnostics Package (PDP), removed it manually from its berth in the cargo bay, and maneuvered it automatically around the orbiter in support of OFT space environment studies. Pilot Gordon Fullerton deployed and reberthed the package. Before one such deployment, the arm automatically found its way to within 3.8 centimeters of the grapple point in accordance with preflight predictions. The crew also verified the computer's ability to automatically stop an arm joint from rotating past the limit of its mobility. The third crew completed forty-eight hours of arm tests, including one unplanned demonstration of the elbow camera's ability to photograph *Columbia*'s nose area during an on-orbit search for missing tiles.

Television cameras provided excellent views of arm operations in both sunshine and darkness, and the STS-4 crew reported that nighttime operations, although marginal, were still possible after three of the six payload bay cameras failed. The third and fourth crews continued evaluating vehicle interactions with arm motion by performing roll maneuvers as the arm held payloads straight up from the cargo bay. This was done with the PDP on STS-3 and with the Induced Environment Contamination Monitor on STS-4, which weighed twice as much. In both cases, the crew noted a slight swaying of the arm when the vehicle stopped, which was expected.

The RMS was designed to move a payload of 29,250 kilograms, but it was tested only with masses under 450 kilograms during OFT. Future arm tests would graduate to heavier payloads, some with grapple points fixed to simulate the inertias of even more massive objects.

The Shuttle Environment. In addition to these hardware checkouts, the test program also assessed the Space Shuttle environment. This was important for planning future missions that would carry instruments sensitive to noise, vibration, radiation, or contamination. During OFT, *Columbia* carried two sensor packages for examining the cargo bay environment. The Dynamic, Acoustic and Thermal Environment experiment—a group of accelerometers, microphones, and heat and strain gauges—established that noise and stress levels inside the bay were generally lower than predicted. The Induced Environment Contamination Monitor, normally secured in the cargo bay, was also moved around by the manipulator arm to perform an environmental survey outside the orbiter on STS-4.

The Contamination Monitor and the Shuttle-Spacelab Induced Atmosphere Experiment and postlanding inspections of the cargo bay backed up the Induced Environment Contamination Monitor's survey of polluting particles and gasses. These inspections revealed minor deposits and some discoloration of films and painted surfaces in the bay, which were still being studied after OFT. A new payload bay lining was added after STS-4.

The PDP measured energy fields around the orbiter on STS-3. The PDP, used in conjunction with the Vehicle Charging and Potential Experiment, mapped the distribution of charged particles around the spacecraft. These readings showed a vehicle that was relatively "quiet" electrically—it moved through the Earth's energy fields with interference levels much lower than the acceptable limits. The crew also discovered a soft glow around some of the Shuttle's surfaces that appeared in several nighttime photographs. An experiment added to STS-4 to identify the glow's spectrum supported a tentative explanation that the phenomenon resulted from the interaction with atomic oxygen in the thin upper atmosphere.

Inside the Shuttle, the cabin and mid-deck areas proved to be livable and practical working environments for the crew members. The test flight crews monitored cabin air quality, pressure, temperature, radiation, and noise levels and filmed their chores and activities in space to document the Shuttle's "habitability." The crews reported that their mobility inside *Columbia* was excellent, and they found that anchoring themselves in low gravity was easier than expected. There was almost no need for special foot restraints, and the crew members could improvise with ordinary duct tape attached to their shoes to hold themselves in place.

Descent and Landing

At the end of its time in orbit, the Space Shuttle's payload bay doors were closed, and the vehicle assumed a tail-first, upside-down posture and retrofired its OMS engines to drop out of orbit. It then flipped to a nose-up attitude and began its descent through the atmosphere back to Earth. Figure 3–11 shows the STS-1 entry flight profile.

The Shuttle's insulation needed to survive intact the burning friction of reentry to fly on the next mission. *Columbia*'s aluminum surface was covered with several different types of insulation during the test program, with their distribution based on predicted heating patterns. These included more

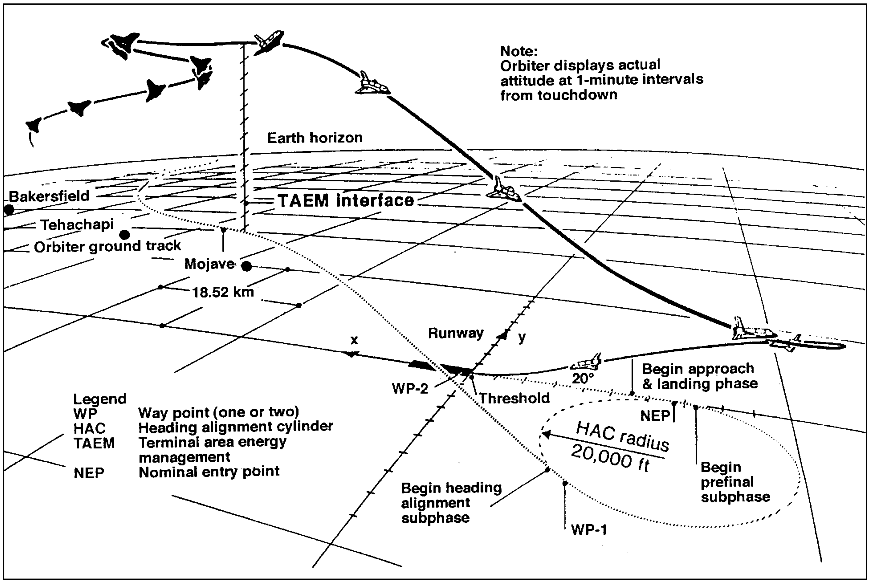

Figure 3-11. STS-1 Entry Flight Profile

than 30,000 rigid silica tiles of two types (black for high temperatures, white for lower) that accounted for over 70 percent of the orbiter's surface area.

Television cameras viewing the outside of the Shuttle clearly revealed that several tiles had shaken loose during the vehicle's ascent and were missing from the aft engine pods. These tiles had not been densified—a process that strengthened the bond between tile and orbiter—as had all the tiles in critical areas and every tile installed after October 1979. No densified tiles were lost during the test flights.

On each flight, there was some damage to tile surfaces during launch and reentry. Vehicle inspection revealed hundreds of pits and gouges after STS-1 and STS-2. While the damage was not critical, many tiles needed to be replaced. Crew reports, launch pad cameras, and cockpit films recorded chunks of ice and/or insulation falling from the external tank; during ascent and launch, pad debris flew up and hit the orbiter, and these impacts were blamed for most of the tile damage. During the test program, NASA instituted a general cleanup of the pad before launch, and the removal of a particular insulation that had come loose from the booster rockets reduced debris significantly. On the external tank, certain pieces of ice-forming hardware were removed. As a result, impact damage to the tiles was greatly reduced. While some 300 tiles needed to be replaced after STS-1, fewer than forty were replaced after STS-4.

Weather also damaged some tiles during the test program. Factory waterproofing of new tiles did not survive the heat of reentry, and *Columbia* had to be sprayed with a commercial waterproofing agent after each mission so as not to absorb rainwater on the pad. The waterproofing agent was found to loosen tile bonds where it formed puddles, though, and STS-3 lost some tiles as a result.

Then, while STS-4 sat on the pad awaiting launch, a heavy hail and rainstorm allowed an estimated 540 kilograms of rainwater to be absorbed into the porous tiles through pits made by hailstones. This water added unwanted weight during ascent and later caused motion disturbances to the vehicle when the water evaporated into space. Shuttle engineers planned to use an injection procedure to waterproof the interior of the tiles for future missions.

As a whole, the thermal protection system kept the orbiter's skin within required limits during the OFT flights, even during the hottest periods of reentry. For the test program's last three flights, the crews performed short-duration maneuver changes in the vehicle's pitch angle that tested the effects of different attitudes on heating. Heating on the control surfaces was increased over the four flights, and on STS-3 and STS-4, the angle of entry into the atmosphere was flown more steeply to collect data under even more demanding conditions. Sensors on the orbiter reported temperatures consistent with preflight predictions. Notable exceptions were the aft engine pods, where some low-temperature flexible insulation was replaced with high-temperature black tiles after STS-1 showed high temperatures and scorching.

Aerodynamic Tests

The major objective of aerodynamic testing was to verify controlled flight over a wide range of altitudes (beginning at 120,000 meters where the air is very thin) and velocities, from hypersonic to subsonic. In both manual and automatic control modes, the vehicle flew very reliably and agreed with wind tunnel predictions.

Each flight crew also conducted a number of maneuvers either as programmed inputs by the guidance computer or as control stick commands by the crew in which the vehicles flaps and rudder were positioned to bring about more demanding flight conditions or to fill data gaps where wind tunnel testing was not adequate. These corrections were executed perfectly. In the thin upper atmosphere, the Space Shuttle used its reaction control thrusters to help maintain its attitude. Over the four test flights, these thrusters showed a greater-than-expected influence on the vehicle's motion. The orbiter's navigation and guidance equipment also performed well during reentry. Probes that monitored air speeds were successfully deployed at speeds below approximately Mach 3, and navigational aids by which the orbiter checks its position relative to the ground worked well with only minor adjustments.

Unlike returning Apollo capsules, the Space Shuttle had some cross-range capability—it could deviate from a purely ballistic path by gliding right or left of its aim point and so, even though it had no powered thrust during final approach, it did have a degree of control over where it landed. The largest cross-range demonstrated during the test program was 930 kilometers on STS-4.

The Space Shuttle could return to Earth under full computer control from atmospheric entry to the runway. During the test program, however, *Columbia*'s approach and landing were partly manual. The STS-1 approach and landing was fully manual. On STS-2, the auto-land control was engaged at 1,500 meters altitude, and the crew took over at ninety meters. Similarly, STS-3 flew on auto-land from 3,000 meters down to thirty-nine meters before the commander took stick control. It was decided after an error in nose attitude during the STS-3 landing that the crew should not take control of the vehicle so short a time before touchdown. The STS-4 crew therefore took control from the auto-land as *Columbia* moved into its final shallow glide slope at 600 meters. Full auto-land capability remained to be demonstrated after STS-5, as did a landing with a runway cross-wind.

Stress gauges on the landing gear and crew reports indicated that a Shuttle landing was smoother than most commercial airplanes. Rollout on the runway after touchdown fell well within the 4,500-meter design limit on each landing, but the actual touchdown points were all considerably beyond the planned touchdown points. This was because the Shuttle had a higher ratio of lift to drag near the ground than was expected, and it "floated" farther down the runway.

Ground Work

The OFT program verified thousands of ground procedures, from mating the vehicle before launch to refurbishing the solid rocket boosters and ferrying the orbiter from landing site to launch pad. As the test program progressed, many ground operations were changed or streamlined. Certain tasks that had been necessary for an untried vehicle before STS-1 could be eliminated altogether. As a result of this learning, the "turnaround" time between missions was shortened dramatically—from 188 days for STS-2 to seventy-five days between STS-4 and STS-5. Major time-saving steps included:

- Leaving cryogenic fuels in their on-board storage tanks between flights rather than removing them after landing
- Alternating the use of primary and backup systems on each flight rather than checking out both sets of redundant hardware on the ground before each launch
- Reducing the number of tests of critical systems as they proved flight-worthy from mission to mission

The OFT program verified the soundness of the STS and its readiness for future scientific, commercial, and defense applications.

Orbiter Experiments Program

Many of the experiments that flew on the first four Shuttle missions were sponsored by the Office of Aeronautics and Space Technology (Code R) through its Orbiter Experiments Program. NASA used the data gathered from these experiments to verify the accuracy of wind tunnel and other ground-based simulations made prior to flight, ground-to-flight extrapolation methods, and theoretical computational methods.

The prime objective of these experiments was to increase the technology reservoir for the development of future (twenty-first century) space transportation systems, such as single-stage-to-orbit, heavy-lift launch vehicles and orbital transfer vehicles that could deploy and service large, automated, person-tended, multifunctional satellite platforms and a staffed, permanent facility in Earth orbit. The Orbiter Experiments Program experiments included:

- Aerodynamic Coefficient Identification Package
- Shuttle Entry Air Data System
- Shuttle Upper Atmospheric Mass Spectrometer
- Data Flight Instrumentation Package
- Dynamic, Acoustic and Thermal Environment Experiment
- Infrared Imagery of Shuttle
- Shuttle Infrared Leeside Temperature Sensing
- Tile Gap Heating Effects Experiment
- Catalytic Surface Effects

Each of these experiments, plus the others listed in Table 3–16, is discussed as part of the individual "mission characteristics" tables (Tables 3–17 through 3–20).

Mission Characteristics of the Test Missions (STS-1 Through STS-4)

STS-1

Objective. The mission objective was to demonstrate a safe ascent and return of the orbiter and crew.

Overview. *Columbia* reported on spacecraft performance and the stresses encountered during launch, flight, and landing. The flight successfully demonstrated two systems: the payload bay doors with their attached heat radiators and the RCS thrusters used for attitude control in orbit. John W. Young and Robert L. Crippen tested all systems and conducted many engineering tests, including opening and closing the cargo bay doors. Opening these doors is critical to deploy the radiators that release the heat that builds up in the crew compartment. Closing them is necessary for the return to Earth.

Young and Crippen also documented their flight in still and motion pictures. One view of the cargo bay that they telecast to Earth indicated that all or part of sixteen heat shielding tiles were lost. The loss was not considered critical as these pods were not subjected to intense heat, which could reach 1,650° C while entering the atmosphere. More than 30,000 tiles did adhere. A detailed inspection of the tiles, carried out later, however, revealed minor damage to approximately 400 tiles. About 200 would require replacement, 100 as a result of flight damage and 100 identified prior to STS-1 as suitable for only one flight.

Observations revealed that the water deluge system designed to suppress the powerful acoustic pressures of liftoff needed to be revised, after the shock from the booster rockets was seen to be much larger than anticipated. In the seconds before and after liftoff, a "rainbird" deluge system had poured tens of thousands of gallons of water onto the launch platform and into flame trenches beneath the rockets to absorb sound energy that might otherwise damage the orbiter or its cargo. Strain gauges and microphones measured the acoustic shock, and they showed up to four times the predicted values in parts of the vehicle closest to the launch pad.

Although *Columbia* suffered no critical damage, the sound suppression system was modified before the launch of STS-2. Rather than dumping into the bottom of the flame trenches, water was injected directly into the exhaust plumes of the booster rockets at a point just below the exhaust nozzles at the time of ignition. In addition, energy-absorbing water troughs were placed over the exhaust openings. The changes were enough to reduce acoustic pressures to 20 to 30 percent of STS-1 levels for the second launch.

STS-2

Objectives. NASA's mission objectives for STS-2 were to:

- Demonstrate the reusability of the orbiter vehicle
- Demonstrate launch, on-orbit, and entry performance under conditions more demanding than STS-1
- Demonstrate orbiter capability to support scientific and applications research with an attached payload
- Conduct RMS tests

Overview. Originally scheduled for five days, the mission was cut short because one of *Columbia*'s three fuel cells that converted supercold (cryogenic) hydrogen and oxygen to electricity failed shortly after the vehicle reached orbit. Milestones were the first tests of the RMS's fifteen-meter arm and the successful operation of Earth-viewing instruments in the cargo bay. The mission also proved the Space Shuttle's reusability.

In spite of the shortened mission, approximately 90 percent of the major test objectives were successfully accomplished, and 60 percent of the tests requiring on-orbit crew involvement were completed. The performance of lower priority tests were consistent with the shortened mission, and 36 percent of these tasks were achieved.

The mission's medical objectives were to provide routine and contingency medical support and to assure the health and well-being of flight personnel during all phases of the STS missions. This objective was achieved through the careful planning, development, training, and implementation of biomedical tests and procedures compatible with STS operations and the application of principles of general preventive medicine. It was also discovered that shortened sleep periods, heavy work loads, inadequate time allocation for food preparation and consumption, and estimated lower water intake were just sufficient for a fifty-four-hour mission. A plan was therefore developed to restructure in-flight timelines and institute corrective health maintenance procedures for longer periods of flight.

OSTA-1 was the major on-board mission payload. Sponsored by the Office of Space and Terrestrial Applications, it is addressed in Chapter 2, "Space Applications," in Volume VI of the *NASA Historical Data Book.*

STS-3

Objectives. The NASA mission objectives for STS-3 were to:

- Demonstrate ascent, on-orbit, and entry performance under conditions more demanding than STS-2 conditions
- Extend orbital flight duration
- Conduct long-duration thermal soak tests
- Conduct scientific and applications research with an attached payload

Overview. NASA designated OSS-1 as the attached payload on STS-3. The Office of Space Science sponsored the mission. This mission is discussed in Chapter 4, "Space Science."

The crew performed tests of the robot arm and extensive thermal testing of *Columbia* itself during this flight. Thermal testing involved exposing the tail, nose, and tip to the Sun for varying periods of time, rolling it ("barbecue roll") in between tests to stabilize temperatures over the entire body. The robot arm tested satisfactorily, moving the PDP experiment around the orbiter.

STS-4

Objectives. The NASA mission objectives for STS-4 were to:

- Demonstrate ascent, on-orbit, and entry performance under conditions more demanding than STS-3 conditions
- Conduct long-duration thermal soak tests
- Conduct scientific and applications research with attached payloads

Overview. This was the first Space Shuttle launch that took place on time and with no schedule delays. The mission tested the flying, handling, and operating characteristics of the orbiter, performed more exercises with the robot arm, conducted several scientific experiments in orbit, and landed at Edwards Air Force Base for the first time on a concrete runway of the same length as the Shuttle Landing Facility at the Kennedy Space Center. *Columbia* also planned to conduct more thermal tests by exposing itself to the Sun in selected altitudes, but these plans were changed because of damage caused by hail, which fell while *Columbia* was on the pad. The hail cut through the protective coating on the tiles and let rainwater inside. In space, the affected area on the underside of the orbiter was turned to the Sun. The heat of the Sun vaporized the water and prevented further possible tile damage from freezing.

The only major problem on this mission was the loss of the two solid rocket booster casings. The main parachutes failed to function properly, and the two casings hit the water at too high a velocity and sank. They were later found and examined by remote camera, but not recovered.

During the mission, the crew members repeated an STS-2 experiment that required the robot arm to move an instrument called the Induced Environmental Contamination Monitor around the orbiter to gather data on any gases or particles being released by the orbiter. They also conducted the Continuous Flow Electrophoresis System experiment, which marked the first use of the Shuttle by a commercial concern, McDonnell Douglas (Figure 3–12). In addition to a classified Air Force payload in the cargo bay, STS-4 carried the first Get-Away Special—a series of nine experiments prepared by students from Utah State University.

The payload bay was exposed to cold shadow for several hours after opening of the doors. When the port-side door was closed at the end of

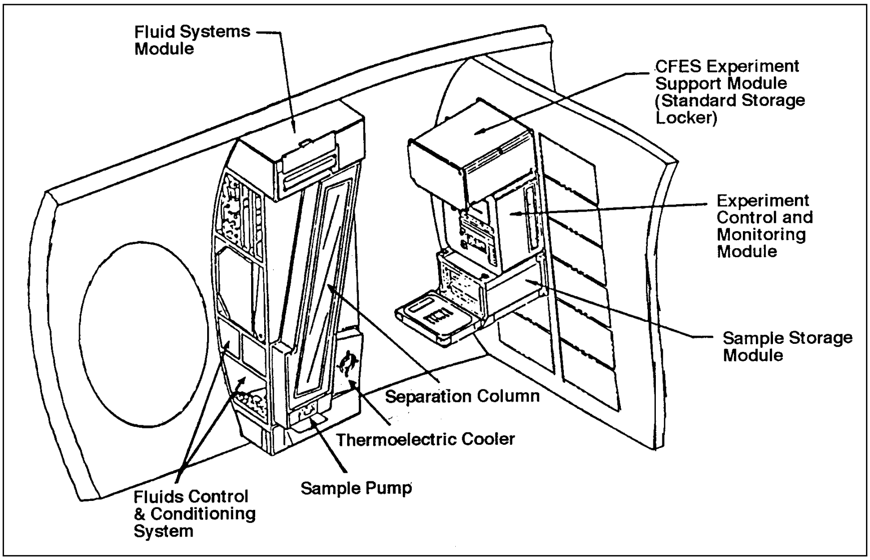

Figure 3–12. Continuous Flow Electrophoresis System Mid-deck Gallery Location

the "coldsoak," it failed to latch properly, as it did during the STS-3 mission. The solution on both flights was the same and was adopted as the standard procedure for closing the doors following a long cold exposure: the orbiter would hold a top-to-Sun position for fifteen minutes to warm the cargo bay, then undergo a short "barbecue roll" to even out vehicle temperatures, allowing the doors to close normally.

Mission Characteristics of the Operational Missions (STS-5 Through STS-27)

The Space Transportation System became operational in 1982, after completing the last of four orbital flight tests. These flights had demonstrated that the Space Shuttle could provide flexible, efficient transportation into space and back for crew members, equipment, scientific experiments, and payloads. From this point, payload requirements would take precedence over spacecraft testing. Table 3–21 summarizes Shuttle mission characteristics. The narrative and tables that follow (Tables 3–22 through 3–44) provide more detailed information on each Shuttle mission.

STS-5

STS-5 was the first operational Space Shuttle mission. The crew adopted the theme "We Deliver" as it deployed two commercial communications satellites: Telesat-E (Anik C-3) for Telesat Canada and SBS-C for Satellite Business Systems. Each was equipped with the Payload Assist Module-D (PAM-D) solid rocket motor, which fired about forty-five minutes after deployment, placing each satellite into highly elliptical orbits.

The mission carried the first crew of four, double the number on the previous four missions. It also carried the first mission specialists—individuals qualified in satellite deployment payload support, EVAs, and the operation of the RMS. This mission featured the first Shuttle landing on the 15,000-foot-long concrete runway at Edwards Air Force Base in California. NASA canceled the first scheduled EVA, or spacewalk, in the Shuttle program because of a malfunction in the spacesuits.

Experiments on this mission were part of the Orbiter Experiments Program, managed by NASA's Office of Aeronautics and Space Technology (OAST). The primary objective of this program was to increase the technology reservoir for the development of future space transportation systems to be used by the Office of Space Flight for further certification of the Shuttle and to expand its operational capabilities. Figure 3–13 shows the STS-5 payload configuration, and Table 3–22 lists the mission's characteristics.

STS-6

STS-6, carrying a crew of four, was the first flight of *Challenger,* NASA's second operational orbiter. The primary objective of this mission was the deployment of the first Tracking and Data Relay Satellite (TDRS-1) to provide improved tracking and data acquisition services to spacecraft in low-Earth orbit. It was to be injected into a geosynchronous transfer orbit by a two-stage inertial upper stage. The first stage fired as planned, but the second stage cut off after only seventy seconds of a

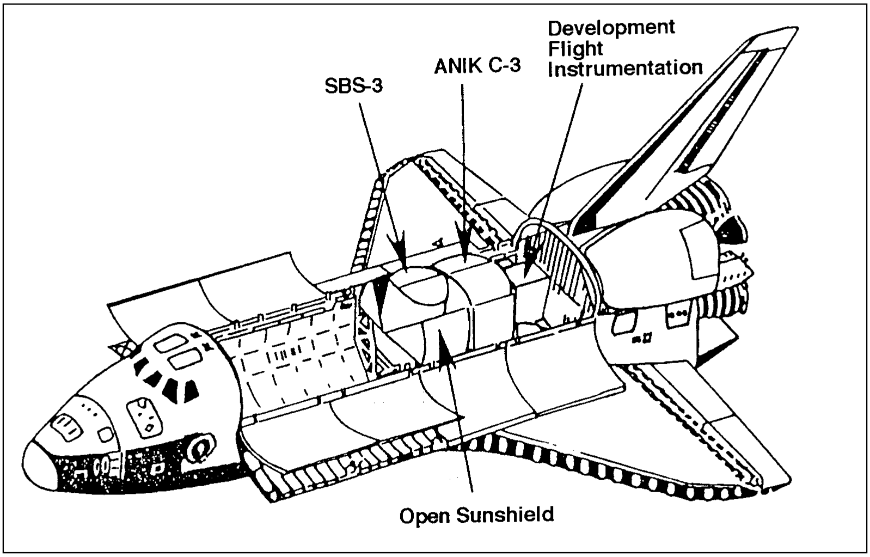

Figure 3–13. STS-5 Payload Configuration
(The payload was covered by a sunshield to protect against thermal extremes when the orbiter bay doors were open. The sunshield, resembling a two-piece baby buggy canopy, was constructed of tubular aluminum and mylar sheeting.)

planned 103-second burn. TDRS entered an unsatisfactory elliptical orbit. Excess propellant was used over the next several months to gradually circularize the orbit, using the spacecraft's own attitude control thrusters. The maneuver was successful, and TDRS-1 reached geosynchronous orbit and entered normal service.

This mission featured the first successful spacewalk of the Space Shuttle program, which was performed by astronauts Donald H. Peterson and F. Story Musgrave. It lasted about four hours, seventeen minutes. The astronauts worked in the cargo bay during three orbits, testing new tools and equipment-handling techniques.

This mission used the first lightweight external tank and lightweight solid rocket booster casings. The lightweight external tank was almost 4,536 kilograms lighter than the external tank on STS-1, with each weighing approximately 30,391 kilograms. The lightweight solid rocket booster casings increased the Shuttle's weight-carrying capability by about 363 kilograms. Each booster's motor case used on STS-6 and future flights weighed about 44,453 kilograms, approximately 1,814 kilograms less than those flown on previous missions. Table 3–23 identifies the characteristics of STS-6.

STS-7

STS-7 deployed two communications satellites, Telesat-F (Anik C-2) and Palapa-B1 into geosynchronous orbit. Also, the Ku-band antenna used with the TDRS was successfully tested.

The OSTA-2 mission was also conducted on STS-7. This mission involved the United States and the Federal Republic of Germany (the former West Germany) in a cooperative materials processing research project in space. Further details of the OSTA-2 mission are in Chapter 2, "Space Applications," in Volume VI of the *NASA Historical Data Book.*

This mission used the RMS to release the Shuttle Pallet Satellite (SPAS-01), which was mounted in the cargo bay. SPAS was the first Space Shuttle cargo commercially financed by a European company, the West German firm Messerschmitt-Bolkow-Blohm. Operating under its own power, SPAS-01 flew alongside *Challenger* for several hours and took the first full photographs of a Shuttle in orbit against a background of Earth. The RMS grappled the SPAS-01 twice and then returned and locked the satellite into position in the cargo bay.

STS-7 was the first Shuttle mission with a crew of five astronauts and the first flight of an American woman, Sally Ride, into space. This mission also had the first repeat crew member—Robert Crippen. Details of the mission are in Table 3–24.

STS-8

STS-8's primary mission objectives were to deploy Insat 1B, complete RMS loaded arm testing using the payload flight test article (PFTA),

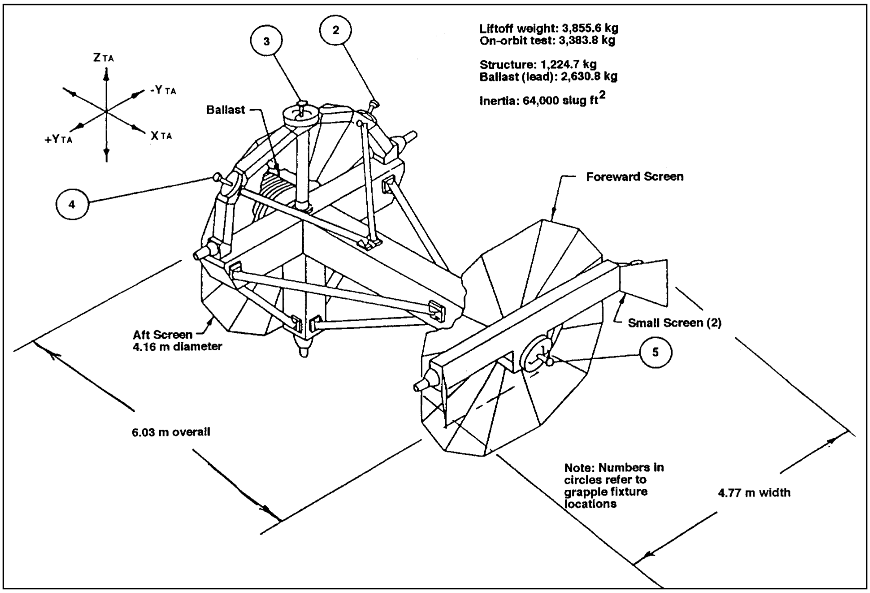

Figure 3–14. Payload Flight Test Article

accomplish TDRS/Ku-band communications testing, and achieve assigned experiments and test objectives. The RMS carried its heaviest loads to date, and the PFTA had several grapple points to simulate the inertias of even heavier cargoes. Figure 3–14 illustrates the PFTA configuration.

STS-8 was the first Space Shuttle mission launched at night. The tracking requirements for the Indian Insat 1B satellite, the primary payload, dictated the time of launch. STS-8 also had the first night landing.

The crew performed the first tests of Shuttle-to-ground communications using TDRS. Launched into geosynchronous orbit on STS-6, TDRS was designed to improve communications between the spacecraft and the ground by relaying signals between the spacecraft and the ground, thus preventing the loss of signal that occurred when using only ground stations.

This mission carried the first African-American astronaut, Guion S. Bluford, to fly in space. Details of STS-8 are listed in Table 3–25.

STS-9

STS-9 carried the first Spacelab mission (Spacelab 1), which was developed by ESA, and the first astronaut to represent ESA, Ulf Merbold of Germany. It successfully implemented the largest combined NASA and ESA partnership to date, with more than 100 investigators from eleven European nations, Canada, Japan, and the United States. It was the longest Space Shuttle mission up to that time in the program and was the first time six crew members were carried into space on a single vehicle. The crew included payload specialists selected by the science community.

The primary mission objectives were to verify the Spacelab system and subsystem performance capability, to determine the Spacelab/orbiter interface capability, and to measure the induced environment. Secondary mission objectives were to obtain valuable scientific, applications, and technology data from a U.S.-European multidisciplinary payload and to demonstrate to the user community the broad capability of Spacelab for scientific research.

ESA and NASA jointly sponsored Spacelab 1 and conducted investigations on a twenty-four-hour basis, demonstrating the capability for advanced research in space. Spacelab was an orbital laboratory with an observations platform composed of cylindrical pressurized modules and U-shaped unpressurized pallets, which remained in the orbiter's cargo bay during flight. It was the first use of a large-scale space airlock for scientific experiments.

Altogether, seventy-three separate investigations were carried out in astronomy and physics, atmospheric physics, Earth observations, life sciences, materials sciences, space plasma physics, and technology—the largest number of disciplines represented on a single mission. These experiments are described in Chapter 4, "Space Science," in Table 4–45. Spacelab 1 had unprecedented large-scale direct interaction of the flight crew with ground-based science investigators.

All of the mission objectives for verifying Spacelab's modules were met, and Earth-based scientists communicated directly with the orbiting space crew who performed their experiments, collected data immediately, and offered directions for the experiments. Table 3–26 list the characteristics of this mission.

STS 41-B

The primary goal of STS 41-B was to deploy into orbit two commercial communications satellites—Western Union's Westar VI and the Indonesian Palapa-B2. (Failure of the PAM-D rocket motors left both satellites in radical low-Earth orbits.) The crew devoted the remainder of STS 41-B to a series of rendezvous maneuvers using an inflatable balloon as the target, the test flights of two Manned Maneuvering Units (Figure 3–15), and the checkout of equipment and procedures in preparation for *Challenger*'s flight (41-C) in April, which would be the Solar Maximum satellite repair mission.

Commander Vance D. Brand led the five-person crew for this mission. He had previously commanded the first operational flight of the Space Shuttle, STS-5. The other crew members, pilot Robert L. "Hoot" Gibson and three mission specialists (Bruce McCandless II, Ronald E. McNair, and Robert L. Stewart), flew in space for the first time.

This mission featured the first untethered spacewalks. Gas-powered backpacks were used to demonstrate spacewalk techniques important for the successful retrieval and repair of the disabled Solar Maximum spacecraft. The crew members also tested several pieces of specialized equipment during the two five-hour EVAs. The Manipulator Foot Restraint, a portable workstation, was attached to the end of and maneuvered by the

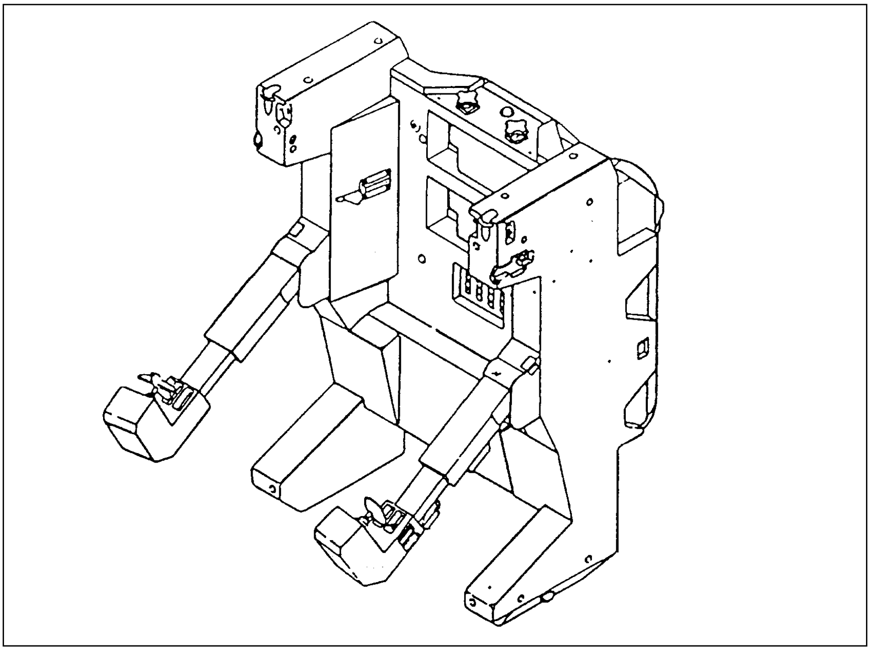

Figure 3–15. Manned Maneuvering Unit

RMS arm. Attached to the foot restraint, an astronaut could use the robot arm as a space-age "cherry picker" to reach and work on various areas of a satellite.

The RMS, just over fifteen meters long and built for the Space Shuttle by the National Research Council of Canada, was to be used to deploy the SPAS as a target for Manned Maneuvering Unit-equipped astronauts to perform docking maneuvers. However, the SPAS remained in the payload bay because of an electrical problem with the RMS. SPAS was to be used as a simulated Solar Maximum satellite. The astronauts were to replace electrical connectors attached to the SPAS during one of the spacewalks to verify procedures that astronauts would perform on the actual repair mission. The Manned Maneuvering Unit-equipped astronauts were also to attempt to dock with the pallet satellite, thereby simulating maneuvers needed to rendezvous, dock, and stabilize the Solar Maximum satellite.

The crew members conducted two days of rendezvous activities using a target balloon (Integrated Rendezvous Target) to evaluate the navigational ability of *Challenger*'s on-board systems, as well as the interaction among the spacecraft, flight crew, and ground control. The activities obtained data from *Challenger*'s various sensors (the rendezvous radar, star tracker, and crew optical alignment sight) required for rendezvous and exercised the navigation and maneuvering capabilities of the on-board software. The rendezvous occurred by maneuvering the orbiter to within 244 meters of its target from a starting distance of approximately 193.1 kilometers. In the process, sensors gathered additional performance data.

This mission initiated the new Shuttle numbering system in which the first numeral stood for the year, the second for the launch site (1 for Kennedy, 2 for Vandenberg Air Force Base), and the letter for the original order of the assignment. The mission characteristics are listed in Table 3–27.

STS 41-C

STS 41-C launched *Challenger* into its highest orbit yet so it could rendezvous with the wobbling, solar flare-studying Solar Maximum satellite, which had been launched in February 1980. Its liftoff from Launch Complex 39's Pad A was the first to use a "direct insertion" ascent technique that put the Space Shuttle into an elliptical orbit with a high point of about 461.8 kilometers and an inclination to the equator of twenty-eight and a half degrees.

On the eleventh Shuttle flight, *Challenger*'s five-person crew successfully performed the first on-orbit repair of a crippled satellite. After failed rescue attempts early in the mission, the robot arm hauled the Solar Max into the cargo bay on the fifth day of the mission (Figure 3–16). *Challenger* then served as an orbiting service station for the astronauts, using the Manned Maneuvering Unit, to repair the satellite's fine-pointing system and to replace the attitude control system and coronagraph/polarimeter electronics box during two six-hour spacewalks.

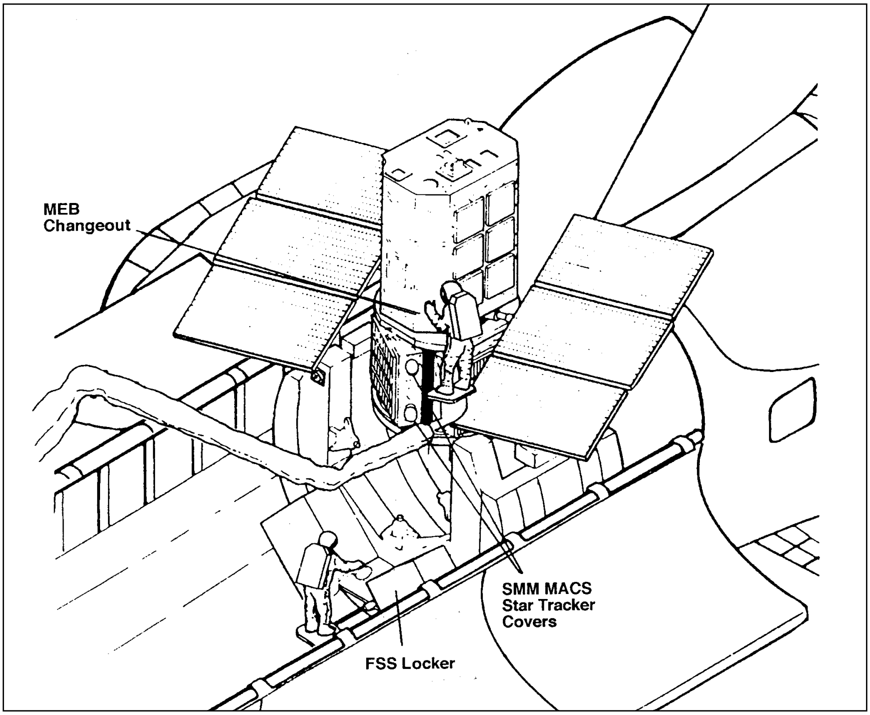

Figure 3–16. Solar Max On-Orbit Berthed Configuration

The robot arm then returned the Solar Max to orbit to continue its study of the violent nature of the Sun's solar activity and its effects on Earth. The successful in-orbit repair demonstrated the STS capability of "in-space" payload processing, which would be exploited on future missions.

Challenger's RMS released the Long Duration Exposure Facility into orbit on this mission (Figure 3–17). Carrying fifty-seven diverse, passive experiments on this mission, it was to be left in space for approximately one year but was left in space for almost six years before being retrieved by STS-32 in January 1990.

Cinema 360 made its second flight, mounted in the cargo bay. The 35mm movie camera recorded the Solar Max rescue mission. A second film camera, IMAX, flew on the Shuttle to record the event on 70mm film designed for projection on very large screens. Table 3–28 contains the details of this mission.

STS 41-D

Discovery made its inaugural flight on this mission, the twelfth flight in the Space Shuttle program. The mission included a combination cargo from some of the payloads originally manifested to fly on STS 41-D and STS 41-F. The decision to remanifest followed the aborted launch of *Discovery* on June 26 and provided for a minimum disruption to the launch schedule.

Failures of the PAM on earlier missions prompted an exhaustive examination of production practices by the NASA-industry team. This team established new test criteria for qualifying the rocket motors. The new testing procedures proved satisfactory when the Shuttle successfully deployed two communications satellites equipped with PAMs, SBS-4 and Telstar 3-C, into precise geosynchronous transfer orbits. A third satellite, Syncom IV-2 (also called Leasat-2), was equipped with a unique upper

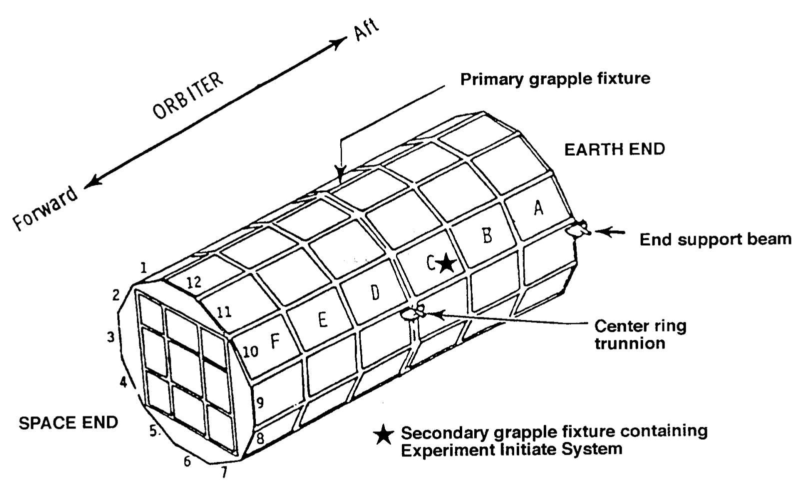

Figure 3–17. Long Duration Exposure Facility Configuration

stage. This satellite was the first built especially for launch from the Shuttle.

NASA's Office of Aeronautics and Space Technology (OAST) sponsored this mission, designated OAST-1. Details of this mission are located in Chapter 3, "Aeronautics and Space Research and Technology," in Volume VI of the *NASA Historical Data Book.* Payload specialist Charles Walker, a McDonnell Douglas employee, was the first commercial payload specialist assigned by NASA to a Shuttle crew. At 21,319.2 kilograms, this mission had the heaviest payload to date. Details of STS 41-D are in Table 3–29.

STS 41-G

This mission was the first with seven crew members and featured the first flight of a Canadian payload specialist, the first to include two women, the first spacewalk by an American woman (Sally Ride), the first crew member to fly a fourth Space Shuttle mission, the first demonstration of a satellite refueling technique in space, and the first flight with a reentry profile crossing the eastern United States. OSTA-3 was the primary payload and was the second in a series of Shuttle payloads that carried experiments to take measurements of Earth. Details of the payload can be found in Chapter 2, "Space Applications," in Volume VI of the *NASA Historical Data Book.*

This mission deployed the Earth Radiation Budget Satellite less than nine hours into flight. This satellite was the first of three planned sets of orbiting instruments in the Earth Radiation Budget Experiment. Overall, the program aimed to measure the amount of energy received from the Sun and reradiated into space and the seasonal movement of energy from the tropics to the poles.

The Orbital Refueling System experiment demonstrated the possibility of refueling satellites in orbit. This experiment required spacesuited astronauts working in the cargo bay to attach a hydrazine servicing tool, already connected to a portable fuel tank, to a simulated satellite panel. After leak checks, the astronauts returned to the orbiter cabin, and the actual movement of hydrazine from tank to tank was controlled from the flight deck. Details of this mission are in Table 3–30.

STS 51-A

This mission deployed two satellites—the Canadian communications satellite Telesat H (Anik-D2) and the Hughes Syncom IV-1 (Leasat-1) communications satellite—both destined for geosynchronous orbit. The crew also retrieved two satellites, Palapa B-2 and Westar 6, deployed during STS 41-B in February 1984. Astronauts Joseph P. Allen and Dale A. Gardner retrieved the two malfunctioning satellites during a spacewalk.

Discovery carried the 3-M Company's Diffusive Mixing of Organic Solutions experiment in the mid-deck. This was the first attempt to grow organic crystals in a microgravity environment. Figure 3–18 shows the STS 51-A cargo configuration, and Table 3–31 lists the mission's characteristics.

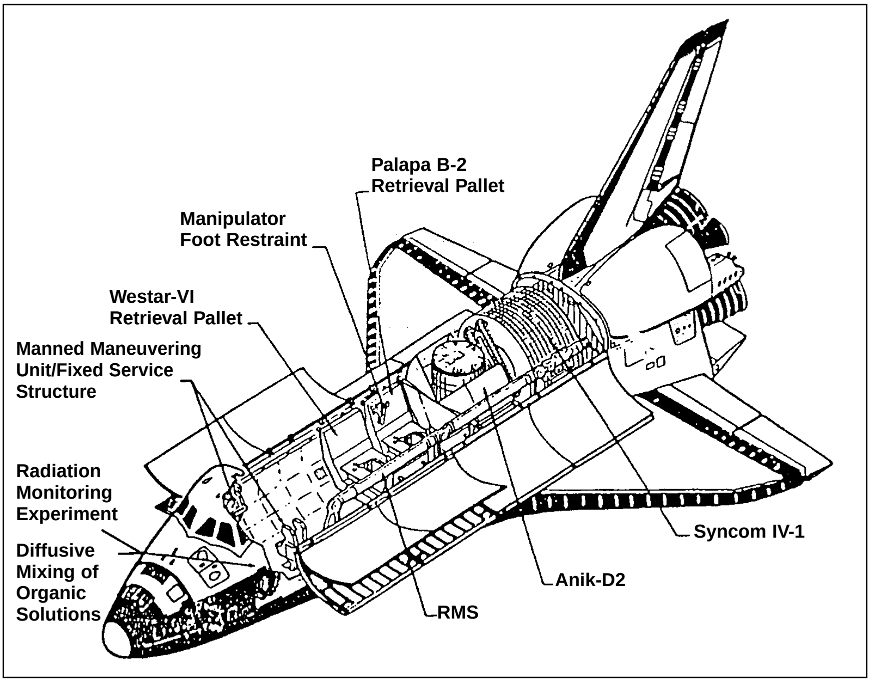

Figure 3–18. STS 51-A Cargo Configuration

STS 51-C

STS 51-C was the first mission dedicated to DOD. A U.S. Air Force inertial upper stage booster was deployed and met the mission objectives.

The Aggregation of Red Cells mid-deck payload tested the capability of NASA's Ames Research Center apparatus to study some characteristics of blood and their disease dependencies under microgravity conditions. NASA's Microgravity Science and Applications Division of the Office of Space Science and Applications sponsored this experiment, which was a cooperative effort between NASA and the Department of Science and Technology of the government of Australia. For details of this mission, see Table 3–32.

STS 51-D

STS 51-D deployed the Telesat-1 (Anik C-1) communications satellite attached to PAM-D motor. The Syncom IV-3 (also called Leasat-3) was also deployed, but the spacecraft sequencer failed to initiate antenna deployment, spinup, and ignition of the perigee kick motor. The mission was extended two days to ensure that the sequencer start levers were in the proper position. Astronauts S. David Griggs and Jeffrey A. Hoffman performed a spacewalk to attach "flyswatter" devices to the RMS. Astronaut M. Rhea Seddon engaged the Leasat lever using the RMS, but the postdeployment sequence failed to begin, and the satellite continued to drift in a low-Earth orbit.

This mission also involved the first public official, Senator Jake Garn from Utah, flying on a Space Shuttle mission; Garn carried out a number of medical experiments. The crew members conducted three mid-deck experiments as part of NASA's microgravity science and applications and space science programs: American Flight Echocardiograph, Phase Partitioning Experiment, and Protein Crystal Growth. Another payload was "Toys in Space," an examination of simple toys in a weightless environment, with the results to be made available to students. The mission's characteristics are in Table 3–33.

STS 51-B

The first operational flight of the Spacelab took place on STS 51-B. Spacelab 3 provided a high-quality microgravity environment for delicate materials processing and fluid experiments. (Table 4–46 describes the individual Spacelab 3 experiments.) The primary mission objective was to conduct science, application, and technology investigations (and acquire intrinsic data) that required the low-gravity environment of Earth orbit and an extended-duration, stable vehicle attitude with emphasis on materials processing. The secondary mission objective was to obtain data on research in materials sciences, life sciences, fluid mechanics, atmospheric science, and astronomy. This mission was the first in which a principal investigator flew with his experiment in space.

The NUSAT Get-Away Special satellite was successfully deployed. The Global Low Orbiting Message Relay satellite failed to deploy from its Get-Away Special canister and was returned to Earth. Details of this mission are in Table 3–34.

STS 51-G

During this mission, NASA flew the first French and Arabian payload specialists. The mission's cargo included domestic communications satellites from the United States, Mexico, and Saudi Arabia—all successfully deployed.

STS 51-G also deployed and retrieved the Spartan-1, using the RMS. The Spartan, a free-flyer carrier developed by NASA's Goddard Space Flight Center, could accommodate scientific instruments originally developed for the sounding rocket program. The Spartan "family" of short-duration satellites were designed to minimize operational interfaces with the orbiter and crew. All pointing sequences and satellite control commands were stored aboard the Spartan in a microcomputer controller. All data were recorded on a tape recorder. No command or telemetry link was provided. Once the Spartan satellite completed its observing sequence, it "safed" all systems and placed itself in a stable attitude to permit its retrieval and return to Earth. NASA's Astrophysics Division within the

Office of Space Science and Applications sponsored the Spartan with a scientific instrument on this mission provided by the Naval Research Laboratory. The mission mapped the x-ray emissions from the Perseus Cluster, the nuclear region of the Milky Way galaxy, and the Scorpius X-2.

In addition, the mission conducted a Strategic Defense Initiative experiment called the High Precision Tracking Experiment. STS 51-G included two French biomedical experiments and housed a materials processing furnace named the Automated Directional Solidification Furnace. Further details are in Table 3–35.

STS 51-F

STS 51-F was the third Space Shuttle flight devoted to Spacelab. Spacelab 2 was the second of two design verification test flights required by the Spacelab Verification Flight Test program. (Spacelab 1 flew on STS-9 in 1983.) Its primary mission objectives were to verify the Spacelab system and subsystem performance capabilities and to determine the Spacelab-orbiter and Spacelab-payload interface capabilities. Secondary mission objectives were to obtain scientific and applications data from a multidisciplinary payload and to demonstrate to the user community the broad capability of Spacelab for scientific research. The monitoring of mission activities and a quick-look analysis of data confirmed that the majority of Verification Flight Test functional objectives were properly performed in accordance with the timeline and flight procedures.

NASA developed the Spacelab 2 payload. Its configuration included an igloo attached to a lead pallet, with the instrument point subsystem mounted on it, a two-pallet train, and an experiment special support structure. The instrument point subsystem—a gimbaled platform attached to a pallet that provides precision pointing for experiments requiring greater pointing accuracy and stability than is provided by the orbiter—flew for the first time on Spacelab 2. The Spacelab system supported and accomplished the experiment phase of the mission. The Spacelab 2 experiments are listed in Table 4–47, and the overall mission characteristics are in Table 3–36.

STS 51-I

STS 51-I deployed three communications satellites, ASC-1, Aussat-1, and Syncom IV-4 (Leasat-4) . It also retrieved, repaired, and redeployed Syncom IV-3 (Leasat-3) so that it could be activated from the ground. Astronauts William F. Fisher and James D.A. van Hoften performed two EVAs totaling eleven hours, fifty-one minutes. Part of the time was spent retrieving, repairing, and redeploying the Syncom IV-3, which was originally deployed on STS 51-D.

Physical Vapor Transport of Organic Solids was the second microgravity-based scientific experiment to fly aboard the Space Shuttle. (The first was the Diffusive Mixing of Organic Solutions, which flew on

STS 51-A in November 1984.) Physical Vapor Transport of Organic Solids consisted of nine independent experimental cells housed in an experimental apparatus container mounted on the aft bulkhead in the middeck area. The crew interface was through a handheld keyboard and display terminal. Using this terminal, the crew selected and activated the experiment cells, monitored cell temperatures and power levels, and performed diagnostic tests. Table 3–37 includes the details of STS 51-I.

STS 51-J

STS 51-J was the second Space Shuttle mission dedicated to DOD. *Atlantis* flew for the first time on this mission. Details are in Table 3–38.

STS 61-A

The "Deutschland Spacelab Mission D-1" was the first of a series of dedicated West German missions on the Space Shuttle. The Federal German Aerospace Research Establishment (DFVLR) managed Spacelab D-1 for the German Federal Ministry of Research and Technology. DFVLR provided the payload and was responsible for payload analytical and physical integration and verification, as well as payload operation on orbit. The Spacelab payload was assembled by MBB/ERNO over a five-year period at a cost of about $175 million. The D-1 was used by German and other European universities, research institutes, and industrial enterprises, and it was dedicated to experimental scientific and technological research.

This mission included 75 experiments, most performed more than once (see Chapter 4). These included basic and applied microgravity research in the fields of materials science, life sciences and technology, and communications and navigation. Weightlessness was the common denominator of the experiments carried out aboard Spacelab D-1. Scientific operations were controlled from the German Space Operations Center at Oberpfaffenhofen near Munich.

The mission was conducted in the long module configuration, which featured the Vestibular Sled designed to provide scientists with data on the functional organization of human vestibular and orientation systems. The Global Low Orbiting Message Relay satellite was also deployed from a Get-Away Special canister. Figure 3–19 shows the STS 61-A cargo configuration, and Table 3–39 lists the mission's characteristics.

STS 61-B

Three communications satellites were deployed on this mission: Morelos-B, AUSSAT-2 and Satcom KU-2. The crew members conducted two experiments to test the assembling of erectable structures in space: Experimental Assembly of Structures in Extravehicular Activity and Assembly Concept for Construction of Erectable Space Structure (EASE/ACCESS), shown in Figure 3–20. These experiments required two

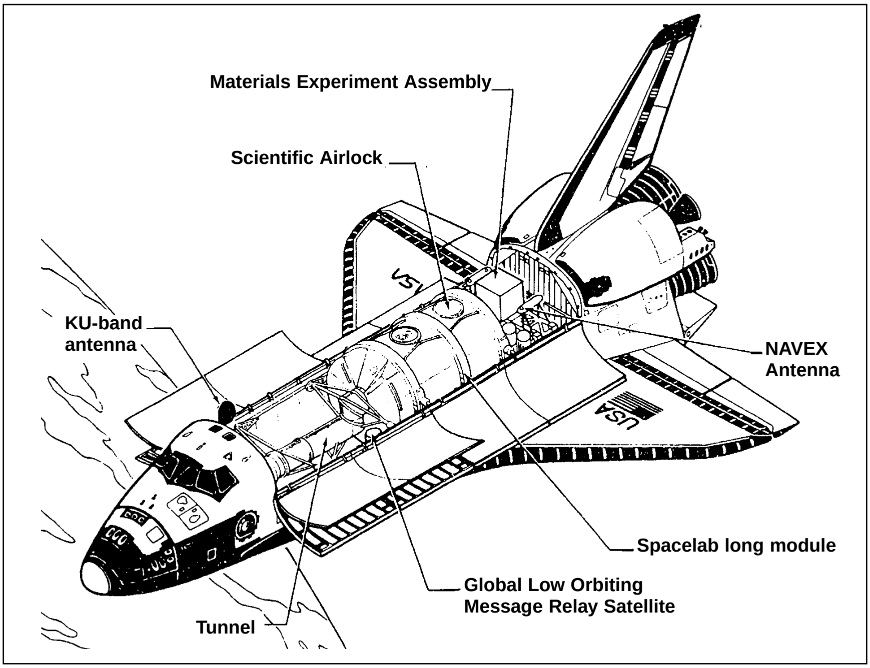

Figure 3–19. STS 61-A Cargo Configuration

spacewalks by Astronauts Sherwood C. Spring and Jerry L. Ross lasting five hours, thirty-two minutes and six hours, thirty-eight minutes, respectively.

This flight featured the first Mexican payload specialist, the first flight of the PAM-D2, the heaviest PAM payload yet (on the Satcom), and the first assembly of a structure in space. Table 3–40 contains STS 61-B's characteristics.

STS 61-C

This mission used the Hitchhiker, a new payload carrier system in the Space Shuttle's payload bay, for the first time. This Hitchhiker flight carrier contained three experiments in the Small Payload Accommodation program: particle analysis cameras to study particle distribution within the Shuttle bay environment, coated mirrors to test the effect of the Shuttle's environment, and a capillary pumped loop heat acquisition and transport system.

Columbia successfully deployed the Satcom KU-1 satellite/PAM-D. However, the Comet Halley Active Monitoring Program experiment, a 35mm camera that was to photograph Comet Halley, did not function properly because of battery problems. This mission also carried Materials Science Laboratory-2 (MSL-2), whose configuration is shown in Figure 3–21.

Franklin R. Chang-Diaz was the first Hispanic American to journey into space. He produced a videotape in Spanish for live distribution to

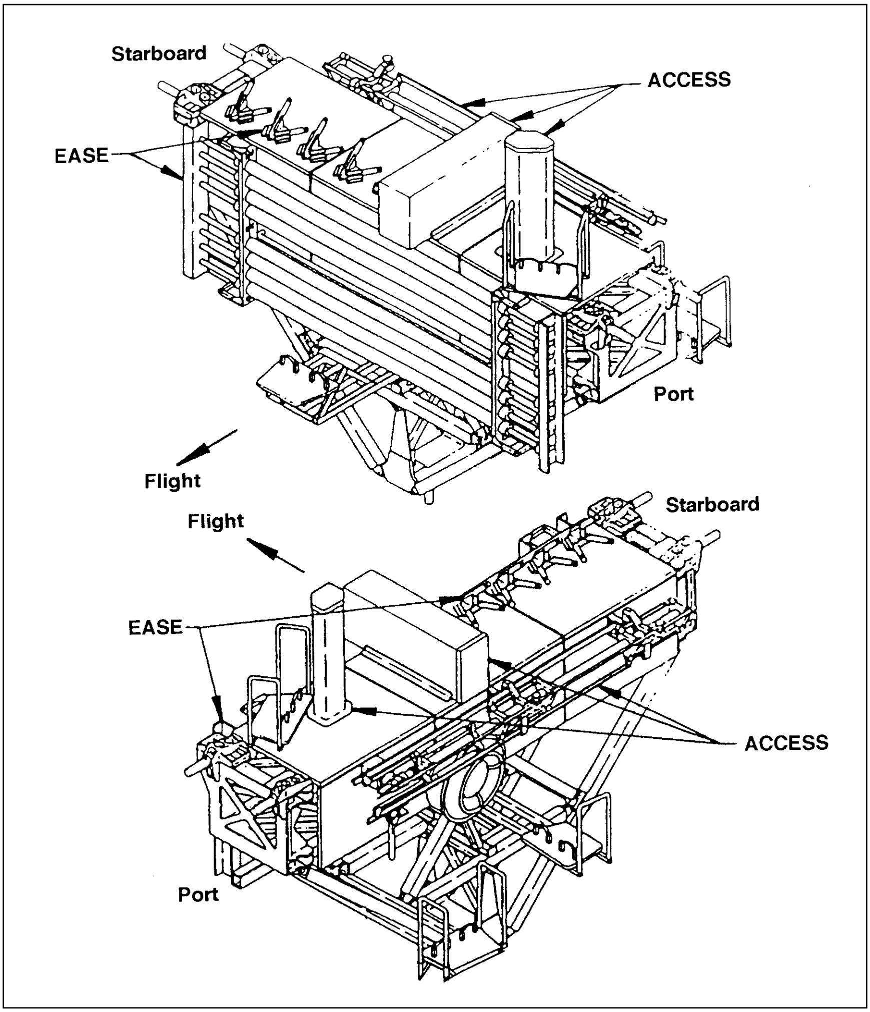

Figure 3–20. EASE/ACCESS Configuration

audiences in the United States and Latin America via the NASA Select television circuit. Details of this mission are in Table 3–41.

STS 51-L

The planned objectives of STS 51-L were the deployment of TDRS-2 and the flying of Shuttle-Pointed Tool for Astronomy (SPARTAN-203)/Halley's Comet Experiment Deployable, a free-flying module designed to observe the tail and coma of Halley's comet with two ultraviolet spectrometers and two cameras. Other cargo included the Fluid Dynamics Experiment, the Comet Halley Active Monitoring Program experiment, the Phase Partitioning Experiment, three SSIP experiments, and a set of lessons for the Teacher in Space Project.

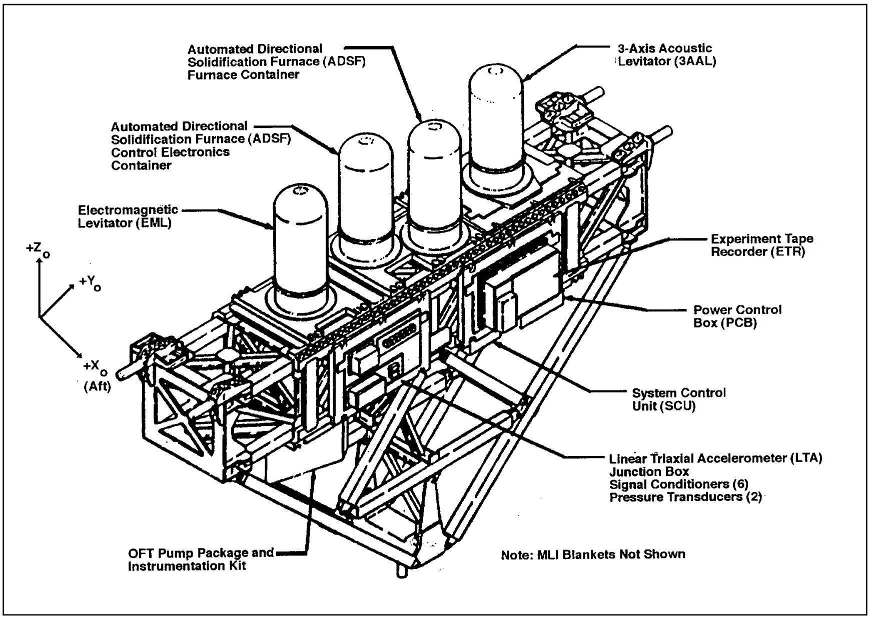

Figure 3–21. Integrated MSL-2 Payload

See the following major section on the *Challenger* accident for detailed information about this mission. STS 51-L's characteristics are listed in Table 3–42.

STS-26

This mission marked the resumption of Space Shuttle flights after the 1986 STS 51-L accident. The primary objective was to deliver TDRS-3 to orbit (Figure 3–22). Meeting this objective, the satellite was boosted to geosynchronous orbit by its inertial upper stage. TDRS-3 was the third TDRS advanced communications spacecraft to be launched from the Shuttle. (TDRS-1 was launched during *Challenger*'s first flight in April 1983. The second, TDRS-2, was lost during the 1986 *Challenger* accident.)

Secondary payloads on *Discovery* included the Physical Vapor Transport of Organic Solids, the Protein Crystal Growth Experiment, the Infrared Communications Flight Experiment, the Aggregation of Red Blood Cells Experiment, the Isoelectric Focusing Experiment, the Mesoscale Lightning Experiment, the Phase Partitioning Experiment, the Earth-Limb Radiance Experiment, the Automated Directional Solidification Furnace, and two SSIP experiments. Special instrumentation was also mounted in the payload bay to record the environment experienced by *Discovery* during the mission. The Orbiter Experiments Autonomous Supporting Instrumentation System-1 (OASIS-1) collected and recorded a variety of environmental measurements during the orbiter's in-flight phases. The data were used to study the effects on the

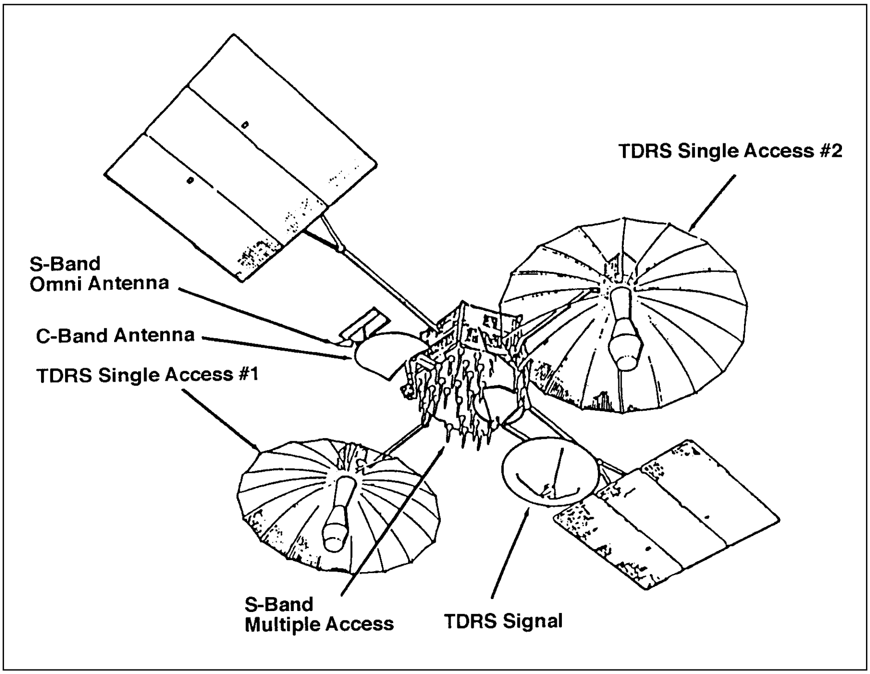

Figure 3–22. Tracking and Data Relay Satellite On-Orbit Configuration

orbiter of temperature, pressure, vibration, sound, acceleration, stress, and strain.

See the section below on the *Challenger* accident and subsequent return to space for information on changes to the Space Shuttle implemented for this mission. STS-26's characteristics are listed in Table 3–43.

STS-27

This was the third STS mission dedicated to DOD. Details of STS-27 are listed in Table 3–44.

The Challenger Accident and Return to Flight

Until the explosion that ended the STS 51-L mission on January 28, 1986, few had been aware of the flaws in the various systems and operations connected with the Space Shuttle. The investigations that followed the accident, which interrupted the program for more than two years, disclosed that long-standing conditions and practices had caused the accident. The following section focuses on the activities of the commission that investigated the explosion, the findings of the various investigations that revealed problems with the Shuttle system in general and with *Challenger* in particular, and the changes that took place in the Shuttle program as a result of the investigations.

The following documents have provided most of the data for this section, and they provide a fascinating look at the events surrounding the accident. The reader might consult them for additional insight about this part of NASA history.

- *STS 51-L Data and Design Analysis Task Force—Historical Summary,* June 1986
- *Report of the Presidential Commission on the Space Shuttle Challenger Accident, Vol. I–IV,* June 6, 1986
- *Report to the President—Actions to Implement the Recommendations of the Presidential Commission on the Space Shuttle Challenger Accident,* July 14, 1986
- "Statement by Dr. James Fletcher," NASA administrator, regarding revised Shuttle manifest, October 3, 1986
- *Report to the President—Implementation of the Recommendations of the Presidential Commission on the Space Shuttle Challenger Accident,* June 30, 1987

Immediately after the *Challenger* explosion, a series of events began that occupied NASA for the next two years, culminating with the launch of *Discovery* on the STS-26 mission. Table 3–45 summarizes the activities that took place from January 28, 1986, through September 29, 1988, the Shuttle's return to flight.

Presidential Commission

Formation and Activities of the Rogers Commission

On February 3, 1986, President Ronald Reagan appointed an independent commission chaired by William P. Rogers, former secretary of state and attorney general, and composed of persons not connected with the mission to investigate the accident. The commission's mandate was to:

1. Review the circumstances surrounding the accident to establish the probable cause or causes of the accident
2. Develop recommendations for corrective or other action based upon the commission's findings and determinations[6]

Immediately after its establishment, the commission began its investigation and, with the full support of the White House, held public hearings on the facts leading up to the accident.

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[6] *Report at a Glance, Report to the President by the Presidential Commission on the Space Shuttle Challenger Accident* (Washington, DC: U.S. Government Printing Office, 1986), Preface (no page number).

The commission construed its mandate to include recommendations on safety matters that were not necessarily involved in this accident but required attention to make future flights safer. Careful attention was given to concerns expressed by astronauts. However, the commission felt that its mandate did not require a detailed investigation of all aspects of the Space Shuttle program nor a review of budgetary matters. Nor did the commission wish to interfere with or displace Congress in the performance of its duties. Rather, the commission focused its attention on the safety aspects of future flights based on the lessons learned from the investigation, with the objective of returning to safe flight. Congress recognized the desirability of having a single investigation of this accident and agreed to await the commission's findings before deciding what further action it might find necessary.

For the first several days after the accident—possibly because of the trauma resulting from the accident—NASA seemed to be withholding information about the accident from the public. After the commission began its work, and at its suggestion, NASA began releasing much information that helped to reassure the public that all aspects of the accident were being investigated and that the full story was being told in an orderly and thorough manner.

Following the suggestion of the commission, NASA also established several teams of persons not involved with the 51-L launch process to supported the commission and its panels. These NASA teams cooperated with the commission and contributed to what was a comprehensive and complete investigation.

Following their swearing in on February 6, 1986, commission members immediately began a series of hearings during which NASA officials outlined agency procedures covering the Space Shuttle program and the status of NASA's investigation of the accident. On February 10, Dr. Alton G. Keel, Jr., associate director of the Office of Management and Budget, was appointed executive director. Dr. Keel gathered a staff of fifteen experienced investigators from various government agencies and the military services, as well as administrative personnel to support commission activities.

Testimony began on February 10 in a closed session, when the commission began to learn of the troubled history of the solid rocket motor joint and seals. Commission members discovered the first indication that the contractor, Morton Thiokol, initially recommended against the launch on January 27, 1986, the night before the launch of STS 51-L, because of concerns regarding the effects of low temperature on the joint and seal. Additional evidence supplied to the commission on February 13 and 14 provided the first evidence that the solid rocket motor joint and seal might have malfunctioned, initiating the accident. The session on February 14 included NASA and contractor participants who had been involved in the discussion on January 27 about whether to launch *Challenger.* Following that session, Chairman Rogers issued a statement noting that "the process [leading to the launch of *Challenger*] may have been flawed" and that NASA's Acting

Administrator Dr. William Graham had been asked “not to include on the investigating teams at NASA, persons involved in that process.”[7]

The commission itself thus assumed the role of investigators and divided itself into four investigative panels:

1. Development and Production, responsible for investigating the acquisition and test and evaluation processes for Space Shuttle elements
2. Pre-Launch Activities, responsible for assessing the Shuttle system processing, launch readiness process, and prelaunch security
3. Mission Planning and Operations, responsible for investigating mission planning and operations, schedule pressures, and crew safety areas
4. Accident Analysis, charged with analyzing the accident data and developing both an anomaly tree and accident scenarios

After the panels were finalized and the new approach described before Congress, the working groups went to the Marshall Space Flight Center, the Kennedy Space Center, and Morton Thiokol to begin analyzing data relating to the accident.

A series of public hearings on February 25, 26, and 27 presented additional information about the launch decision obtained from testimony by Thiokol, Rockwell, and NASA officials. At that time, details about the history of problems with the then-suspect solid rocket motor joints and seals also began emerging and focused the commission’s attention on the need to document fully the extent of knowledge and awareness about the problems within both Thiokol and NASA.

Following these hearings, separate panels conducted much of the commission’s investigative efforts in parallel with full commission hearings. Panel members made numerous trips to Kennedy, Marshall, the Johnson Space Center, and Thiokol facilities in Utah to hold interviews and gather and analyze data relating to their panels’ respective responsibilities.

At the same time, a general investigative staff held a series of individual interviews to document fully the teleconference between NASA and Thiokol officials the night before the launch; the history of joint design and O-ring problems; NASA safety, reliability, and quality assurance functions; and the assembly of the right solid rocket booster for STS 51-L. Subsequent investigations by this group were directed toward the effectiveness of NASA’s organizational structure, particularly the Shuttle program structure, and allegations that there had been external pressure on NASA to launch on January 28.

Members of the commission and its staff interviewed more than 160 individuals and held more than thirty-five formal panel investigations, which generated almost 12,000 pages of transcript. Almost 6,300 documents, totaling more than 122,000 pages, and hundreds of

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[7] *Ibid.,* Appendix A, Commission Activities, p. 206.

photographs were examined and became part of the commission's permanent data base and archives. These sessions and all the data gathered added to the 2,800 pages of hearing transcripts generated by the commission in both closed and open sessions.

In addition to the work of the commission and its staff, more than 1,300 employees from all NASA facilities were involved in the investigation and were supported by more than 1,600 people from other government agencies and more than 3,100 from NASA's contractor organizations. Particularly significant were the activities of the military, the Coast Guard, and the National Transportation Safety Board in the salvage and analysis of the Shuttle wreckage.

Description of the Accident

The flight of *Challenger* on STS 51-L began at 11:38 a.m., Eastern Standard Time, on January 28, 1986. It ended 73 seconds later with the explosion and breakup of the vehicle. All seven members of the crew were killed. They were Francis R. Scobee, commander; Michael J. Smith, pilot; mission specialists Judith A. Resnik, Ellison Onizuka, and Ronald E. McNair; and payload specialists Gregory Jarvis of Hughes Aircraft and S. Christa McAuliffe, a New Hampshire teacher—the first Space Shuttle passenger/observer participating in the NASA Teacher in Space Program. She had planned to teach lessons during live television transmissions.

The primary cargo was the second TDRS. Also on board was a SPARTAN free-flying module that was to observe Halley's comet.

The commission determined the sequence of flight events during the 73 seconds before the explosion and 37 seconds following the explosion based on visual examination and image enhancement of film from NASA-operated cameras and telemetry data transmitted by the Shuttle to ground stations. Table 3–46 lists this sequence of events.

The launch had been the first from Pad B at Kennedy's Launch Complex 39. The flight had been scheduled six times earlier but had been delayed because of technical problems and bad weather.

Investigation and Findings of the Cause of the Accident

Throughout the investigation, the commission focused on three critical questions:

1. What circumstances surrounding mission 51-L contributed to the catastrophic termination of that flight in contrast to twenty-four successful flights preceding it?
2. What evidence pointed to the right solid rocket booster as the source of the accident as opposed to other elements of the Space Shuttle?
3. Finally, what was the mechanism of failure?

Using mission data, subsequently completed tests and analyses, and recovered wreckage, the commission identified all possible faults that could originate in the respective flight elements of the Space Shuttle that might have led to loss of *Challenger.* The commission examined the launch pad, the external tank, the Space Shuttle main engines, the orbiter and related equipment, payload/orbiter interfaces, the payload, the solid rocket boosters, and the solid rocket motors. They also examined the possibility of and ruled out sabotage.

The commission eliminated all elements except the right solid rocket motor as a cause of the accident. Four areas related to the functioning of that motor received detailed analysis to determine their part in the accident:

1. Structural loads were evaluated, and the commission determined that these loads were well below the design limit loads and were not considered the cause of the accident.
2. Failure of the case wall (case membrane) was considered, with the conclusion that the assessments did not support a failure that started in the membrane and progressed slowly to the joint or one that started in the membrane and grew rapidly the length of the solid rocket motor segment.
3. Propellant anomalies were considered, with the conclusion that it was improbable that propellant anomalies contributed to the STS 51-L accident.
4. The remaining area relating to the functioning of the right solid rocket motor, the loss of the pressure seal at the case joint, was determined to be the cause of the accident.

The commission released its report and findings on the cause of the accident on June 9, 1986. The consensus of the commission and participating investigative agencies was that the loss of *Challenger* was caused by a failure in the joint between the two lower segments of the right solid rocket motor. The specific failure was the destruction of the seals that were intended to prevent hot gases from leaking through the joint during the propellant burn of the rocket motor. The evidence assembled by the commission indicated that no other element of the Space Shuttle system contributed to this failure.

In arriving at this conclusion, the commission reviewed in detail all available data, reports, and records, directed and supervised numerous tests, analyses, and experiments by NASA, civilian contractors, and various government agencies, and then developed specific scenarios and the range of most probable causative factors. The commission released the following sixteen findings:

1. *A combustion gas leak through the right solid rocket motor aft field joint initiated at or shortly after ignition eventually weakened and/or penetrated the external tank initiating vehicle structural breakup and loss of the Space Shuttle* Challenger *during STS mission 51-L.*

2. *The evidence shows that no other STS 51-L Shuttle element or the payload contributed to the causes of the right solid rocket motor aft field joint combustion gas leak. Sabotage was not a factor.*
3. *Evidence examined in the review of Space Shuttle material, manufacturing, assembly, quality control, and processing on nonconformance reports found no flight hardware shipped to the launch site that fell outside the limits of Shuttle design specifications.*
4. *Launch site activities, including assembly and preparation, from receipt of the flight hardware to launch were generally in accord with established procedures and were not considered a factor in the accident.*
5. *Launch site records show that the right solid rocket motor segments were assembled using approved procedures. However, significant out-of-round conditions existed between the two segments joined at the right solid rocket motor aft field joint (the joint that failed).*
    a. *While the assembly conditions had the potential of generating debris or damage that could cause O-ring seal failure, these were not considered factors in this accident.*
    b. *The diameters of the two solid rocket motor segments had grown as a result of prior use.*
    c. *The growth resulted in a condition at time of launch wherein the maximum gap between the tang and clevis in the region of the joint's O-rings was no more than 0.008 inch (0.2032 millimeter) and the average gap would have been 0.004 inch (0.1016 millimeter).*
    d. *With a tang-to-clevis gap of 0.004 inch (0.1016 millimeter), the O-ring in the joint would be compressed to the extent that it pressed against all three walls of the O-ring retaining channel.*
    e. *The lack of roundness of the segments was such that the smallest tang-to-clevis clearance occurred at the initiation of the assembly operation at positions of 120 degrees and 300 degrees around the circumference of the aft field joint. It is uncertain if this tight condition and the resultant greater compression of the O-rings at these points persisted to the time of launch.*
6. *The ambient temperature at time of launch was 36 degrees F, or 15 degrees lower than the next coldest previous launch.*
    a. *The temperature at the 300-degree position on the right aft field joint circumference was estimated to be 28 degrees plus or minus 5 degrees F. This was the coldest point on the joint.*
    b. *Temperature on the opposite side of the right solid rocket booster facing the sun was estimated to be about 50 degrees F.*
7. *Other joints on the left and right solid rocket boosters experienced similar combinations of tang-to-clevis gap clearance and temperature. It is not known whether these joints experienced distress during the flight of 51-L.*

8. *Experimental evidence indicates that due to several effects associated with the solid rocket booster's ignition and combustion pressures and associated vehicle motions, the gap between the tang and the clevis will open as much as 0.017 and 0.029 inches (0.4318 and 0.7366 millimeters) at the secondary and primary O-rings, respectively.*
   - a. *This opening begins upon ignition, reaches its maximum rate of opening at about 200–300 milliseconds, and is essentially complete at 600 milliseconds when the solid rocket booster reaches its operating pressure.*
   - b. *The external tank and right solid rocket booster are connected by several struts, including one at 310 degrees near the aft field joint that failed. This strut's effect on the joint dynamics is to enhance the opening of the gap between the tang and clevis by about 10–20 percent in the region of 300–320 degrees.*
9. *O-ring resiliency is directly related to its temperature.*
   - a. *A warm O-ring that has been compressed will return to its original shape much quicker than will a cold O-ring when compression is relieved. Thus, a warm O-ring will follow the opening of the tang-to-clevis gap. A cold O-ring may not.*
   - b. *A compressed O-ring at 75 degrees F is five times more responsive in returning to its uncompressed shape than a cold O-ring at 30 degrees F.*
   - c. *As a result it is probable that the O-rings in the right solid booster aft field joint were not following the opening of the gap between the tang and clevis at time of ignition.*
10. *Experiments indicate that the primary mechanism that actuates O-ring sealing is the application of gas pressure to the upstream (high-pressure) side of the O-ring as it sits in its groove or channel.*
   - a. *For this pressure actuation to work most effectively, a space between the O-ring and its upstream channel wall should exist during pressurization.*
   - b. *A tang-to-clevis gap of 0.004 inch (0.1016 millimeter), as probably existed in the failed joint, would have initially compressed the O-ring to the degree that no clearance existed between the O-ring and its upstream channel wall and the other two surfaces of the channel.*
   - c. *At the cold launch temperature experienced, the O-ring would be very slow in returning to its normal rounded shape. It would not follow the opening of the tang-to-clevis gap. It would remain in its compressed position in the O-ring channel and not provide a space between itself and the upstream channel wall. Thus, it is probable the O-ring would not be pressure actuated to seal the gap in time to preclude joint failure due to blow-by and erosion from hot combustion gases.*

11. *The sealing characteristics of the solid rocket booster O-rings are enhanced by timely application of motor pressure.*
    a. *Ideally, motor pressure should be applied to actuate the O-ring and seal the joint prior to significant opening of the tang-to-clevis gap (100 to 200 milliseconds after motor ignition).*
    b. *Experimental evidence indicates that temperature, humidity and other variables in the putty compound used to seal the joint can delay pressure application to the joint by 500 milliseconds or more.*
    c. *This delay in pressure could be a factor in initial joint failure.*
12. *Of 21 launches with ambient temperatures of 61 degrees F or greater, only four showed signs of O-ring thermal distress; i.e., erosion or blow-by and soot. Each of the launches below 61 degrees F resulted in one or more O-rings showing signs of thermal distress.*
    a. *Of these improper joint sealing actions, one-half occurred in the aft field joints, 20 percent in the center field joints, and 30 percent in the upper field joints. The division between left and right solid rocket boosters was roughly equal.*
    b. *Each instance of thermal O-ring distress was accompanied by a leak path in the insulating putty. The leak path connects the rocket's combustion chamber with the O-ring region of the tang and clevis. Joints that actuated without incident may also have had these leak paths.*
13. *There is a possibility that there was water in the clevis of the STS 51-L joints since water was found in the STS-9 joints during a destack operation after exposure to less rainfall than STS 51-L. At time of launch, it was cold enough that water present in the joint would freeze. Tests show that ice in the joint can inhibit proper secondary seal performance.*
14. *A series of puffs of smoke were observed emanating from the 51-L aft field joint area of the right solid rocket booster between 0.678 and 2.500 seconds after ignition of the Shuttle solid rocket motors.*
    a. *The puffs appeared at a frequency of about three puffs per second. This roughly matches the natural structural frequency of the solids at lift off and is reflected in slight cyclic changes of the tang-to-clevis gap opening.*
    b. *The puffs were seen to be moving upward along the surface of the booster above the aft field joint.*
    c. *The smoke was estimated to originate at a circumferential position of between 270 degrees and 315 degrees on the booster aft field joint, emerging from the top of the joint.*
15. *This smoke from the aft field joint at Shuttle lift off was the first sign of the failure of the solid rocket booster O-ring seals on STS 51-L.*
16. *The leak was again clearly evident as a flame at approximately 58 seconds into the flight. It is possible that the leak was continuous but unobservable or non-existent in portions of the intervening period. It is possible in either case that thrust vectoring and normal vehicle response to wind shear as well as planned maneuvers reinitiated*

or magnified the leakage from a degraded seal in the period preceding the observed flames. The estimated position of the flame, centered at a point 307 degrees around the circumference of the aft field joint, was confirmed by the recovery of two fragments of the right solid rocket booster.

a. A small leak could have been present that may have grown to breach the joint in flame at a time on the order of 58 to 60 seconds after lift off.
b. Alternatively, the O-ring gap could have been resealed by deposition of a fragile buildup of aluminum oxide and other combustion debris. This resealed section of the joint could have been disturbed by thrust vectoring, Space Shuttle motion and flight loads inducted by changing winds aloft.
c. The winds aloft caused control actions in the time interval of 32 seconds to 62 seconds into the flight that were typical of the largest values experienced on previous missions.

Conclusion. *In view of the findings, the commission concluded that the cause of the* Challenger *accident was the failure of the pressure seal in the aft field joint of the right solid rocket booster. The failure was due to a faulty design unacceptably sensitive to a number of factors. These factors were the effects of temperature, physical dimensions, the character of materials, the effects of reusability, processing and the reaction of the joint to dynamic loading.*[8]

Contributing Causes of the Accident

In addition to the failure of the pressure seal as the primary cause of the accident, the commission identified a contributing cause of the accident having to do with the decision to launch. The commission concluded that the decision-making process was flawed in several ways. The testimony revealed failures in communication, which resulted in a decision to launch based on incomplete and sometimes misleading information, a conflict between engineering data and management judgments, and a NASA management structure that permitted internal flight safety problems to bypass key Shuttle managers.

The decision to launch concerned two problem areas. One was the low temperature and its effect on the O-ring. The second was the ice that formed on the launch pad. The commission concluded that concerns regarding these issues had either not been communicated adequately to senior management or had not been given sufficient weight by those who made the decision to launch.

O-Ring Concerns. Formal preparations for launch, consisting of the Level I Flight Readiness Review and Certification of Flight Readiness to

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[8] *Ibid.,* Findings, pp. 70–72.

the Level II program manager at the Johnson Space Center, were followed in a procedural sense for STS 51-L. However, the commission concluded that relevant concerns of Level III NASA personnel and element contractors had not been, in critical areas, adequately communicated to the NASA Levels I and II management responsible for the launch. In particular, objections to the launch voiced by Morton Thiokol engineers about the detrimental effect of cold temperatures on the performance of the solid rocket motor joint seal and the degree of concern of Thiokol and the Marshall Space Flight Center about the erosion of the joint seals in prior Shuttle flights, notably STS 51-C and 51-B, were not communicated sufficiently.

Since December 1982, the O-rings had been designated a “Criticality 1” feature of the solid rocket booster design, meaning that component failure without backup could cause a loss of life or vehicle. In July 1985, after a nozzle joint on STS 51-B showed secondary O-ring erosion, indicating that the primary seal failed, a launch constraint was placed on flight STS 51-F and subsequent launches. These constraints had been imposed and regularly waived by the solid rocket booster project manager at Marshall, Lawrence B. Mulloy. Neither the launch constraint, the reason for it, nor the six consecutive waivers prior to STS 51-L were known to Associate Administrator for Space Flight Jesse W. Moore (Level I), Aldrich Arnold, the manager of space transportation programs at the Johnson Space Center (Level II), or James Thomas, the deputy director of launch and landing operations at the Kennedy Space Center at the time of the Flight Readiness Review process for STS 51-L.

In addition, no mention of the O-ring problems appeared in the Certification of Flight Readiness for the solid rocket booster set designated BI026 signed for Thiokol on January 9, 1986, by Joseph Kilminster. Similarly, no mention appeared in the certification endorsement, signed on January 15, 1986, by Kilminster and Mulloy. No mention appeared in the entire chain of readiness reviews for STS 51-L, contrary to testimony by Mulloy, who claimed that concern about the O-ring was “in the Flight Readiness Review record that went all the way to the L-I review.”[9]

On January 27 and through the night to January 28, NASA and contractor personnel debated the wisdom of launching on January 28, in light of the O-ring performance under low temperatures. Table 3–47 presents the chronology of discussions relating to temperature and the decision to launch. Information is based on testimony and documents provided to the commission through February 24, 1986. Except for the time of launch, all times are approximate.

According to the commission, the decision to launch *Challenger* was flawed. Those who made that decision were unaware of the recent history of problems concerning the O-rings and the joints and were unaware

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[9] *Ibid.*, p. 85, from Commission Hearing Transcript, May 2, 1986, pp. 2610–11.

of the initial written recommendation of the contractor advising against the launch at temperatures below 53 degrees F and the continuing opposition of the engineers at Thiokol after management reversed its position. If the decision makers had known all of the facts, it is highly unlikely that they would have decided to launch STS 51-L on January 28, 1986. The commission revealed the following four findings:

1. The commission concluded that there was a serious flaw in the decision-making process leading up to the launch of flight 51-L. A well-structured and managed system emphasizing safety would have flagged the rising doubts about the solid rocket booster joint seal. Had these matters been clearly stated and emphasized in the flight readiness process in terms reflecting the views of most of the Thiokol engineers and at least some of the Marshall engineers, it seems likely that the launch of 51-L might not have occurred when it did.
2. The waiving of launch constraints seems to have been at the expense of flight safety. There was no system that mandated that launch constraints and waivers of launch constraints be considered by all levels of management.
3. The commission noted what seemed to be a propensity of management at Marshall to contain potentially serious problems and to attempt to resolve them internally rather than communicate them forward. This tendency, the commission stated, was contrary to the need for Marshall to function as part of a system working toward successful flight missions, interfacing and communicating with the other parts of the system that worked to the same end.
4. The commission concluded that Thiokol management reversed its position and recommended the launch of 51-L at the urging of Marshall and contrary to the views of its engineers in order to accommodate a major customer.

Ice on the Launch Pad. The commission also found that decision makers did not clearly understand Rockwell's concern that launching was unsafe because of ice on the launch pad and whether Rockwell had indeed recommended the launch. They expressed concern about three aspects of this issue:

1. An analysis of all of the testimony and interviews established that Rockwell's recommendation on launch was ambiguous. The commission found it difficult, as did Aldrich, to conclude that there was a no-launch recommendation. Moreover, all parties were asked specifically to contact Aldrich or other NASA officials after the 9:00 a.m. Mission Management Team meeting and subsequent to the resumption of the countdown.
2. The commission was also concerned about NASA's response to Rockwell's position at the 9:00 a.m. meeting. The commission was not convinced Levels I and II appropriately considered Rockwell's

concern about the ice. However ambiguous as Rockwell's position was, it was clear that Rockwell did tell NASA that the ice was an unknown condition. Given the extent of the ice on the pad, the admitted unknown effect of the solid rocket motor and Space Shuttle main engines' ignition on the ice, as well as the fact that debris striking the orbiter was a potential flight safety hazard, the commission found the decision to launch questionable. In this situation, NASA seemed to be requiring a contractor to prove that it was *not* safe to launch, rather than proving it *was* safe. Nevertheless, the commission determined that the ice was not a cause of the 51-L accident and did not conclude that NASA's decision to launch specifically overrode a no-launch recommendation by an element contractor.

3. The commission concluded that the freeze protection plan for Launch Pad 39-B was inadequate. The commission believed that the severe cold and presence of so much ice on the fixed service structure made it inadvisable to launch and that margins of safety were whittled down too far. Additionally, access to the crew emergency slide wire baskets was hazardous due to icy conditions. Had the crew been required to evacuate the orbiter on the launch pad, they would have been running on an icy surface. The commission believed that the crew should have been told of the condition and that greater consideration should have been given to delaying the launch.

Precursor to the Accident

Earlier events helped set the stage for the conditions that caused the STS 51-L accident. The commission stated that the Space Shuttle's solid rocket booster problem began with the faulty design of its joint and increased as both NASA and contractor management first failed to recognize the problem, then failed to fix it, and finally treated it as an acceptable flight risk.

Morton Thiokol did not accept the implication of tests early in the program that the design had a serious and unanticipated flaw. NASA did not accept the judgment of its engineers that the design was unacceptable, and as the joint problems grew in number and severity, NASA minimized them in management briefings and reports. Thiokol's stated position was that "the condition is not desirable but is acceptable."[10]

Neither Thiokol nor NASA expected the rubber O-rings sealing the joints to be touched by hot gases of motor ignition, much less to be partially burned. However, as tests and then flights confirmed damage to the sealing rings, the reaction by both NASA and Thiokol was to increase the amount of damage considered "acceptable." At no time, the commission found, did management either recommend a redesign of the joint or call for the Shuttle's grounding until the problem was solved.

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[10] *Ibid.*, p. 120, from Report, "STS-3 Through STS-25 Flight Readiness Reviews to Level III Center Board," NASA.

The commission stated that the genesis of the *Challenger* accident—the failure of the joint of the right solid rocket motor—began with decisions made in the design of the joint and in the failure by both Thiokol and NASA's solid rocket booster project office to understand and respond to facts obtained during testing. The commission concluded that neither Thiokol nor NASA responded adequately to internal warnings about the faulty seal design. Furthermore, Thiokol and NASA did not make a timely attempt to develop and verify a new seal after the initial design was shown to be deficient. Neither organization developed a solution to the unexpected occurrences of O-ring erosion and blow-by, even though this problem was experienced frequently during the Shuttle's flight history. Instead, Thiokol and NASA management came to accept erosion and blow-by as unavoidable and an acceptable flight risk. Specifically, the commission found that:

1. The joint test and certification program was inadequate. There was no requirement to configure the qualifications test motor as it would be in flight, and the motors were static-tested in a horizontal position, not in the vertical flight position.
2. Prior to the accident, neither NASA nor Thiokol fully understood the mechanism by which the joint sealing action took place.
3. NASA and Thiokol accepted escalating risk apparently because they "got away with it last time." As Commissioner Richard Feynman observed, the decision making was "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."[11]
4. NASA's system for tracking anomalies for Flight Readiness Reviews failed in that, despite a history of persistent O-ring erosion and blow-by, flight was still permitted. It failed again in the sequence of six consecutive launch constraint waivers prior to 51-L, permitting it to fly without any record of a waiver, or even of an explicit constraint. Tracking and continuing only anomalies that are "outside the data base" of prior flight allowed major problems to be removed from and lost by the reporting system.
5. The O-ring erosion history presented to Level I at NASA Headquarters in August 1985 was sufficiently detailed to require corrective action prior to the next flight.
6. A careful analysis of the flight history of O-ring performance would have revealed the correlation of O-ring damage and low temperature. Neither NASA nor Thiokol carried out such an analysis; consequently, they were unprepared to properly evaluate the risks of launching

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[11] *Ibid.,* p. 148, from Commission Hearing Testimony, April 3, 1986, p. 2469.

the 51-L mission in conditions more extreme than they had encountered before.

NASA's Safety Program

The commission found surprising and disturbing the lack of reference to NASA's safety staff. Individuals who testified before the commission did not mention the quality assurance staff, and no reliability and quality assurance engineer had been asked to participate in the discussions that took place prior to launch.

The commission concluded that "the extensive and redundant safety assurance functions" that had existed "during and after the lunar program to discover any safety problems" had become ineffective between that period and 1986. This loss of effectiveness seriously degraded the checks and balances essential for maintaining flight safety.[12] Although NASA had a safety program in place, communications failures relating to safety procedures did not operate properly during STS 51-L.

On April 3, 1986, Arnold Aldrich, the Space Shuttle program manager, appeared before the commission at a public hearing in Washington, D.C. He described five different communications or organizational failures that affected the launch decision on January 28, 1986. Four of those failures related directly to faults within the safety program: lack of problem reporting requirements, inadequate trend analysis, misrepresentation of criticality, and lack of involvement in critical discussions. A properly staffed, supported, and robust safety organization, he stated, might well have avoided these faults and thus eliminated the communications failures. The commission found that:

1. Reductions in the safety, reliability and quality assurance work force at the Marshall and NASA Headquarters seriously limited capability in those vital functions.
2. Organizational structures at Kennedy and Marshall placed safety, reliability, and quality assurance offices under the supervision of the very organizations and activities whose efforts they are to check.
3. Problem reporting requirements were not concise and failed to get critical information to the proper levels of management.
4. Little or no trend analysis was performed on O-ring erosion and blow-by problems.
5. As the flight rate increased, the Marshall safety, reliability, and quality assurance work force was decreasing, which adversely affected mission safety.
6. Five weeks after the 51-L accident, the criticality of the solid rocket motor field joint had still not been properly documented in the problem reporting system at Marshall.

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[12] *Ibid.,* p. 152.

Pressures on the System

From the Space Shuttle's inception, NASA had advertised that the Shuttle would make space operations "routine and economical." The implication was that the greater annual number of flights, the more routine Shuttle flights would become. Thus, NASA placed heavy emphasis on the schedule. However, one effect of the agency's determination to meet an accelerated flight rate was the dilution of resources available for any one mission. In addition, NASA had difficulty evolving from its single-flight focus to a system that could support an ongoing schedule of flights. Managers forgot in their insistence on proving it operational, the commission stated, that the Shuttle system was still in its early phase. There might not have been enough preparation for what "operational" entailed. For instance, routine and regular postflight maintenance and inspections, spare parts production or acquisition, and software tools and training facilities developed during a test program were not suitable for the high volume of work required in an operational environment. The challenge was to streamline the processes to provide the needed support without compromising quality.

Mission planning requires establishing the manifest, defining the objectives, constraints, and capabilities of the mission, and translating those into hardware, software, and flight procedures. Within each of these major goals is a series of milestones in which managers decide whether to proceed to the next step. Once a decision has been made to go ahead and the activity begun, if a substantial change occurs, it may be necessary to go back and repeat the preceding process. In addition, if one group fails to meet its due date, the delay cascades throughout the system.

The ambitious flight rate meant that less and less time was available for completing each of the steps in the mission planning and preparation process. In addition, a lack of efficient production processing and manifest changes disrupted the production system. In particular, the commission found that manifest changes, which forced repeating certain steps in the production cycle, sometimes severely affected the entire cycle and placed impossible demands on the system.

The commission found that pressures on the STS to launch at an overambitious rate contributed to severe strains on the system. The flight rate did not seem to be based on an assessment of available resources and capabilities and was not modified to accommodate the capacity of the work force. The commission stated that NASA had not provided adequate resources to support its launch schedule and that the system had been strained by the modest nine missions that had launched in 1985.

After the accident, rumors appeared that persons who made the decision to launch might have been subjected to outside pressures to launch. The commission examined these rumors and concluded that the decision to launch was made solely by the appropriate NASA officials without any outside intervention or pressure.[13] The commission listed the following findings:

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[13] *Ibid.,* p. 176.

1. The capabilities of the system were stretched to the limit to support the flight rate in the winter of 1985–86. Projections into the spring and summer of 1986 showed that the system, as it existed, would have been unable to deliver crew training software for scheduled flights by the designated dates. The result would have been an unacceptable compression of the time available for the crews to accomplish their required training.
2. Spare parts were in critically short supply. The Space Shuttle program made a conscious decision to postpone spare parts procurements in favor of budget items of perceived higher priority. The lack of spare parts would likely have limited flight operations in 1986.
3. The stated manifesting policies were not enforced. Numerous late manifest changes (after the cargo integration review) were made to both major payloads and minor payloads throughout the Shuttle program. These changes required additional resources and used existing resources more rapidly. They also adversely affected crew training and the development of procedures for subsequent missions.
4. The scheduled flight rate did not accurately reflect the capabilities and resources.
    - The flight rate was not reduced to accommodate periods of adjustment in the capacity of the work force. No margin existed in the system to accommodate unforeseen hardware problems.
    - Resources were primarily directed toward supporting the flights and thus were inadequate to improve and expand facilities needed to support a higher flight rate.
5. Training simulators may be the limiting factor on the flight rate; the two current simulators cannot train crews for more than twelve to fifteen flights per year.
6. When flights come in rapid succession, current requirements do not ensure that critical anomalies occurring during one flight are identified and addressed appropriately before the next flight.

Other Safety Considerations

During its investigation, the commission examined other safety-related issues that had played no part in the STS 51-L accident but nonetheless might lead to safety problems in the future. These safety-related areas were ascent (including abort capabilities and crew escape options), landing (including weather considerations, orbiter tires and brakes, and choice of a landing site), Shuttle elements other than the solid rocket booster, processing and assembly (including record keeping and inspections), capabilities of Launch Pad 39-B, and involvement of the development contractors.

Ascent. The events of flight 51-L illustrated the dangers of the first stage of a Space Shuttle ascent. The accident also focused attention on orbiter abort capabilities and crew escape. The current abort capabilities, options to improve those capabilities, options for crew escape, and the performance of the range safety system were of particular concern to the commission.

The Shuttle's design capabilities allowed for successful intact mission abort (a survivable landing) on a runway after a single main engine failure. The Shuttle's design specifications did not require that the orbiter be able to manage an intact abort if a second main engine should fail. If two or three main engines failed, the Shuttle would land in water in a contingency abort or ditching. This maneuver was not believed to be survivable because of damage incurred at water impact. In addition, the Shuttle system was not designed to survive a failure of the solid rocket boosters. Furthermore, although technically the orbiter had the capability to separate from the external tank during the first stage, analysis had shown that if it were attempted while the solid rocket boosters were still thrusting, the orbiter would "hang up" on its aft attach points and pitch violently, with probable loss of the orbiter and crew. This "fast separation" would provide a useful means of escape during first stage only if solid rocket booster thrust could be terminated first.[14]

Studies identified no viable means of crew escape during first-stage ascent. The commission supported the further study of escape options. However, it concluded that no corrective actions could have been taken that would have saved the *Challenger*'s flight crew.

Landing. The Space Shuttle's entry and landing formed another risky and complicated part of a mission. Because the crew could not divert to an alternate landing site after entry, the landing decision must be both timely and accurate. In addition, the landing gear, including the wheels, tires, and brakes, must function properly.

Although the orbiter tires were designed to support a landing up to 108,864 kilograms at 416.7 kilometers per hour with thirty-seven kilometers per hour of crosswind and have successfully passed testing programs, they had shown excessive wear during landings at Kennedy, especially when crosswinds were involved. The tires were rated as Criticality 1 because the loss of a single tire could cause a loss of control and a subsequent loss of the vehicle and crew. Because actual wear on a runway did not correspond to test results, NASA directed testing to examine actual tire, wheel, and strut failure to better understand this failure case.

The commission found that the brakes used on the orbiter were known to have little or no margin, because they were designed based on the orbiter's design weight. As the actual orbiter's weight grew, the brakes were not redesigned; rather, the runway length was extended. Actual flight experience had shown brake damage on most flights, which required that special crew procedures be developed to ensure successful braking.

The original Shuttle plan called for routine landings at Kennedy to minimize turnaround time and cost per flight and to provide efficient operations for both the Shuttle system and the cargo elements. While those considerations remained important, concerns such as the performance of the orbiter tires and brakes and the difficulty of accurate weather prediction in Florida had called the plan into question.

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[14] *Ibid.,* p. 180.

When the Shuttle landed at Edwards Air Force Base, approximately six days are added to the turnaround time. The commission stated that although there were valid programmatic reasons for landing the Shuttle routinely at Kennedy, the demanding nature of landing and the impact of weather conditions might dictate the prudence of using Edwards on a regular basis for landing. The cost associated with regular scheduled landing and turnaround operations at Edwards was thus a necessary program cost. Decisions governing Shuttle operations, the commission stated, must coincide with the philosophy that unnecessary risks have to be eliminated.

Shuttle Elements. The Space Shuttle main engine teams at Marshall and Rocketdyne had developed engines that achieved their performance goals and performed extremely well. Nevertheless, according to the commission, the main engines continued to be highly complex and critical components of the Shuttle, with an element of risk principally because important components of the engines degraded more rapidly with flight use than anticipated. Both NASA and Rocketdyne took steps to contain that risk. An important aspect of the main engine program was the extensive "hot fire" ground tests. Unfortunately, the vitality of the test program, the commission found, was reduced because of budgetary constraints.

The number of engine test firings per month had decreased over the two years prior to STS 51-L. Yet this test program had not demonstrated the limits of engine operation parameters or included tests over the full operating envelope to show full engine capability. In addition, tests had not yet been deliberately conducted to the point of failure to determine actual engine operating margins.

The commission also identified one serious potential failure mode related to the disconnect valves between the orbiter and the external tank.

Processing and Assembly. During the processing and assembly of the elements of flight 51-L, the commission found various problems that could bear on the safety of future flights. These involved structural inspections in which waivers were granted on sixty of the 146 required orbiter structural inspections, errors in the recordkeeping for the Space Shuttle main engine/main propulsion system and the orbiter, areas in which items called for by the Operational Maintenance Requirements and Specifications Document were not met and were not formally waived or excepted, the Shuttle processing contractor's policy of using "designated verifiers" to supplement quality assurance personnel, and the lack of accidental damage reporting because technicians were concerned about losing their jobs.

Launch Pad 39-B. The damage to the launch pad from the explosion was considered to be normal or minor, with three exceptions: the loss of the springs and plungers of the booster hold-down posts, the failure of the gaseous hydrogen vent arm to latch, and the loss of bricks from the flame trench.

Involvement of Development Contractors. The commission determined that, although NASA considered the Shuttle program to be operational, it was "clearly a developmental program and must be treated as such by NASA."[15] Using procedures accepted by the transportation industry was only partly valid because each mission expanded system and performance requirements. The Shuttle's developmental status demanded that both NASA and all its contractors maintain a high level of in-house experience and technical ability. The demands of the developmental aspects of the program required:

1. Maintaining a significant engineering design and development capability among the Shuttle contractors and an ongoing engineering capability within NASA
2. Maintaining an active analytical capability so that the evolving capabilities of the Shuttle can be matched to the demands on the Shuttle

Recommendations of the Presidential Commission

The commission unanimously adopted nine recommendations, which they submitted to President Reagan. They also urged NASA's administrator to submit a report to the president on the progress NASA made in implementing the recommendations. These recommendations are restated below.

I

Design. *The faulty solid rocket motor joint and seal must be changed. This could be a new design eliminating the joint or a redesign of the current joint and seal. No design options should be prematurely precluded because of schedule, cost or reliance on existing hardware. All solid rocket motor joints should satisfy the following requirements:*

- *The joints should be fully understood, tested and verified.*
- *The integrity of the structure and of the seals of all joints should be not less than that of the case walls throughout the design envelope.*
- *The integrity of the joints should be insensitive to:*
    - *Dimensional tolerances.*
    - *Transportation and handling.*
    - *Assembly procedures.*
    - *Inspection and test procedures.*
    - *Environmental effects.*
    - *Internal case operating pressure.*
    - *Recovery and reuse effects.*
    - *Flight and water impact loads.*
- *The certification of the new design should include:*
    - *Tests which duplicate the actual launch configuration as closely as possible.*

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[15] *Ibid.,* p. 194.

  - *Tests over the full range of operating conditions, including temperature.*
- *Full consideration should be given to conducting static firings of the exact flight configuration in a vertical attitude.*

Independent Oversight. *The administrator of NASA should request the National Research Council to form an independent solid rocket motor design oversight committee to implement the commission's design recommendations and oversee the design effort. This committee should:*

- *Review and evaluate certification requirements.*
- *Provide technical oversight of the design, test program and certification.*
- *Report to the administrator of NASA on the adequacy of the design and make appropriate recommendations.*

II

Shuttle Management Structure. *The Shuttle Program Structure should be reviewed. The project managers for the various elements of the Shuttle program felt more accountable to their center management than to the Shuttle program organization. Shuttle element funding, work package definition, and vital program information frequently bypass the National STS (Shuttle) Program Manager.*

A redefinition of the Program Manager's responsibility is essential. This redefinition should give the Program Manager the requisite authority for all ongoing STS operations. Program funding and all Shuttle Program work at the centers should be placed clearly under the Program Manager's authority.

Astronauts in Management. *The commission observes that there appears to be a departure from the philosophy of the 1960s and 1970s relating to the use of astronauts in management positions. These individuals brought to their positions flight experience and a keen appreciation of operations and flight safety.*

- *NASA should encourage the transition of qualified astronauts into agency management positions.*
- *The function of the Flight Crew Operations director should be elevated in the NASA organization structure.*

Shuttle Safety Panel. *NASA should establish an STS Safety Advisory Panel reporting to the STS Program Manager. The Charter of this panel should include Shuttle operational issues, launch commit criteria, flight rules, flight readiness and risk management. The panel should include representation from the safety organization, mission operations, and the astronaut office.*

III

Criticality Review and Hazard Analysis. *NASA and the primary Shuttle contractors should review all Criticality 1, 1R, 2, and 2R items and hazard analyses. This review should identify those items that must be improved prior to flight to ensure mission safety. An Audit Panel, appointed by the National Research Council, should verify the adequacy of the effort and report directly to the administrator of NASA.*

IV

Safety Organization. *NASA should establish an Office of Safety, Reliability and Quality Assurance to be headed by an associate administrator, reporting directly to the NASA administrator. It would have direct authority for safety, reliability, and quality assurance throughout the agency. The office should be assigned the work force to ensure adequate oversight of its functions and should be independent of other NASA functional and program responsibilities.*

The responsibilities of this office should include:

- *The safety, reliability and quality assurance functions as they relate to all NASA activities and programs.*
- *Direction of reporting and documentation of problems, problem resolution and trends associated with flight safety.*

V

Improved Communications. *The commission found that Marshall Space Flight Center project managers, because of a tendency at Marshall to management isolation, failed to provide full and timely information bearing on the safety of flight 51-L to other vital elements of Shuttle program management.*

- *NASA should take energetic steps to eliminate this tendency at Marshall Space Flight Center, whether by changes of personnel, organization, indoctrination or all three.*
- *A policy should be developed which governs the imposition and removal of Shuttle launch constraints.*
- *Flight Readiness Reviews and Mission Management Team meetings should be recorded.*
- *The flight crew commander, or a designated representative, should attend the Flight Readiness Review, participate in acceptance of the vehicle for flight, and certify that the crew is properly prepared for flight.*

VI

Landing Safety. *NASA must take actions to improve landing safety:*

- *The tire, brake and nose wheel steering systems must be improved. These systems do not have sufficient safety margin, particularly at abort landing sites.*
- *The specific conditions under which planned landings at Kennedy would be acceptable should be determined. Criteria must be established for tires, brakes and nose wheel steering. Until the systems meet those criteria in high fidelity testing that is verified at Edwards, landing at Kennedy should not be planned.*
- *Committing to a specific landing site requires that landing area weather be forecast more than an hour in advance. During unpredictable weather periods at Kennedy, program officials should plan on Edwards landings. Increased landings at Edwards may necessitate a dual ferry capability.*

VII

Launch Abort and Crew Escape. *The Shuttle program management considered first-stage abort options and crew escape options several times during the history of the program, but because of limited utility, technical unfeasibility, or program cost and schedule, no systems were implemented. The commission recommends that NASA:*

- *Make all efforts to provide a crew escape system for use during controlled gliding flight.*
- *Make every effort to increase the range of flight conditions under which an emergency runway landing can be successfully conducted in the event that two or three main engines fail early in ascent.*

VIII

Flight Rate. *The nation’s reliance on the Shuttle as its principal space launch capability created a relentless pressure on NASA to increase the flight rate. Such reliance on a single launch capability should be avoided in the future.*

NASA must establish a flight rate that is consistent with its resources. A firm payload assignment policy should be established. The policy should include rigorous controls on cargo manifest changes to limit the pressures such changes exert on schedules and crew training.

IX

Maintenance Safeguards. *Installation, test, and maintenance procedures must be especially rigorous for Space Shuttle items designated*

Criticality 1. NASA should establish a system of analyzing and reporting performance trends of such items.

Maintenance procedures for such items should be specified in the Critical Items List, especially for those such as the liquid-fueled main engines, which require unstinting maintenance and overhaul.

With regard to the orbiters, NASA should:

- *Develop and execute a comprehensive maintenance inspection plan.*
- *Perform periodic structural inspections when scheduled and not permit them to be waived.*
- *Restore and support the maintenance and spare parts programs, and stop the practice of removing parts from one orbiter to supply another.*[16]

Concluding Thought

The commission urged that NASA continue to receive the support of the administration and the nation. The agency constitutes a national resource that plays a critical role in space exploration and development. It also provides a symbol of national pride and technological leadership.

The commission applauded NASA's spectacular achievements of the past and anticipated impressive achievements in the future. The findings and recommendations presented in this report were intended to contribute to future NASA successes that the nation both expects and requires as the 21st century approaches.

STS 51-L Investigations and Actions by NASA

Safely Returning the Shuttle to Flight Status

While the Presidential Commission investigated the accident, NASA also conducted an investigation to determine strategies and major actions for safely returning to flight status. In a March 24, 1986, memorandum, Associate Administrator for Space Flight Richard H. Truly defined NASA's comprehensive strategy and major actions that would allow for resuming the Space Shuttle's schedule. He stated that NASA Headquarters (particularly the Office of Space Flight), the Office of Space Flight centers, the NSTS program organization, and its various contractors would use the guidance supplied in the memo to proceed with "the realistic, practical actions necessary to return to the NSTS flight schedule with emphasis on flight safety."[17] In his memo, Truly focused on three areas: actions required prior to the next flight, first flight/first year operations, and development of sustainable safe flight rate.

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[16] *Ibid.,* p. 196.

[17] Richard H. Truly, NASA Memorandum, "Strategy for Safely Returning the Space Shuttle to Flight Status," March 24, 1986.

Actions Required Prior to the Next Flight. Truly directed NASA to take the following steps before the return to flight:

- Reassess the entire program management structure and operation
- Redesign the solid rocket motor joint (A dedicated solid rocket motor joint design group would be established at Marshall to recommend a program plan to quantify the solid rocket motor joints problem and to accomplish the solid rocket motor joints redesign.)
- Reverify design requirements
- Complete Critical Item List (CIL)/Operations and Maintenance Instructions reviews (NASA would review all Category 1 and 1R critical items and implement a complete reapproval process. Any items not revalidated by this review would be redesigned, certified, and qualified for flight.)
- Complete Operations and Maintenance Requirements and Specifications Document review
- Reassess launch and abort rules and philosophy

First Flight/First Year Operations. The first flight mission design would incorporate:

- Daylight Kennedy launch
- Conservative flight design to minimize transatlantic-abort-launch exposure
- Repeat payload (not a new payload class)
- No waiver on landing weight
- Conservative launch/launch abort/landing weather
- NASA-only flight crew
- Engine thrust within the experience base
- No active ascent/entry Developmental Test Objectives
- Conservative mission rules
- Early, stable flight plan with supporting flight software and training load
- Daylight Edwards Air Force Base landing

The planning for the flight schedule for the first year of operation would reflect a conservative launch rate. The first year of operation would be maintained within the current flight experience base, and any expansion of the base, including new classes of payloads, would be approved only after a very thorough safety review.

Development of Sustainable Safe Flight Rate. This flight rate would be developed using a "bottoms-up" approach in which all required work was identified and that work was optimized, keeping in mind the available work force. Factors with the potential for disrupting schedules as well as the availability of resources would be considered when developing the flight rate.

Design and Development Task Force

Also while the Presidential Commission was meeting, NASA formed the 51-L Data and Design Analysis Task Force. This group supported the Presidential Commission and was responsible for:

1. Determining, reviewing, and analyzing the facts and circumstances surrounding the STS 51-L launch
2. Reviewing all factors relating to the accident determined to be relevant, including studies, findings, recommendations, and other actions that were or might be undertaken by the program offices, field centers, and contractors involved
3. Examining all other factors that could relate to the accident, including design issues, procedures, organization, and management factors
4. Using the full required technical and scientific expertise and resources available within NASA and those available to NASA
5. Documenting task force findings and determinations and conclusions derived from the findings.
6. Providing information and documentation to the commission regarding task force activities.

The task force, which was chaired by Truly, established teams to examine development and production; prelaunch activities; accident analysis; mission planning and operations; and search, recovery, and reconstruction; and a photo and TV support team. Figure 3–23 shows the task force organization.

Each task force team submitted multivolume reports to the Presidential Commission, which included descriptions of the accident as

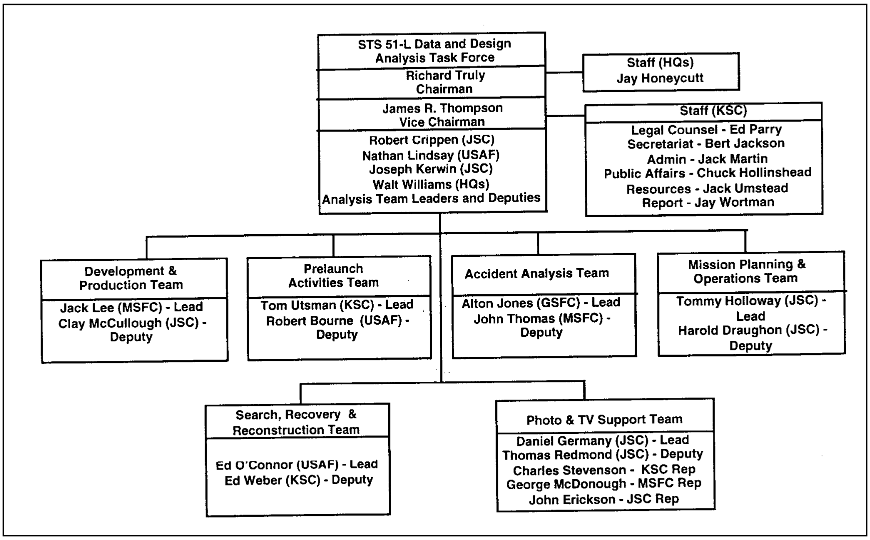

Figure 3–23. STS 51-L Data and Design Analysis Task Force

well as numerous corrective measures needed to be taken. Called "Lessons Learned and Collateral Findings," this report contained eight lessons learned and twenty-nine collateral findings, all addressing virtually every aspect of Shuttle planning, processing, launch, and recovery.[18] The task force also briefed members of Congress on its findings.

Actions to Implement Recommendations

After the report of the Presidential Commission was published (on June 9, 1986), President Reagan directed NASA Administrator James Fletcher on June 13 to report to him within 30 days on how and when the commission's recommendations would be implemented. The president said that "this report should include milestones by which progress in the implementation process can be measured."[19] NASA's *Report to the President: Actions to Implement the Recommendations of the Presidential Commission on the Space Shuttle Challenger Accident,* submitted to the president on July 14, 1986, responded to each of the commission's recommendations and included a key milestone schedule that illustrated the planned implementation (Figure 3–24).

The proposed actions and the steps that NASA had already taken when the report was issued follow in the narrative below. Table 3–48 presents an implementation timetable.[20]

Recommendation I

Solid Rocket Motor Design. At NASA's direction, the Marshall Space Flight Center formed a solid rocket motor joint redesign team to include participants from Marshall and other NASA centers and individuals from outside NASA.

The Marshall team evaluated several design alternatives and began analysis and testing to determine the preferred approaches that minimized hardware redesign. To ensure adequate program contingency, the redesign team would also develop, at least through concept definition, a totally new design that did not use existing hardware. The design verification and certification program would be emphasized and would include tests that duplicated the actual launch loads as closely as feasible and provided for tests over the full range of operating conditions. The verification effort included a trade study to determine the preferred test orientation (vertical or horizontal) of the full-scale motor firings. The

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[18] *STS 51-L Data and Design Analysis Task Force, Historical Summary* (Washington, DC: U.S. Government Printing Office, June 1986), p. 3–90.

[19] Ronald Reagan, Letter to James C. Fletcher, NASA Administrator, June 13, 1986.

[20] *Report to the President: Actions to Implement the Recommendations of the Presidential Commission on the Space Shuttle Challenger Accident* (Washington, DC: U.S. Government Printing Office, July 14, 1986), Executive Summary.

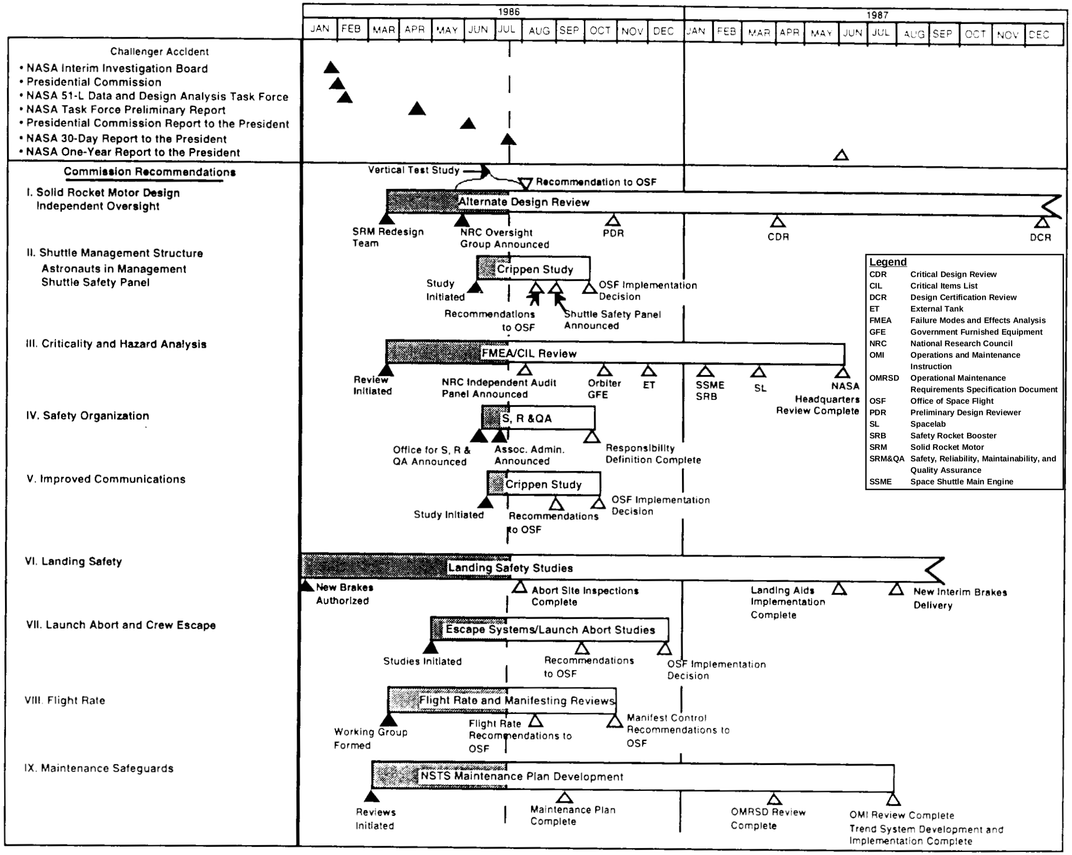

Figure 3–24. Space Shuttle Return to Flight

solid rocket motor redesign and certification schedule was under review to fully understand and plan for the implementation of the design solutions. The schedule would be reassessed after the solid rocket motor Preliminary Design Review in September 1986.

Independent Oversight. In accordance with the commission's recommendation, the National Research Council (NRC) established an Independent Oversight Group chaired by Dr. H. Guyford Stever and reporting to the NASA administrator. The NRC Independent Oversight Group was briefed on Shuttle system requirements, implementation, and control; solid rocket motor background; and candidate modifications. The group established a near-term plan, which included briefings and visits to review inflight loads, assembly processing, redesign status, and other solid rocket motor designs, including participation in the solid rocket motor Preliminary Design Review in September 1986.

Recommendation II

Shuttle Management Structure. The NASA administrator appointed General Samuel C. Phillips to study how NASA managed its programs, including relationships between various field centers and NASA Headquarters and emphasizing the Space Shuttle management structure.

On June 25, 1986, the administrator directed Astronaut Robert L. Crippen to form a fact-finding group to assess the Space Shuttle management structure. The group would report recommendations to the associate administrator for spaceflight by August 15, 1986. Specifically, this group will address the roles and responsibilities of the Space Shuttle program manager to assure that the position had the authority commensurate with its responsibilities. General Phillips and the administrator would review the results of this study with a decision on implementation of the recommendations by October 1, 1986.

Astronauts in Management. The Crippen group would also address ways to stimulate the transition of astronauts into management positions. It would also determine the appropriate position for the flight crew operations directorate within the NASA.

Shuttle Safety Panel. The associate administrator for spaceflight would establish a Shuttle Safety Panel by September 1, 1986, with direct access to the Space Shuttle program manager.

Recommendation III

Critical Item Review and Hazard Analysis. On March 13, 1986, NASA initiated a complete review of all Space Shuttle program failure modes and effects analyses and associated Critical Item Lists. Each Space Shuttle project element and associated prime contractor was conducting separate comprehensive reviews which would culminate in a program-wide review with the Space Shuttle program manager at Johnson Space Center later in 1986. Technical specialists outside the Space Shuttle program were assigned as formal members of each of these review teams. All Criticality 1 and 1R critical item waivers were canceled. The teams reassessed and resubmitted waivers in categories recommended for continued program applicability. Items which could not be revalidated would be redesigned, qualified, and certified for flight. All Criticality 2 and 3 Critical Item Lists were being reviewed for reacceptance and proper categorization. This activity would culminate in a comprehensive final review with NASA Headquarters beginning in March 1987.

As recommended by the commission, the National Research Council agreed to form an Independent Audit Panel, reporting to the NASA administrator, to verify the adequacy of this effort.

Recommendation IV

Safety Organization. The NASA administrator announced the appointment of George A. Rodney to the position of associate administrator for safety, reliability, maintainability, and quality assurance (SRM&QA) on July 8, 1986. This office would oversee the safety, reliability, and quality assurance functions related to all NASA activities and programs and the implementation system for anomaly documentation and resolution, including a trend analysis program. One of Rodney's first actions would be to assess the available resources, including the work force required to ensure adequate execution of the safety organization functions. In addition, he would assure appropriate interfaces between the functions of the new safety organization and the Shuttle Safety Panel, which would be established in response to the commission Recommendation II.

Recommendation V

Improved Communications. Astronaut Robert Crippen's team (formed as part of Recommendation II) developed plans and recommended policies for the following:

- Implementation of effective management communications at all levels
- Standardization of the imposition and removal of STS launch constraints and other operational constraints
- Conduct of Flight Readiness Review and Mission Management Team meetings, including requirements for documentation and flight crew participation

This review of effective communications would consider the activities and information flow at NASA Headquarters and the field centers that supported the Shuttle program. The study team would present findings and recommendations to the associate administrator for spaceflight by August 15, 1986.

Recommendation VI

Landing Safety. A Landing Safety Team was established to review and implement the commission's findings and recommendations on landing safety. All Shuttle hardware and systems were undergoing design reviews to ensure compliance with the specifications and safety concerns. The tires, brakes, and nose wheel steering system were included in this activity, and funding for a new carbon brakes system was approved. Ongoing runway surface tests and landing aid requirement reviews were continuing. Landing aid implementation would be complete by July 1987. The interim brake system would be delivered by August 1987.

Improved methods of local weather forecasting and weather-related support were being developed. Until the Shuttle program demonstrated satisfactory safety margins through high fidelity testing and during actual landings at Edwards Air Force Base, the Kennedy Space Center landing site would not be used for nominal end-of-mission landings.

Recommendation VII

Launch Abort and Crew Escape. On April 7, 1986, NASA initiated a Shuttle Crew Egress and Escape review. The analysis focused on egress and escape capabilities from launch through landing and would analyze concepts, feasibility assessments, cost, and schedules for pad abort, bailout, ejection systems, water landings, and powered flight separation. This review would specifically assess options for crew escape during controlled gliding flight and options for extending the intact abort flight envelope to include failure of two or three main engines during the early ascent phase.

In conjunction with this activity, NASA established a Launch Abort Reassessment Team to review all launch and launch abort rules to ensure that launch commit criteria, flight rules, range safety systems and procedures, landing aids, runway configurations and lengths, performance versus abort exposure, abort and end-of-mission landing weights, runway surfaces, and other landing-related capabilities provided the proper margin of safety to the vehicle and crew. Crew escape and launch abort studies would be complete on October 1, 1986, with an implementation decision in December 1986.

Recommendation VIII

Flight Rate. In March 1986, NASA established a Flight Rate Capability Working Group that studied:

1. The capabilities and constraints that governed the Shuttle processing flows at the Kennedy Space Center
2. The impact of flight specific crew training and software delivery/certification on flight rates

The working group would present flight rate recommendations to the Office of Space Flight by August 15, 1986. Other collateral studies in progress addressed commission recommendations related to spares provisioning, maintenance, and structural inspection. This effort would also consider the NRC independent review of flight rate, which a congressional subcommittee had requested.

The report emphasized NASA's strong support for a mixed fleet to satisfy launch requirements and actions to revitalize the United States expendable launch vehicle capabilities. Additionally, NASA Headquarters was formulating a new cargo manifest policy, which would establish manifest ground rules and impose constraints to late changes. Manifest control policy recommendations would be completed in November 1986.

Recommendation IX

Maintenance Safeguards. A Maintenance Safeguards Team was established to develop a comprehensive plan for defining and implementing actions to comply with the commission recommendations concerning maintenance activities. The team was preparing a Maintenance Plan to ensure that uniform maintenance requirements were imposed on all elements of the Space Shuttle program. The plan would also define organizational responsibilities, reporting, and control requirements for Space Shuttle maintenance activities. The Maintenance Plan would be completed by September 30, 1986.

In addition to the actions described above, a Space Shuttle Design Requirements Review Team headed by the Space Shuttle Systems Integration Office at the Johnson Space Center was reviewing all Shuttle design requirements and associated technical verification. The team focused on each Shuttle project element and on total Space Shuttle system design requirements. This activity was to culminate in a Space Shuttle Incremental Design Certification Review approximately three months before the next Space Shuttle launch.

Because of the number, complexity, and interrelationships among the many activities leading to the next flight, the Space Shuttle program manager at the Johnson Space Center initiated a series of formal Program Management Reviews for the Space Shuttle program. These reviews were to be regular face-to-face discussions among the managers of all major Space Shuttle program activities. Each meeting would focus on progress, schedules, and actions associated with each of the major program review activities and would be tailored directly to current program activity for the time period involved. The first of these meetings was held at the Marshall Space Flight Center on May 5–6, 1986, with the second at the Kennedy Space Center on June 25, 1986. Follow-on reviews will occur approximately every six weeks. Results of these reviews will be reported to the associate administrator for spaceflight and to the NASA administrator.

On June 19, 1986, the NASA administrator announced the termination of the development of the Centaur upper stage for use aboard the Space Shuttle. NASA had planned to use the Centaur upper stage for NASA planetary spacecraft launches as well as for certain national security satellite launches. Major safety reviews of the Centaur system were under way at the time of the *Challenger* accident, and these reviews were intensified to determine whether the program should be continued. NASA decided to terminate because, even with certain modifications identified by the ongoing reviews, the resultant stage would not meet safety criteria being applied to other cargo or elements of the Space Shuttle system.

Revised Manifest

On October 3, 1986, NASA Administrator James C. Fletcher announced NASA's plan to resume Space Shuttle flights on February 18, 1988. He also announced a revised manifest for the thirty-nine months following the resumption of Shuttle flights (Table 3–49). (The manifest was revised several times prior to the resumption of Shuttle flights. Most flights did not launch on the dates listed here.)

Fletcher stated that the manifest was based on a reduced flight rate goal that was "acceptable and prudent" and that complied with presidential policy that limited use of the Shuttle for commercial and foreign payloads to those that were Shuttle-unique or those with national security or foreign policy implications. Prior to the *Challenger* accident, roughly one-third of the Shuttle manifest was devoted to DOD missions, another third to scientific missions, and the remainder to commercial satellites and foreign government missions. Fletcher said that for the seven-year period following resumption of Shuttle flights (through 1994), NASA would use 40 percent of the Shuttle's capability for DOD needs, 47 percent for NASA needs, and 12 percent to accommodate commercial, foreign government, and U.S. government civil space requirements. This reflected the priorities for payload assignments with national security at the top, STS operational capability (TDRS) and dedicated science payloads next, and other science and foreign and commercial needs last. He stated that at the beginning of this seven-year period, DOD would use considerable Shuttle capability to reduce its payload backlog, but for the remaining years, DOD's use would even out at approximately one-third of Shuttle capability.

Fletcher stated that the revised manifest placed a high priority on major NASA science payloads. The Hubble Space Telescope, Ulysses, and Galileo, which had been scheduled for a 1986 launch, would be launched "as expeditiously as possible."[21]

Implementing the Commission's Recommendations

Approximately one year after NASA addressed how it would implement the recommendations of the Presidential Commission, NASA issued a report to the president that described the actions taken by NASA in response to the commission's recommendations on how to return to safe, reliable spaceflight.[22] This report and the accompanying milestone

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[21] Statement by Dr. James C. Fletcher, Press Briefing, NASA Headquarters, October 3, 1986.

[22] *Report to the President: Implementation of the Recommendations of the Presidential Commission on the Space Shuttle Challenger Accident* (Washington, DC: U.S. Government Printing Office, June 1987).

chart (Figure 3–25) showed the significant progress NASA made in meeting its implementation milestones. The recovery activity, as described in the report, focused on three key aspects: the technical engineering changes being selected and implemented; the new procedures, safeguards, and internal communication processes that had been or were being put in place; and the changes in personnel, organizations, and attitudes that occurred.

Responding to the commission's findings as to the cause of the accident, NASA changed the design of the solid rocket motor. The new design eliminated the weakness that had led to the accident and incorporated of a number of improvements. The new rocket motors were to be tested in a series of full-scale firings before the next Shuttle flight. In addition, NASA reviewed every element of the Shuttle system and added improved hardware and software to enhance safety. Improved or modified items or systems included the landing system, the main liquid-fueled engines, and the flight and ground systems.

NASA implemented new procedures to provide independent SRM&QA functions. A completely new organization, the SRM&QA office, which reported directly to the NASA administrator, now provided independent oversight of all critical flight safety matters. The new office worked directly with the responsible program organization to solve technical problems while still retaining its separate identity as final arbiter of safety and related matters.

NASA completed personnel and organizational changes that had begun immediately after the accident. A new, streamlined management team was put in place at NASA Headquarters, with new people well down within the field centers. Special attention was given to the critical issues of management isolation and the tendency toward technical complacency, which, combined with schedule pressure, led to an erosion in flight safety. This awareness of the risk of spaceflight operations, along with NASA's responsibility to control and contain that risk without claiming its elimination, became the controlling philosophy the Space Shuttle program.

The report addressed the nine recommendations made by the Presidential Commission and other related concerns.

Recommendation I

The commission recommended that the design of the solid rocket motor be changed, that the testing of the new design reflect the operational environment, and that the National Research Council (NRC) form a committee to provide technical oversight of the redesign effort.

NASA thoroughly evaluated the solid rocket motor design. As well as the solid rocket motor field joint, this evaluation resulted in design changes to many components of the motor. The field joint was redesigned to provide high confidence in its ability to seal under all operating conditions (Figure 3–26). In addition, the redesign included a new tang capture latch that controlled movement between the tang and clevis in the joint, a third O-ring seal, insulation design improvements, and an external heater

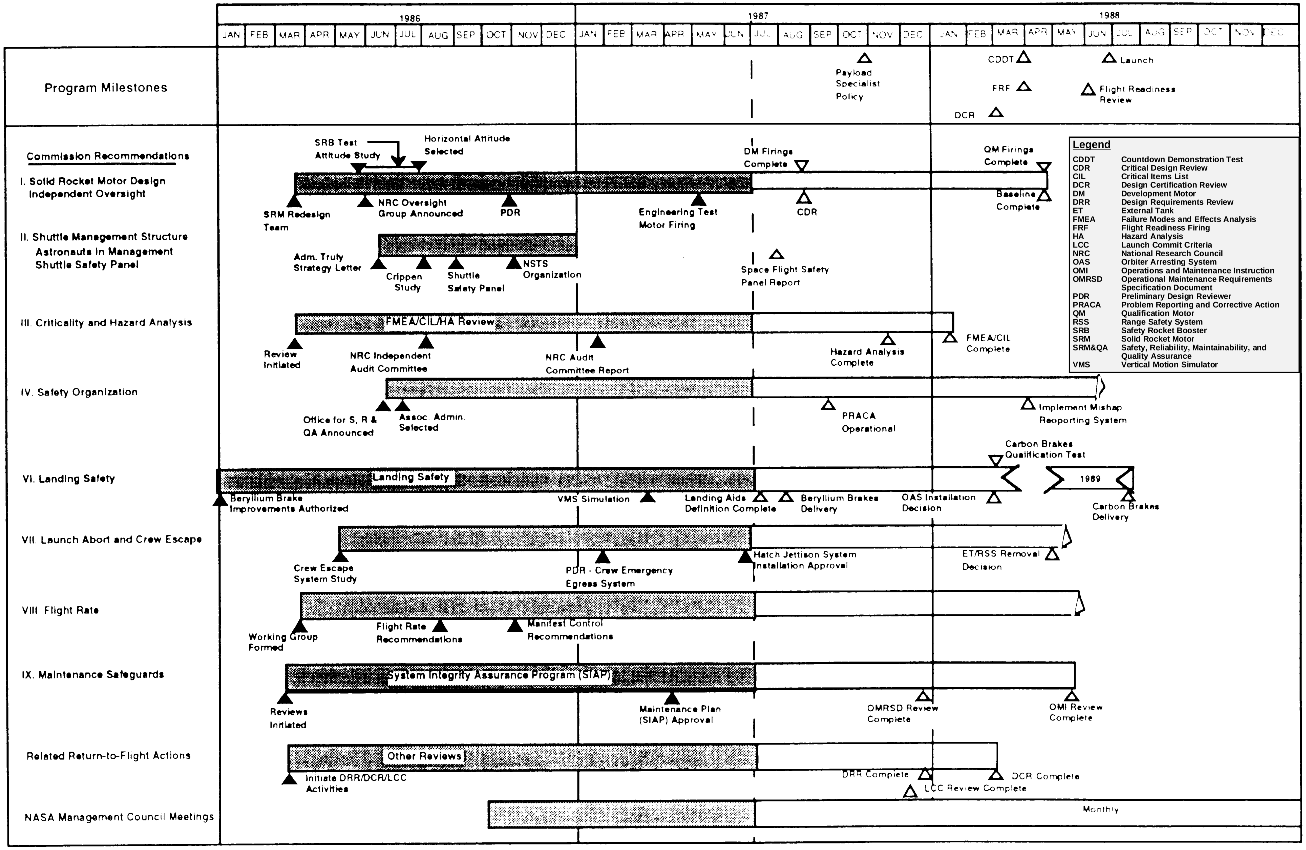

Figure 3–25. Space Shuttle Return to Flight Milestones

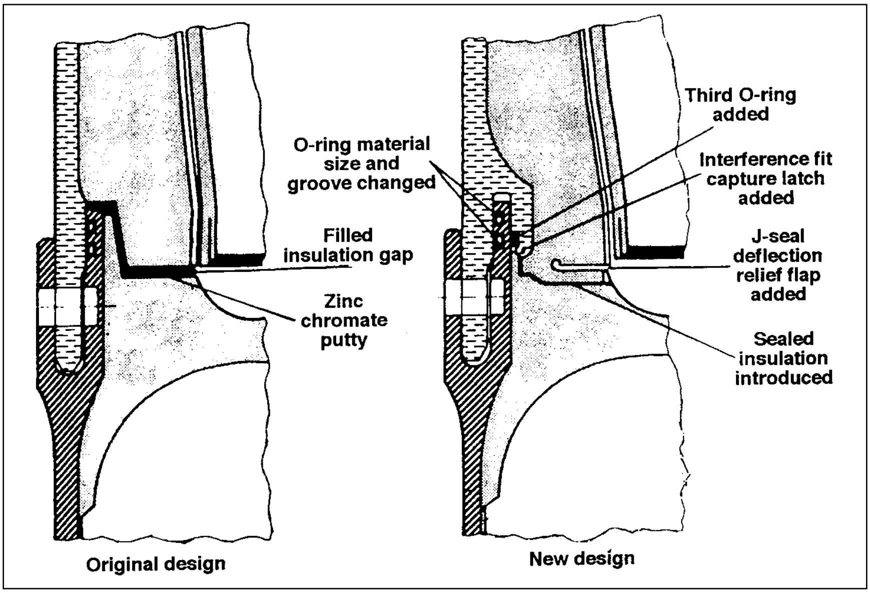

Figure 3–26. Field Joint Redesign

with integral weather seals. The nozzle-to-case joint, the case parts, insulation, and seals were redesigned to preclude seal leakage observed in prior flights. The nozzle metal parts, ablative components, and seals were redesigned to improve redundancy and to provide pressure verification of seals. Other nozzle modifications included improvements to the inlet, cowl/boot, and aft exit assemblies.

Modifications were incorporated into the igniter case chamber and into the factory joints to improve their margins of safety. The igniter case chamber wall thickness was being increased. Additional internal insulation and an external weather seal were added to the factory joint. Ground support equipment was redesigned to minimize case distortion during storage and handling, to improve case measurement and rounding techniques for assembly, and to improve leak testing capabilities.

Component laboratory tests, combined with subscale simulation tests and full-scale tests, were being conducted to meet verification requirements. Several small-scale and full-scale joint tests were successfully completed, confirming insulation designs and joint deflection analyses. One engineering test, two developmental tests, and three qualification full-scale motor test firings were to be completed before STS-26. The engineering test motor was fired on May 27, 1987, and early analysis of the data indicated that the test met its objectives.

NASA selected the horizontal attitude as the optimum position for static firing, and a second test stand, which could introduce dynamic loads at the external tank/solid rocket motor aft attach struts, was constructed. Improved nondestructive evaluation techniques were being developed, in conjunction with the Air Force, to perform ultrasonic inspection and mechanical testing of propellant and insulation bonding surfaces. Complete x-ray testing of all segments were reinstated for near-term flights.

Contingency planning included development of alternate designs, which did not utilize existing hardware, for the field and nozzle-to-case joints and for the rocket motor nozzle. An NRC Solid Rocket Motor Independent Oversight Panel, chaired by Dr. H. Guyford Stever, was actively reviewing the solid rocket motor design, verification analyses, and test planning and was participating in the major program reviews, including the preliminary requirements and the preliminary design reviews. A separate technical advisory group, consisting of twelve senior engineers from NASA and the aerospace industry and a separate group of representatives from four major solid motor manufacturers, worked directly with the solid rocket motor design team to review the redesign status and provide suggestions and recommendations to NASA and Morton Thiokol.

The solid rocket motor manufacturers—Aerojet Strategic Propulsion Company, Atlantic Research Corporation, Hercules Inc., and United Technologies Corporation (Chemical Systems Division)—were reviewing and commenting on the present design approach and proposing alternate approaches that they felt would enhance the design. As a result of these and other studies, NASA initiated a definition study for a new advanced solid rocket motor. Additional details of the redesigned solid rocket motor can be found in Chapter 2 as part of the discussion of the Shuttle's propulsion system.

Recommendations II and V

The commission recommended [II] that the Space Shuttle Program management structure be reviewed, that astronauts be encouraged to make the transition into management positions, and that a flight safety panel be established. The commission recommended [V] that the tendency for management isolation be eliminated, that a policy on launch constraints be developed, and that critical launch readiness reviews be recorded.

In March 1986, Associate Administrator for Space Flight Rear Admiral Richard Truly initiated a review of the Shuttle program management structure and communications. After the commission report was issued, he assigned Captain Robert L. Crippen responsibility for developing the response to commission recommendations II and V. This effort resulted in the establishment of a director, NSTS, reporting directly to the associate administrator for spaceflight, and other changes necessary to strengthen the Shuttle program management structure and improve lines of authority and communication (see Figure 3–1) at the beginning of this chapter. The NSTS funding process was revised, and the director, NSTS, now was given control over program funding at the centers.

Additionally, the flight readiness review and mission management team processes were strengthened. The director of flight crew operations would participate in both of these activities, and the flight crew commander, or a representative, would attend the flight readiness review. These meetings would be recorded and formal minutes published.

Since the accident, several current and former astronauts were assigned to top management positions. These included: the associate administrator for spaceflight; the associate administrator for external affairs; the acting assistant administrator, office of exploration; chief, Headquarters operational safety branch; the deputy director, NSTS operations; the Johnson Space Center deputy center director; the chairman of the Space Flight Safety Panel; and the former chief of the astronaut office as special assistant to the Johnson director for engineering, operations, and safety.

A Space Flight Safety Panel, chaired by astronaut Bryan O'Connor, was established. The panel reported to the associate administrator for SRM&QA. The panel's charter was to promote flight safety for all NASA spaceflight programs involving flight crews, including the Space Shuttle and Space Station programs.

Recommendation III

The Commission recommended that the critical items and hazard analyses be reviewed to identify items requiring improvement prior to flight to ensure safety and that the NRC verify the adequacy of this effort.

The NSTS uses failure modes and effects analyses, critical item lists, and hazard analyses as techniques to identify the potential for failure of critical flight hardware, to determine the effect of the failure on the crew, vehicle, or mission, and to ensure that the criticality of the item is reflected in the program documentation. Several reviews were initiated by program management in March 1986 to reevaluate failure analyses of critical hardware items and hazards. These reviews provided improved analyses and identified hardware designs requiring improvement prior to flight to ensure mission success and enhance flight safety.

A review of critical items, failure modes and effects analyses, and hazard analyses for all Space Shuttle systems was under way. NASA developed detailed instructions for the preparation of these items to ensure that common ground rules were applied to each project element analysis. Each NASA element project office and its prime contractor, as well as the astronaut office and mission operations directorate, were reviewing their systems to identify any areas in which the design did not meet program requirements, to verify the assigned criticality of items, to identify new items, and to update the documentation. An independent contractor was conducting a parallel review for each element. Upon completion of this effort, each element would submit those items with failure modes that could not meet full design objectives to the Program Requirements Control Board, chaired by the director, NSTS. The board would review the documentation, concur with the proposed rationale for safely accepting the item, and issue a waiver to the design requirement, if appropriate.

The NRC Committee on Shuttle Criticality Review and Hazard Analysis Audit, chaired by retired U.S. Air Force General Alton Slay, was responsible for verifying the adequacy of the proposed actions for returning the Space Shuttle to flight status. In its interim report of January 13, 1987, the committee expressed concern that critical items were not adequately prioritized to highlight items that may be most significant. NASA was implementing a critical items prioritization system for the Shuttle program to alleviate the committee's concerns.

Recommendation IV

The commission recommended that NASA establish an Office of Safety, Reliability, and Quality Assurance, reporting to the NASA administrator, with responsibility for related functions in all NASA activities and programs.

The NASA administrator established a new NASA Headquarters organization, the Office of Safety, Reliability, Maintainability, and Quality Assurance (SRM&QA), and appointed George Rodney as associate administrator. The Operational Safety Branch of that office was headed by astronaut Frederick Gregory. The new organization centralized agency policy in its areas of responsibility, provided for NASA-wide standards and procedures, and established an independent reporting line to top management for critical problem identification and analysis. The new office exercised functional management responsibility and authority over the related organizations at all NASA field centers and major contractors.

The new organization was participating in specific NSTS activities, such as the hardware redesign, failure modes and effects analysis, critical item identification, hazard analysis, risk assessment, and spaceflight system assurance. This approach allowed the NSTS program line management at Headquarters and in the field to benefit from the professional safety contributions of an independent office without interrupting the two different reporting lines to top management. Additional safeguards were added by both the line project management and the SRM&QA organization to ensure free, open, rapid communication upward and downward within all agency activities responsible for flight safety. Such robust multiple communications pathways were expected to eliminate the possibility of serious issues not rising to the attention of senior management.

Recommendation VI

The commission recommended that NASA take action to improve landing system safety margin and to determine the criteria under which planned landings at Kennedy would be acceptable.

Several orbiter landing system modifications to improve landing system safety margins would be incorporated for the first flight. These included a tire pressure monitoring system, a thick-stator beryllium brake to increase brake energy margin, a change to the flow rates in the brake hydraulic system, a stiffer main gear axle, and a balanced brake pressure application feature that would decrease brake wear upon landing and provide additional safety margin.

Several other changes were being evaluated to support longer term upgrading of the landing system. A new structural carbon brake, with increased energy capacity, was approved and would be available in 1989. A fail-operational/fail-safe nose wheel steering design, including redundant nose wheel hydraulics capability, was being reviewed by the orbiter project office for later implementation.

The initial Shuttle flights were scheduled to land at the Edwards Air Force Base complex. A total understanding of landing performance data, the successful resolution of significant landing system anomalies, and increased confidence in weather prediction capabilities were preconditions to resuming planned end-of-mission landings at the Kennedy Space Center.

Recommendation VII

The commission recommended that NASA make every effort to increase the capability for an emergency runway landing following the loss of two or three engines during early ascent and to provide a crew escape system for use during controlled gliding flight.

Launch and launch abort mode definition, flight and ground procedures, range safety, weather, flight and ground software, flight rules, and launch commit criteria were reviewed. Changes resulting from this review were being incorporated into the appropriate documentation, including ground operating procedures, and the on-board flight data file. NASA reviewed abort trajectories, vehicle performance, weather requirements, abort site locations, support software, ground and on-board procedures, and abort decision criteria to ensure that the requirements provided for maximum crew safety in the event an abort was required. The review resulted in three actions: the landing field at Ben Guerir, Morocco, was selected as an additional transatlantic abort landing site; ground rules for managing nominal and abort performance were established and the ascent data base was validated and documented; and a permanent Launch Abort Panel was established to coordinate all operational and engineering aspects of ascent-phase contingencies.

Representatives from NASA and the Air Force were reviewing the external tank range safety system. This review readdressed the issue of whether the range safety system is required to ensure propellant dispersal capability in the event of an abort during the critical first minutes of flight. The results of this analysis would be available in early 1988.

Flight rules (which define the response to specific vehicle anomalies that might occur during flight) were being reviewed and updated. The Flight Rules Document was being reformatted to include both the technical and operational rationales for each rule. Launch commit criteria (which define responses to specific vehicle and ground support system anomalies that might occur during launch countdown) were being reviewed and updated. These criteria were being modified to include the technical and operational rationale and to document any procedural workarounds that would allow the countdown to proceed in the event one of the criteria was violated.

Although a final decision to implement a Space Shuttle crew escape capability was not made, the requirements for a system to provide crew egress during controlled gliding flight were established. The requirements for safe egress of up to eight crew members were determined through a review of escape routes, time lines, escape scenarios, and proposed orbiter modifications. The options for crew egress involved manual and powered extraction techniques. Design activities and wind tunnel assessments for each were initiated. The manual egress design would ensure that the crew member did not contact the vehicle immediately after exiting the crew module. Several approaches being assessed for reducing potential contact included a deployable side hatch tunnel that provided sufficient initial velocity to prevent crew/vehicle contact and an extendable rod and/or rope that placed the crew release point in a region of safe exit (Figure 3–27). Both approaches provided for crew egress through the orbiter side hatch.

The director, NSTS, authorized the development of a rocket-powered extraction capability for use in a crew egress/escape system. Crew escape would be initiated during controlled gliding flight at an altitude of 6,096 meters and a velocity of 321.8 kilometers per hour. The system consisted of a jettisonable crew hatch (which has been approved for installation and also applied to the manual bail-out mode) and individual rockets to extract the crew from the vehicle before it reached an altitude of 3,048 meters.

Ground egress procedures and support systems were being reviewed to determine their capability to ensure safe emergency evacuation from the orbiter at the pad or following a non-nominal landing. An egress slide,

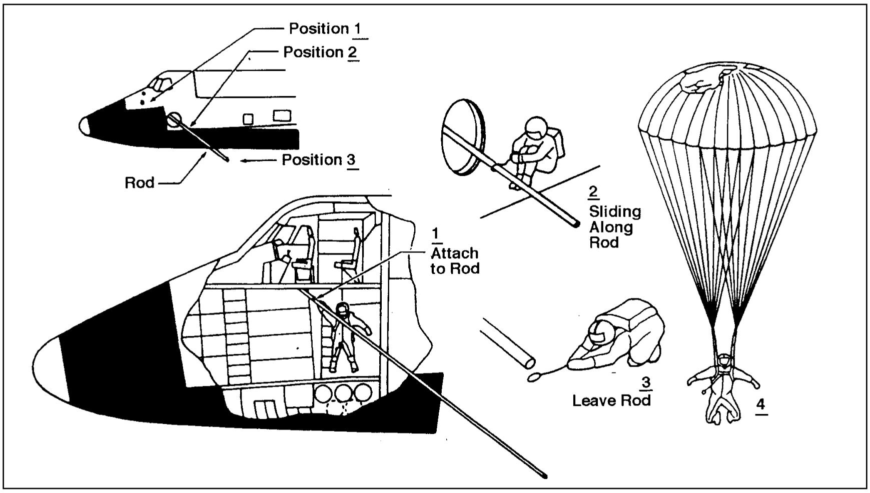

Figure 3–27. Extendible Rod Escape System

(In this system, the crew module hatch would be jettisoned and the rod would be extended through the hatch opening. The crew member would attach a lanyard to the rod, exit the vehicle in a tucked position, release at the end of the rod, and parachute to a ground or water landing.)

similar to that used on commercial aircraft, was being designed for use should an emergency escape be required after a runway landing. A study was initiated to evaluate future escape systems that would potentially expand the crew survival potential to include first-stage (solid rocket boosters thrusting) flight.

Recommendation VIII

The commission recommended that the nation not rely on a single launch vehicle capability for the future and that NASA establish a flight rate that is consistent with its resources.

Several major actions reduced the overall requirements for NSTS launches and provided for a mixed fleet of expendable launch vehicles and the Space Shuttle to ensure that the nation did not rely on a single launch vehicle for access to space. NASA and DOD worked together to identify DOD payloads for launch on expendable launch vehicles and to replan the overall launch strategy to reflect their launches on expendable launch vehicles. The presidential decision to limit the use of the NSTS for the launch of communications satellites to those with national security or foreign policy implications resulted in many commercial communications satellites, previously scheduled for launch on the NSTS, being reassigned to commercial expendable launch vehicles.

In March 1986, Admiral Truly directed that a “bottoms-up” Shuttle flight rate capability assessment be conducted. NASA established a flight rate capability working group with representatives from each Shuttle program element that affects flight rate. The working group developed ground rules to ensure that projected flight rates were realistic. These ground rules addressed such items as overall staffing of the work force, work shifts, overtime, crew training, and maintenance requirements for the orbiter, main engine, solid rocket motor, and other critical systems. The group identified enhancements required in the Shuttle mission simulator, the Orbiter Processing Facility, the Mission Control Center, and other areas, such as training aircraft and provisioning of spares. With these enhancements and the replacement orbiter, NASA projected a maximum flight rate capability of fourteen per year with four orbiters. This capacity, considering lead time constraints, “learning curves,” and budget limitations, could be achieved no earlier than 1994 (Figure 3–28).

Controls were implemented to ensure that the Shuttle program elements were protected from pressures resulting from late manifest changes. While the manifest projects the payload assignments several years into the future, missions within eighteen months of launch were placed under the control of a formal change process controlled by the director, NSTS. Any manifest change not consistent with the defined capabilities of the Shuttle system would result in the rescheduling of the payload to another mission.

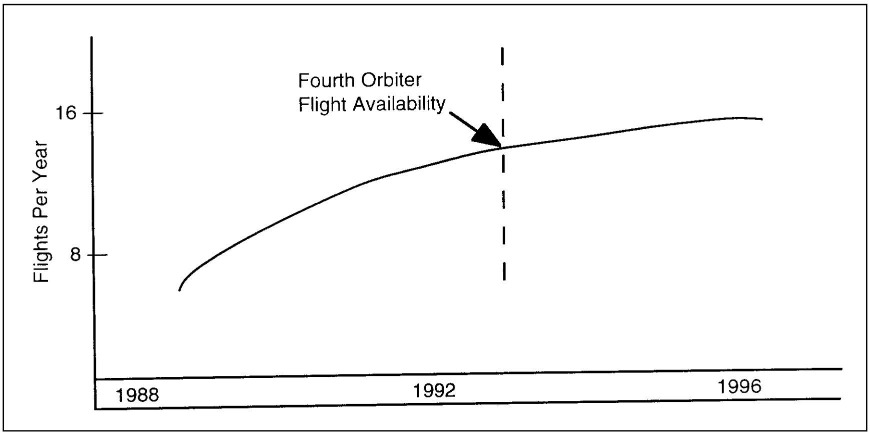

Figure 3–28. Availability of Fourth Orbiter
(With a fourth orbiter available, fourteen flights per year would be possible in 1994.)

Recommendation IX

The commission recommended that NASA develop and execute a maintenance inspection plan, perform structural inspections when scheduled, and restore the maintenance and spare parts program.

NASA updated the overall maintenance and flight readiness philosophy of the NSTS program to ensure that it was a rigorous and prominent part of the safety-of-flight process. A System Integrity Assurance Program was developed that encompassed the overall maintenance strategy, procedures, and test requirements for each element of flight hardware and software to ensure that each item was properly maintained and tested and was ready for launch. Figure 3–29 reflects the major capabilities of the System Integrity Assurance Program.

NASA alleviated the requirement for the routine removal of parts from one vehicle to supply another by expanding and accelerating various aspects of the NSTS logistics program. Procedures were being instituted to ensure that a sufficient rationale supported any future requirement for such removal of parts and that a decision to remove them underwent a formal review and approval process.

A vehicle checkout philosophy was defined that ensured that systems remain within performance limits and that their design redundancy features functioned properly before each launch. Requirements were established for identifying critical hardware items in the Operational Maintenance Requirements Specification Document (defines the work to be performed on the vehicle during each turnaround flow) and the Operations and Maintenance Instruction (lists procedures used in performing the work).

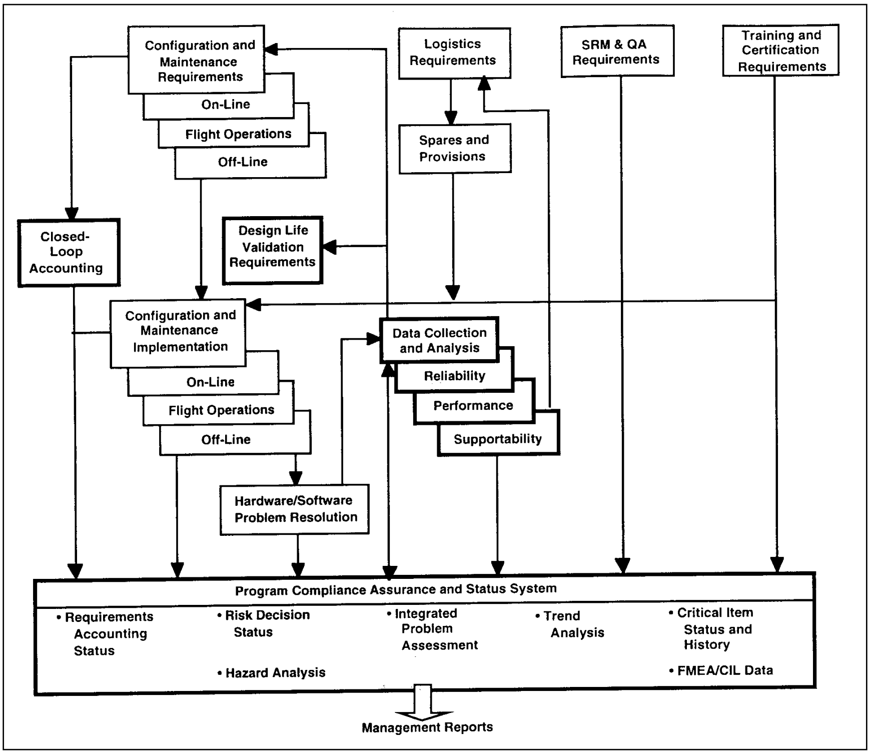

Figure 3–29. System Integrity Assurance Program
(This program established the functional responsibilities and program requirements necessary to provide the proper configuration, operations, inspection, maintenance, logistics, and certified personnel to ensure that the NSTS was ready for flight.)

Related Return-to-Flight Actions

At the time of the Rogers Commission report, NASA was engaged in several tasks in support of the return-to-flight activities that were not directly related to commission recommendations:

- A new launch target date and flight crew for the first flight were identified.
- The program requirements for flight and ground system hardware and software were being updated to provide a clear definition of the criteria that the project element designs must satisfy.
- The NSTS system designs were reviewed, and items requiring modification prior to flight were identified.
- Existing and modified hardware and software designs were being verified to ensure that they complied with the design requirements.
- The program and project documents, which implemented the redefined program requirements, were being reviewed and updated.

- Major testing, training, and launch preparation activities were continuing or were planned.

Orbiter Operational Improvements and Modifications. The NSTS program initiated the System Design Review process to ensure the review of all hardware and software systems and to identify items requiring redesign, analysis, or test prior to flight. The review included a complete description of the system issue, its potential consequences, recommended correction action, and alternatives. The orbiter System Design Review identified approximately sixty Category 1 system or component changes out of a total of 226 identified changes.[23] (Category 1 changes are those required prior to the next flight because the current design may not contain a sufficient safety margin.) Figure 3–30 illustrates the major improvements or modifications made to the orbiter.

Space Shuttle Main Engine. Improvements made to the Shuttle's main engines are addressed in Chapter 2 as part of the discussion of the Shuttle's propulsion system.

Orbital Maneuvering System/Reaction Control System AC-Motor-Operated Valves.[24] The sixty-four valves operated by AC motors in the OMS and RCS were modified to incorporate a "sniff" line for each valve to permit the monitoring of nitrogen tetroxide or monomethyl hydrazine in the electrical portion of the valves during ground operations. This new line reduced the probability of floating particles in the electrical microswitch portion of each valve, which could affect the operation of the

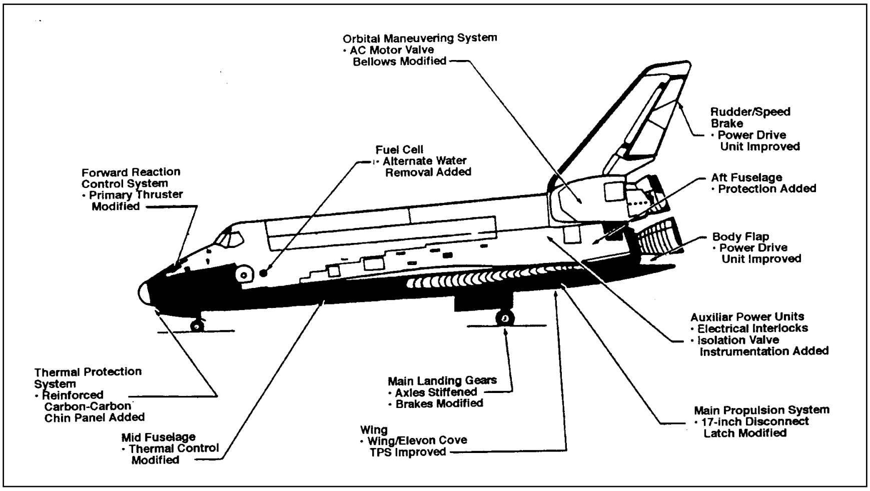

Figure 3–30. Major Orbiter Modifications

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[23] *Aeronautics and Space Report of the President, 1988* (Washington, DC: U.S. Government Printing Office, 1989) p. 24.

[24] The information regarding additional changes presented from this point onward came from the *NSTS Shuttle Reference Manual* (1988), on-line from the Kennedy Space Center Home Page.

microswitch position indicators for on-board displays and telemetry. It also reduces the probability of nitrogen tetroxide or monomethyl hydrazine leakage into the bellows of each AC-motor-operated valve.

Primary RCS Modifications. The wiring of the fuel and oxidizer injector solenoid valves was wrapped around each of the thirty-eight primary RCS thrust chambers to remove electrical power from these valves in the event of a primary RCS thruster instability.

Fuel Cell Modifications. Modifications to the fuel cell included the deletion of end-cell heaters on each fuel cell power plant because of potential electrical failures and replacement with Freon coolant loop passages to maintain uniform temperature throughout the power plants; the improvement of the hydrogen pump and water separator of each fuel cell power plant to minimize excessive hydrogen gas entrained in the power plant product water; the addition of a current measurement detector to monitor the hydrogen pump of each fuel cell power plant and provide an early indication of hydrogen pump overload; the modification of the starting and sustaining heater system for each fuel cell power plant to prevent overheating and the loss of heater elements; and the addition of a stack inlet temperature measurement to each fuel cell power plant for full visibility of thermal conditions. Other improvements included the modification of the product water lines from all three fuel cell power plants to incorporate a parallel (redundant) path of product water to the Environmental Control and Life Support System's potable water tank B in the event of a freeze-up in the single water relief panel and the addition of a water purity sensor (pH) at the common product water outlet of the water relief panel to provide a redundant measurement of water purity.

Auxiliary Power Unit Modifications. The auxiliary power units that were used to date had a limited life. Each unit was refurbished after twenty-five hours of operation because of cracks in the turbine housing, degradation of the gas generator catalyst (which varied up to approximately thirty hours of operation), and operation of the gas generator valve module (which also varied up to approximately thirty hours of operation). The remaining parts of the auxiliary power unit were qualified for forty hours of operation.

Improved auxiliary power units were scheduled for delivery in late 1988. A new turbine housing would increase the life of the housing to seventy-five hours of operation (fifty missions); a new gas generator increased its life to seventy-five hours; a new standoff design of the gas generator valve module and fuel pump deleted the requirement for a water spray system that was required previously for each auxiliary power unit upon shutdown after the first OMS thrusting period or orbital checkout; and the addition of a third seal in the middle of the two existing seals for the shaft of the fuel pump/lube oil system (previously only two seals were located on the shaft, one on the fuel pump side and one on the gearbox lube oil side) reduced the probability of hydrazine leaking into the lube oil system. The deletion of the water spray system for the gas generator valve module and fuel pump for each auxiliary power unit resulted in a weight reduction of approximately sixty-eight kilograms for each orbiter. Upon the delivery of the improved units, the life-limited auxiliary power units would be refurbished to the upgraded design.

Main Landing Gear. The following modifications were made to improve the performance of the main landing gear elements:

1. An increase in the thickness of the main landing gear axle to provide a stiffer configuration that reduces brake-to-axle deflections, precludes brake damage experienced in previous landings, and minimizes tire wear
2. The addition of orifices to hydraulic passages in the brake's piston housing to prevent pressure surges and brake damage caused by a wobble/pump effect
3. The modification of the electronic brake control boxes to balance hydraulic pressure between adjacent brakes and equalize energy applications, with the removal of the anti-skid circuitry previously used to reduce brake pressure to the opposite wheel if a flat tire was detected
4. The replacement of the carbon-lined beryllium stator discs in each main landing gear brake with thicker discs to increase braking energy significantly
5. A long-term structural carbon brake program to replace the carbon-lined beryllium stator discs with a carbon configuration that provides higher braking capacity by increasing maximum energy absorption
6. The addition of strain gauges to each nose and main landing gear wheel to monitor tire pressure before launch, deorbit, and landing
7. Other studies involving arresting barriers at the end of landing site runways (except lake bed runways), the installation of a skid on the landing gear that could preclude the potential for a second blown tire on the same gear after the first tire has blown, the provision of "roll on rim" for a predictable roll if both tires are lost on a single or multiple gear, and the addition of a drag chute

Studies of landing gear tire improvements were conducted to determine how best to decrease tire wear observed after previous Kennedy Space Center landings and how to improve crosswind landing capability. Modifications were made to the Kennedy Space Center's Shuttle landing facility runway. The primary purpose of the modifications was to enhance safety by reducing tire wear during landing.

Nose Wheel Steering Modifications. The nose wheel steering system was modified on *Columbia* (OV-102) for the 61-C mission, and *Discovery* (OV-103) and *Atlantis* (OV-104) were being similarly modified before their return to flight. The modification allowed for a safe high-speed engagement of the nose wheel steering system and provided positive lateral directional control of the orbiter during rollout in the presence of high crosswinds and blown tires.

Thermal Protection System Modifications. The area aft of the reinforced carbon-carbon nose cap to the nose landing gear doors were damaged (tile slumping) during flight operations from impact during ascent and overheating during reentry. This area, which previously was covered with high-temperature reusable surface insulation tiles, would now be covered with reinforced carbon-carbon. The low-temperature thermal protection system tiles on *Columbia*'s mid-body, payload bay doors, and vertical tail were replaced with advanced flexible reusable surface insulation blankets. Because of evidence of plasma flow on the lower wing trailing edge and elevon landing edge tiles (wing/elevon cove) at the outboard elevon tip and inboard elevon, the low-temperature tiles were being replaced with fibrous refractory composite insulation and high-temperature tiles along with gap fillers on *Discovery* and *Atlantis.* On *Columbia,* only gap fillers were installed in this area.

Wing Modification. Before the wings for *Discovery* and *Atlantis* were manufactured, NASA instituted a weight reduction program that resulted in a redesign of certain areas of the wing structure. An assessment of wing air loads from actual flight data indicated greater loads on the wing structure than predicted. To maintain positive margins of safety during ascent, structural modifications were made.

Mid-Fuselage Modifications. Because of additional detailed analysis of actual flight data concerning descent-stress thermal-gradient loads, torsional straps were added to tie all the lower mid-fuselage stringers in bays 1 through 11 together in a manner similar to a box section. This eliminated rotational (torsional) capabilities to provide positive margins of safety. Also, because of the detailed analysis of actual descent flight data, room-temperature vulcanizing silicone rubber material was bonded to the lower mid-fuselage from bays 4 through 11 to act as a heat sink, distributing temperatures evenly across the bottom of the mid-fuselage, reducing thermal gradients, and ensuring positive margins of safety.

General Purpose Computers. NASA was to replace the existing general purpose computers aboard the Space Shuttle orbiters with new upgraded general purpose computers in late 1988 or early 1989. The upgraded computers allowed NASA to incorporate more capabilities into the orbiters and apply advanced computer technologies that were not available when the orbiter was first designed. The upgraded general purpose computers would provide two and a half times the existing memory capacity and up to three times the existing processor speed, with minimum impact on flight software. They would be half the size, weigh approximately half as much, and require less power to operate.

Inertial Measurement Unit Modifications. The new high-accuracy inertial navigation system were to be phased in to augment the KT-70 inertial measurement units in 1988–89. These new inertial measurement units would result in lower program costs over the next decade, ongoing production support, improved performance, lower failure rates, and reduced size and weight. The HAINS inertial measurement units also would contain an internal dedicated microprocessor with memory for processing and storing compensation and scale factor data from the vendor's calibration, thereby reducing the need for extensive initial load data for the orbiter's computers.

Crew Escape System. Hardware changes were made to the orbiter and to the software system to accommodate the crew escape system addressed in Recommendation VII.

Seventeen-Inch Orbiter/External Tank Disconnects. Each mated pair of seventeen-inch disconnects contained two flapper valves: one on the orbiter side and one on the external tank side. Both valves in each disconnect pair were opened to permit propellant flow between the orbiter and the external tank. Prior to separation from the external tank, both valves in each mated pair of disconnects were commanded closed by pneumatic (helium) pressure from the main propulsion system. The closure of both valves in each disconnect pair prevented propellant discharge from the external tank or orbiter at external tank separation. Valve closure on the orbiter side of each disconnect also prevented contamination of the orbiter main propulsion system during landing and ground operations.

Inadvertent closure of either valve in a seventeen-inch disconnect during main engine thrusting would stop propellant flow from the external tank to all three main engines. Catastrophic failure of the main engines and external tank feed lines would result. To prevent the inadvertent closure of the seventeen-inch disconnect valves during the Space Shuttle main engine thrusting period, a latch mechanism was added in each orbiter half of the disconnect. The latch mechanism provided a mechanical backup to the normal fluid-induced-open forces. The latch was mounted on a shaft in the flow stream so that it overlapped both flappers and obstructed closure for any reason.

In preparation for external tank separation, both valves in each seventeen-inch disconnect were commanded closed. Pneumatic pressure from the main propulsion system caused the latch actuator to rotate the shaft in each orbiter seventeen-inch disconnect ninety degrees, thus freeing the flapper valves to close as required for external tank separation. A backup mechanical separation capability was provided in case a latch pneumatic actuator malfunctioned. When the orbiter umbilical initially moved away from the external tank umbilical, the mechanical latch disengaged from the external tank flapper valve and permitted the orbiter disconnect flapper to toggle the latch. This action permitted both flappers to close.

Changes made to the Space Shuttle main engines as part of the Margin Improvement Program and solid rocket motor redesign were addressed in Chapter 2 as part of the discussion of launch systems.

Return to Flight

Preparation for STS-26

NASA selected *Discovery* as the Space Shuttle for the STS-26 mission in 1986. At the time of the STS 51-L accident, *Discovery* was in temporary storage in the Kennedy Space Center's Vehicle Assembly Building, awaiting transfer to the Orbiter Processing Facility for preparation for the first Shuttle flight from Vandenberg Air Force Base, California, scheduled for later that year. *Discovery* last flew in August 1985 on STS 51-I, the orbiter's sixth flight since it joined the fleet in November 1983.

In January 1986, *Atlantis* was in the Orbiter Processing Facility, prepared for the Galileo mission and ready to be mated to the boosters and tank in the Vehicle Assembly Building. *Columbia* had just completed the STS 61-C mission a few weeks prior to the *Challenger* accident and was also in the Orbiter Processing Facility undergoing postflight deconfiguration.

NASA was considering various Shuttle manifest options, and it was determined that *Atlantis* would be rolled out to Launch Pad 39-B for fit checks of new weather protection modifications and for an emergency egress exercise and a countdown demonstration test. During that year, NASA also decided that *Columbia* would be flown to Vandenberg for fit checks. *Discovery* was then selected for the STS-26 mission.

Discovery was moved from the Vehicle Assembly Building High Bay 2, where it was in temporary storage, into the Orbiter Processing Facility the last week of June 1986. Power-up modifications were active on the orbiter's systems until mid-September 1986, when *Discovery* was transferred to the Vehicle Assembly Building while technicians performed facility modifications in Bay 1 of Orbiter Processing Facility.

Discovery was moved back into the Orbiter Processing Facility's Bay 1 on October 30, 1987, a milestone that initiated an extensive modification and processing flow to ready the vehicle for flight. The hiatus in launching offered an opportunity to "tune up" and fully check out all of the orbiter's systems and treat the orbiter as if it was a new vehicle. Technicians removed most of the orbiter's major systems and components and sent them to the respective vendors for modifications or rebuilding.

After an extensive powered-down period of six months, which began in February 1987, *Discovery*'s systems were awakened when power surged through its electrical systems on August 3, 1987. *Discovery* remained in the Orbiter Processing Facility while workers implemented more than 200 modifications and outfitted the payload bay for the TDRS. Flight processing began in mid-September with the reinstallation and checkout of the major components of the vehicle, including the main engines, the right- and lefthand OMS pods, and the forward RCS.

In January 1988, *Discovery*'s three main engines arrived at the Kennedy Space Center and were installed. Engine 2019 arrived on January 6, 1988, and was installed in the number one position on January 10. Engine 2022 arrived on January 15 and was installed in the number two position on January 24. Engine 2028 arrived on January 21 and was installed in the number three position also on January 24.

The redesigned solid rocket motor segments began arriving at Kennedy on March 1, and the first segment, the left aft booster, was stacked on Mobile Launcher 2 in the Vehicle Assembly Building's High

Bay 3 on March 29. Technicians started with the left aft booster and continued stacking the four lefthand segments before beginning the righthand segments on May 5. They attached the forward assemblies/nose cones on May 27 and 28. The solid rocket boosters' field joints were closed out prior to mating the external tank to the boosters on June 10. An interface test between the boosters and tank was conducted a few days later to verify the connections.

The OASIS payload was installed in *Discovery*'s payload bay on April 19. TDRS arrived at the Orbiter Processing Facility on May 16, and its inertial upper stage arrived on May 24. The TDRS/inertial upper stage mechanical mating took place on May 31. *Discovery* was moved from the Orbiter Processing Facility to the Vehicle Assembly Building on June 21, where it was mated to the external tank and solid rocket boosters. A Shuttle interface test conducted shortly after the mate checked out the mechanical and electrical connections among the various elements of the Shuttle vehicle and the function of the on-board flight systems.

The assembled Space Shuttle vehicle aboard its mobile launcher platform was rolled out of the Vehicle Assembly Building on July 4. It traveled just over four miles to Launch Pad 39-B for a few major tests and final launch preparations.

A few days after *Discovery*'s OMS system pods were loaded with hypergolic propellants, a tiny leak was detected in the left pod (June 14). Through the use of a small, snake-like, fiber optics television camera, called a Cobra borescope, workers pinpointed the leak to a dynatube fitting in the vent line for the RCS nitrogen tetroxide storage tank, located in the top of the OMS pod. The tiny leak was stabilized and controlled by "pulse-purging" the tank with helium—an inert gas. Pulse-purge is an automated method of maintaining a certain amount of helium in the tank. In addition, console operators in the Launch Control Center firing room monitored the tank for any change that may have required immediate attention. It was determined that the leak would not affect the scheduled Wet Countdown Demonstration Test and the Flight Readiness Firing, and repair was delayed until after these tests.

The Wet Countdown Demonstration Test, in which the external tank was loaded with liquid oxygen and liquid hydrogen, was conducted on August 1. A few problems with ground support equipment resulted in unplanned holds during the course of the countdown. A leak in the hydrogen umbilical connection at the Shuttle tail service mast developed while liquid hydrogen was being loaded into the external tank. Engineers traced the leak to a pressure monitoring connector. During the Wet Countdown Demonstration Test, the leak developed again. The test was completed with the liquid hydrogen tank partially full, and the special tanking tests were deleted. Seals in the eight-inch fill line in the tail service mast were replaced and leak-checked prior to the Flight Readiness Firing. In addition, the loading pumps in the liquid oxygen storage farm were not functioning properly. The pumps and their associated motors were repaired.

After an aborted first attempt, the twenty-two-second Flight Readiness Firing of *Discovery*'s main engines took place on August 10. The first Flight Readiness Firing attempt was halted inside the T-ten-second mark because of a sluggish fuel bleed valve on the number two main engine. Technicians replaced this valve prior to the Flight Readiness Firing. This firing verified that the entire Shuttle system, including launch equipment, flight hardware, and the launch team, were ready for flight. With more than 700 pieces of instrumentation installed on the vehicle elements and launch pad, the test provided engineers with valuable data, including characteristics of the redesigned solid rocker boosters.

After the test, a team of Rockwell technicians began repairs to the OMS pod leak. They cut four holes into two bulkheads with an air-powered router on August 17 and bolted a metal “clamshell” device around the leaking dynatube fitting. The clamshell was filled with Furmanite—a dark thick material consisting of graphite, silicon, heavy grease, and glass fiber. After performing a successful initial leak check, covers were bolted over the holes on August 19, and the tank was pressurized to monitor any decay. No leakage or decay in pressure was noted, and the fix was deemed a success.

TDRS-C and its inertial upper stage were transferred from the Orbiter Processing Facility to Launch Pad 39-B on August 15. The payload was installed into *Discovery*'s payload bay on August 29. Then a Countdown Demonstration Test was conducted on September 8. Other launch preparations held prior to launch countdown included final vehicle ordinance activities, such as power-on stray-voltage checks and resistance checks of firing circuits, the loading of the fuel cell storage tanks, the pressurization of the hypergolic propellant tanks aboard the vehicle, final payload closeouts, and a final functional check of the range safety and solid rocket booster ignition, safe, and arm devices.

STS-26 Mission Overview

The Space Shuttle program returned to flight with the successful launch of *Discovery* on September 29, 1988. The Shuttle successfully deployed the TDRS, a 2,225-kilogram communications satellite attached to a 14,943-kilogram rocket. In addition, eleven scheduled scientific and technological experiments were carried out during the flight.

The STS-26 crew consisted of only experienced astronauts. Twenty months of preflight training emphasized crew safety. The crew members prepared for every conceivable mishap or malfunction.

Among the changes made in the Shuttle orbiter was a crew escape system for use if an engine should malfunction during ascent to orbit or if a controlled landing was risky or impossible. As part of this escape system, the crew wore newly designed partially pressurized flight suits during ascent, reentry, and landing. Each suit contained oxygen supplies, a parachute, a raft, and other survival equipment. The new escape system would permit astronauts to bail out of the spacecraft in an emergency during certain segments of their ascent toward orbit. To escape, the astronauts would blow off a hatch in the spacecraft cabin wall, extend a telescoping pole 3.65 meters beyond the spacecraft, and slide along the pole. From the pole, they would parachute to Earth.

The improved main engines were test-fired for a total of 100,000 seconds, which is equal to their use time in sixty-five Shuttle launches. The solid rocket boosters were tested with fourteen different flaws deliberately etched into critical components.

The launch was delayed for one hour and thirty-eight minutes because of unsuitable weather conditions in the upper atmosphere. Winds at altitudes between 9,144 and 12,192 meters were lighter than usual for that time of the year, and launch was prohibited because this condition had not been programmed into the spacecraft's computer. However, after specialists analyzed the situation, they judged that *Discovery* could withstand these upper-air conditions. Shuttle managers approved a waiver of the established flight rule and allowed the launch to proceed under the existing light wind conditions.

Upon the conclusion of the mission, *Discovery* began its return to Earth at 11:35 a.m., Eastern Daylight Time, on October 3. *Discovery* was traveling at about twenty-five times the speed of sound over the Indian Ocean when the astronauts fired the deorbit engines and started the hour-long descent. Touchdown was on a dry lake bed at Edwards Air Force Base.

Space Station

Overview and Background

The notion of a space station was not new or revolutionary when, in his State of the Union message of January 25, 1984, President Ronald Reagan directed NASA to develop a permanently occupied space station within the next ten years. Even before the idea of a Space Shuttle had been conceived in the late 1960s, NASA had envisioned a space station as a way to support high-priority science missions. Once the Shuttle's development was under way, a space station was considered as its natural complement—a destination for the orbiter and a base for its trip back to Earth. By 1984, NASA had already conducted preliminary planning efforts that sought the best space station concept to satisfy the requirements of potential users.

Reagan's space station directive underscored a national commitment to maintaining U.S. leadership in space. A space station would, NASA claimed, stimulate technology resulting in "spinoffs" that would improve the quality of life, create jobs, and maintain the U.S. skilled industrial base. It would improve the nation's competitive stance at a time when more and more high-technology products were being purchased in other countries. It offered the opportunity to add significantly to knowledge of

Earth and the universe.[25] The president followed up his directive with a request for $150 million for space station efforts in FY 1985. Congress approved this request and added $5.5 million in earlier year appropriations to total $155.5 million for the space station in FY 1985.[26]

From its start, international participation was a major objective of the Space Station program. Other governments would conduct their own definition and preliminary design programs in parallel with NASA and would provide funding. NASA anticipated international station partners who defined missions and used station capabilities, participated in the definition and development activities and who contributed to the station capabilities, and supported the operational activities of the station.

Events moved ahead, and on September 14, 1984, NASA issued a request for proposal (RFP) to U.S. industry for the station's preliminary design and definition. The RFP solicited proposals for four separate "work packages" that covered the definition and preliminary design of station elements:

1. Pressurized "common" modules with appropriate systems for use as laboratories, living areas, and logistics transport; environmental control and propulsive systems; plans for equipping one module as a laboratory and others as logistics modules; and plans for accommodations for orbital maneuvering and orbital transfer systems
2. The structural framework to which the various elements of the station would be attached; interface between the station and the Space Shuttle; mechanisms such as the RMS and attitude control, thermal control, communications, and data management systems; plans for equipping a module with sleeping quarters, wardroom, and galley; and plans for EVA
3. Automated free-flying platforms and provisions to service and repair the platforms and other free-flying spacecraft; provisions for instruments and payloads to be attached externally to the station; and plans for equipping a module for a laboratory
4. Electrical power generation, conducting, and storage systems.[27]

Proposals from industry were received in November 1984. Also in 1984, NASA designated the Johnson Space Center as the lead center for the Space Station program. In addition, NASA established seven inter-

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[25] "Space Station," NASA Information Summaries, December 1986, p. 2.

[26] U.S. Congress, Conference Report, June 16, 1984, Chronological History, Fiscal Year 1985 Budget Submission authorized the initial $150 million. The Conference Committee authorized the additional $5 million from fiscal year 1984 appropriations as part of a supplemental appropriations bill, approved August 15, 1985.

[27] Space Station Definition and Preliminary Design, Request for Proposal, September 15, 1984.

center teams to conduct advanced development activities for high-potential technologies to be used in station design and development, and the agency assigned definition and preliminary design responsibilities to four field centers: the Marshall Space Flight Center, Johnson, the Goddard Space Flight Center, and the Lewis Research Center. The agency also established a Headquarters-based Space Station Program Office to provide overall policy and program direction.

Response to proposals for a space station was not uniformly favorable. In particular, the *New York Times* criticized the usefulness of the project. It called the proposed space station "an expensive yawn in space" (January 29, 1984) and "the ultimate junket" (November 9, 1984).[28] The *Times* claimed that unoccupied space platforms could accomplish anything that an occupied space platform could. Nevertheless, Reagan remained an enthusiastic proponent of the project, and NASA moved ahead.

NASA defined three categories of missions as the basis for space station design. Science and applications missions included astrophysics, Earth science and applications, solar system exploration, life sciences, materials science, and communications. Commercial missions included materials processing in space, Earth and ocean observations, communications, and industrial services. Technology development missions included materials and structures, energy conversion, computer science and electronics, propulsion, controls and human factors, station systems/operations, fluid and thermal physics, and automation and robotics.

NASA's 1984 plans called for the station to be operational in the early 1990s, with an original estimated U.S. investment of $8.0 billion (1984 dollars).[29] The station would be capable of growth both in size and capability and was intended to operate for several decades. It would be assembled at an altitude of about 500 kilometers at an inclination to the equator of twenty-eight and a half degrees. All elements of the station would be launched and tended by the Space Shuttle.[30]

On April 19, 1985, NASA's Space Station Program Office Manager Neil Hutchinson authorized the start of the definition phase contracts. Marshall, Johnson, Goddard, and Lewis each awarded competitive contracts on one of four work packages to eight industry teams (Table 3–50). These contracts extended for twenty-one months and defined the system requirements, developed supporting technologies and technology development plans, performed supporting systems and trade studies, developed preliminary designs and defined system interfaces, and developed plans, cost estimates, and schedules for the Phase C/D (design and development)

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[28] *New York Times,* January 29, 1984; *New York Times,* November 9, 1984.

[29] Philip E. Culbertson, "Space Station: A Cooperative Endeavor," paper to 25th International Meeting on Space, Rome, Italy, March 26–28, 1985, p. 4, NASA Historical Reference Collection, NASA Headquarters, Washington, DC.

[30] Leonard David, *Space Station Freedom—A Foothold on the Future,* NASA pamphlet, Office of Space Science, 1986.

activities. In addition to the lead centers for each work package, the Kennedy Space Center was responsible for preflight and launch operations and would participate in logistics support activities. Other NASA centers would also support the definition and preliminary design activities.

Also during 1985, NASA signed memoranda of understanding (MOUs) with Canada, ESA, and Japan. The agreements provided a framework for cooperation during the definition and preliminary design phase (Phase B) of the program. Under the MOUs, the United States and its international partners would conduct and coordinate simultaneous Phase B studies. NASA also signed an MOU with Space Industries, Inc., of Houston, a privately funded venture to exchange information during Phase B. Space Industries planned to develop a pressurized laboratory that would be launched by the Space Shuttle and could be serviced from the station.

Progress on the station continued through 1986.[31] NASA issued a Technical and Management Information System (TMIS) RFP in July. The TMIS would be a computer-based system that would support the technical and management functions of the overall Space Station program. NASA also issued a Software Support Environment RFP for the "environment" that would be used for all computer software developed for the program. A draft RFP for the station's development phase (Phase C/D) was also issued in November 1986, with the definitive RFP released on April 24, 1987.[32]

In 1987, in accordance with a requirement in the Authorization Act for FY 1988, NASA began preparing a total cost plan spanning three years. Called the Capital Development Plan, it included the estimated cost of all direct research and development, spaceflight, control and data communications, construction of facilities, and resource and program management. This plan complemented the Space Station Development Plan submitted to Congress in November 1987.

Also during 1987, NASA awarded several station development contracts:

1. Boeing Computer Services Company was selected in May to develop the TMIS.
2. Lockheed Missiles and Space Company was chosen in June to develop the Software Support Environment contract.

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[31] It is interesting to note that by 1986, the Soviet Union had already operated several versions of a space station. In February 1986, it placed into orbit a new space station called *Mir*, the Russian word for peace. The Soviets indicated they intended to occupy *Mir* permanently and make it the core of a busy complex of space-based factories, construction and repair facilities, and laboratories.

[32] "NASA Issues Requests for Proposals for Space Station Development," *NASA News*, Release 87-65, April 24, 1987.

3. Grumman Aerospace Corporation was picked in July to provide the Space Station Program Office with systems engineering and integration, in addition to a broad base of management support.

In addition, Grumman and Martin Marietta Astronautics Company were selected in November for definition and preliminary design of the Flight Telerobotic System, a space robot that would perform station assembly and spacecraft servicing tasks.

In December 1987, NASA selected the four work package contractors. These four aerospace firms were to design and build the orbital research base. Boeing Aerospace was selected to build the pressurized modules where the crews would work and live (Work Package 1). NASA chose McDonnell Douglas Astronautics Company to develop the structural framework for the station, as well as most of the major subsystems required to operate the facility (Work Package 2). GE Astro-Space Division was picked to develop the scientific platform that would operate above Earth's poles and the mounting points for instruments placed on the occupied base (Work Package 3). NASA selected the Rocketdyne Division of Rockwell International to develop the system that would furnish and distribute electricity throughout the station (Work Package 4).

The contracts included two program phases. Phase I covered the approximately ten-year period from contract start through one year after completion of station assembly. Phase II was a priced option that, if exercised, would enhance the capabilities of the station by adding an upper and lower truss structure, additional external payload attachment points, a solar dynamic power system, a free-flying co-orbiting platform, and a servicing facility. Contract negotiations with Boeing, McDonnell Douglas, GE Astro-Space, and Rocketdyne to design and build *Freedom*'s occupied base and polar platform were completed in September 1988. With these contracts in place, the definition and preliminary design (Phase B) ended and detailed design and development (Phase C/D) began. The award of these contracts followed approval by Congress and President Reagan of the overall federal funding bill that made available more than $500 million in FY 1988 for station development activities. This amount included funds remaining from the FY 1987 station appropriation as well as the new funding provided under the FY 1988 bill.[33]

In February 1988, the associate administrator for space station signed the Program Requirements Document. This top-level document contained requirements for station design, assembly, utilization, schedule, safety, evolution, management, and cost. In May, the Program Requirements Review began at the NASA Headquarters program office and was completed at the four work package centers by the end of the year. The Program Requirements Review provided a foundation to begin the

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[33] "NASA Awards Contracts to Space Station Contractors," *NASA News*, Release 87-187, December 23, 1987.

detailed design and development process by verifying program requirements and ensuring that those requirements could be traced across all levels of the program and be met within the available technical and fiscal resources.

In July 1988, President Reagan named the international station *Freedom.* The U.S. international partners signed agreements to cooperate with the United States in developing, using, and operating the station. Government-level agreements between the United States and nine European nations, Japan, and Canada, and MOUs between NASA and ESA and between NASA and Canada were signed in September. The NASA-industry team proceeded to develop detailed requirements to guide design work beginning early in 1989.

Proposed Configurations

For the purpose of the 1984 RFP, NASA selected the "power tower" as the reference configuration for the station. NASA anticipated that this configuration could evolve over time. The power tower would consist of a girder 136 meters in length that would circle Earth in a gravity-gradient attitude. Pressurized laboratory modules, service sheds, and docking ports would be placed on the end always pointing downward; instruments for celestial observation would be mounted skyward; and the solar power arrays would be mounted on a perpendicular boom halfway up the tower.

After intensive reviews, NASA replaced the power tower configuration in 1985 with the "dual keel" configuration (Figure 3–31). This configuration featured two parallel 22.6-meter vertical keels, crossed by a single horizontal beam, which supported the solar-powered energy system by a double truss, rectangular-shaped arrangement that shortened the height of the station to ninety-one meters. This configuration made a stronger frame, thus better dampening the oscillations expected during operations. The design also moved the laboratory modules to the station's center of gravity to allow scientists and materials processing researchers to work near the quality microgravity zone within the station. Finally, the dual keel offered a far larger area for positioning facilities, attaching payloads, and storing supplies and parts. NASA formally adopted this design at its May 1986 Systems Requirements Review. Its Critical Evaluation Task Force modified the design in the fall of 1986 to increase the size of the nodes to accommodate avionics packages slated for attachment to the truss, thereby increasing pressurized volume available as well as decreasing the requirement for EVA.

In 1987, NASA and the administration, responding to significant increases in program costs, decided to take a phased approach to station development. In April 1987, the Space Station program was divided into Block I and Block II. Block I, the Revised Baseline Configuration, included the U.S. laboratory and habitat modules, the accommodation of attached payloads, polar platform(s), seventy-five kilowatts of photovoltaic power, European and Japanese modules, the Canadian Mobile

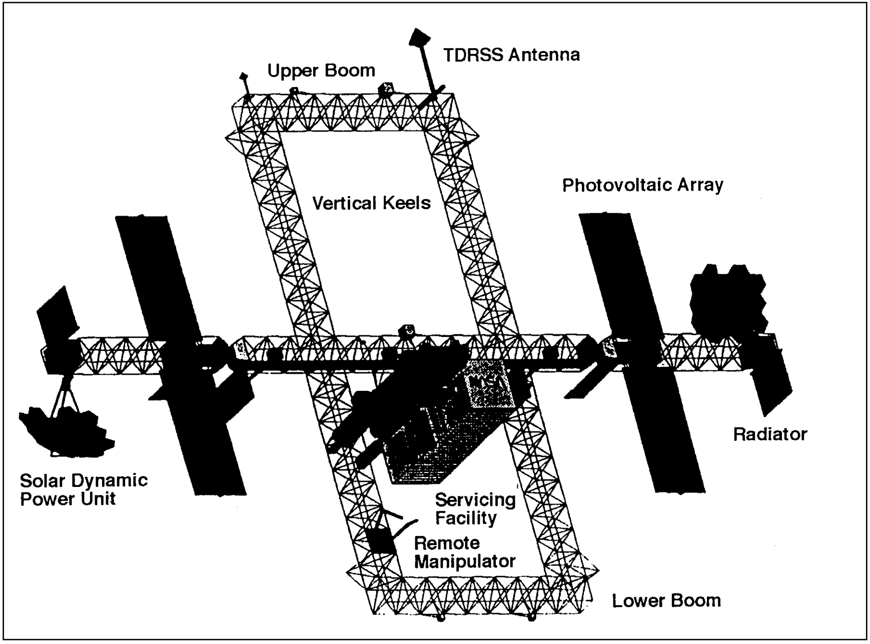

Figure 3–31. Dual Keel Final Assembly Configuration (adopted at May 1986 Systems Requirements Review)

Servicing System, and provisions for evolution (Figure 3–32). The modules would be attached to a 110-meter boom. Block II, an Enhanced Configuration, would have an additional fifty kilowatts of power via a solar dynamic system, additional accommodation of attached payloads on dual keels and upper and lower booms, a servicing bay, and co-orbiting platforms (Figure 3–33).

Operations and Utilization Planning

NASA first formulated an operations concept for the space station in 1985 that considered preliminary launch, orbit, and logistics operational requirements, objectives such as reduced life-cycle costs, and international operations. It was determined that the station elements fulfill user requirements affordably and that NASA be able to afford the overall system infrastructure and logistics.

In 1985, the Space Station Utilization Data Base (later called the Mission Requirements Data Base) included more than 300 potential payloads from the commercial sector and from technology development, science, and applications communities. The information in this data base was used to evaluate potential designs of the station and associated platforms. Besides NASA, user sponsors included ESA, Canada, Japan, and the National Oceanic and Atmospheric Administration. In addition, a large number of private-sector users had requested accommodations on the station. Considerable interest was also expressed in using polar

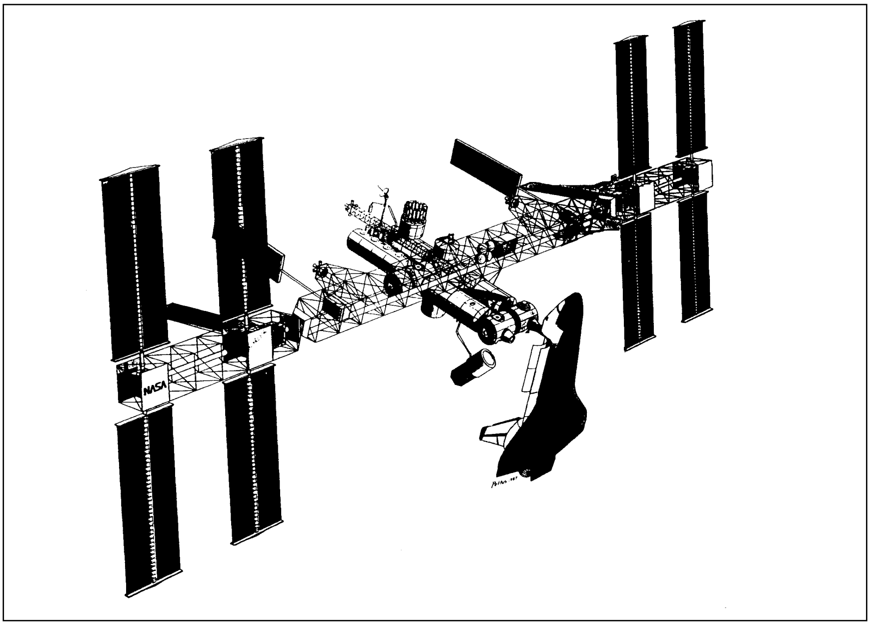

Figure 3–32. Revised Baseline Configuration (1987), Block I
(This configuration would include the U.S. laboratory and habitat modules, accommodation of attached payloads, polar platform(s), seventy-five kilowatts of photovoltaic power, European and Japanese modules, the Canadian Mobile Servicing System, and provisions for evolution.)

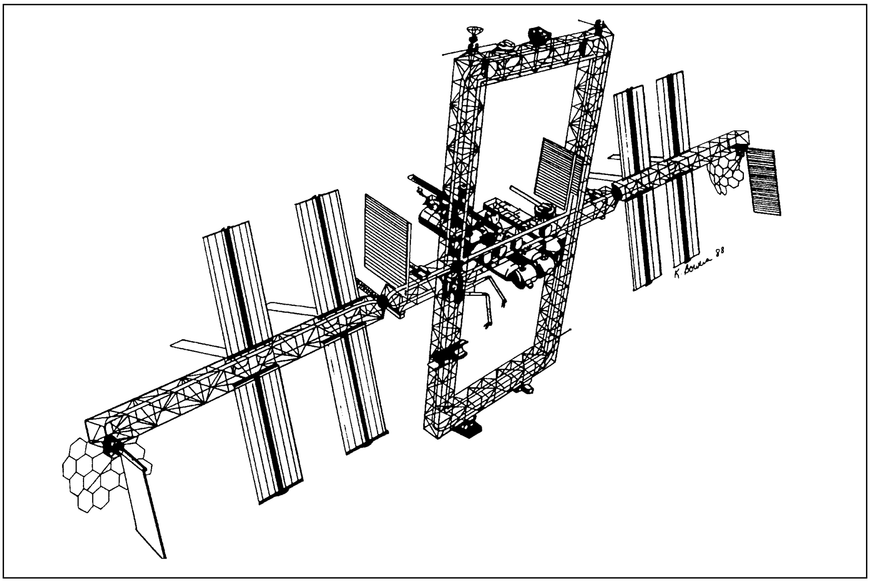

Figure 3–33. Enhanced Configuration, Block II
(This would have an additional fifty kilowatts of power via a solar dynamic system, additional accommodation of attached payloads on dual keels and upper and lower booms, a servicing bay, and co-orbiting platforms.)

platforms for solar-terrestrial physics, life sciences, astronomy, and Earth observation investigations. Polar platforms could support many related instruments, provide operational flexibility because of their modular design, and have indefinitely long lifetimes because they could be serviced while in orbit.

In 1986, NASA formulated an Operations Management Concept that outlined the philosophy and management approaches to station operations. Using the concept as a point of departure, an Operations Task Force was established to perform a functional analysis of future station operations. In 1987, the Operations Task Force developed an operations concept and concluded its formal report in April. NASA also implemented an operations plan, carried out further study of cost management, and conducted a study on science operations management that was completed in August.

NASA issued a preliminary draft of a *Space Station User's Handbook* that would be a guide to the station for commercial and government users. Pricing policy studies were also initiated, and NASA also revised the Mission Requirements Data Base. Part of the utilization effort was aimed at defining the user environment. The "Space Station Microgravity Environment" report submitted to Congress in July 1988 described the microgravity characteristics expected to be achieved in the U.S. Laboratory and compared these characteristics to baseline program operations and utilization requirements.

Evolution Planning

The station was designed to evolve as new requirements emerged and new capabilities became available. The design featured "hooks" and "scars," which were electronic and mechanical interfaces that would allow station designers to expand its capability. In this way, new and upgraded components, such as computer hardware, data management software, and power systems, could be installed easily.

The Enhanced Configuration was an example of evolution planning. In this version, two 103-meter-long vertical spines connected to the horizontal cross boom. With a near-rectangle shape comparable in size to a football field, the frame would be much stiffer and allow ample room for additional payloads.

In 1987, NASA established an Evolution Management Council. The Langley Research Center was designated as responsible for station evolution to meet future requirements. This responsibility included conducting mission, systems, and operations analyses, providing systems-level planning of options/configurations, coordinating and integrating study results by others, chairing the evolution working group, and supporting advanced development program planning.

A presidential directive of February 11, 1988, on "National Space Policy" stated that the "Space Station would allow evolution in keeping with the needs of station users and the long-term goals of the U.S."[34] This directive reaffirmed NASA's objective to design and build a station that could expand capabilities and incorporate improved technologies. Planning for evolution would occur in parallel with the design and development of the baseline station.

To support initiatives such as the Humans to Mars and Lunar Base projects, the station would serve as a facility for life science research and technology development and eventually as a transportation node for vehicle assembly and servicing. Another evolutionary path involved growth of the station as a multipurpose research and development facility. For these options, Langley conducted mission and systems analyses to determine primary resource requirements such as power, crew, and volume.

NASA Center Involvement

Marshall Space Flight Center

The Marshall Space Flight Center in Huntsville, Alabama, was designated as the Work Package 1 Center. Work Package 1 included the design and manufacture of the astronauts' living quarters, known as the habitation module (Figure 3–34); the U.S. Laboratory module; logistics elements, used for resupply and storage; node structures connecting the modules; the Environmental Control and Life Support System; and the thermal control and audio/video systems located within the pressurized modules.

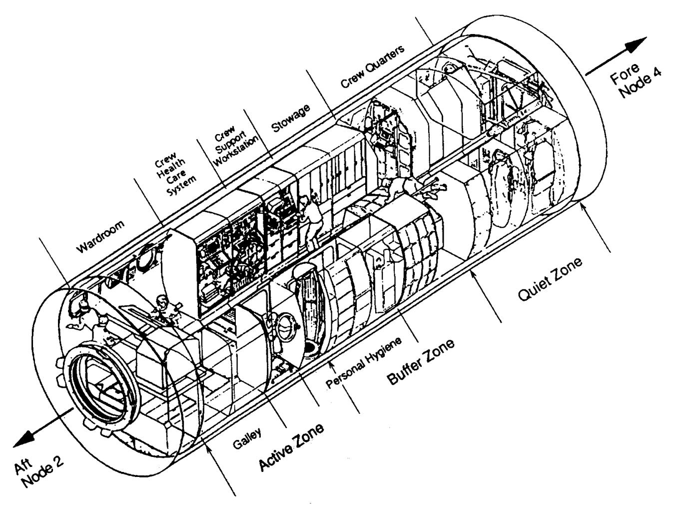

Figure 3–34. Habitation Module

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[34] Office of the Press Secretary, "Fact Sheet: Presidential Directive on National Space Policy," February 11, 1988.

Marshall established the Space Station Freedom Projects Office to manage and direct the various design, development, and operational activities needed to successfully complete the Work Package 1 assignment, as well as several facilities to support its work package activities. These included the Payload Operations Integration Center, the Engineering Support Center, and the Payload Training Facility.

Johnson Space Center

The Johnson Space Center near Houston was responsible for the design, development, verification, assembly, and delivery of Work Package 2 flight elements and systems. This included the integrated truss assembly, propulsion assembly, mobile transporter, resource node design and outfitting, external thermal control, data management, operations management, communications and tracking, extravehicular systems, guidance, navigation, and control systems, and airlocks. Johnson was also responsible for the attachment systems, the STS for its periodic visits, the flight crews, crew training and crew emergency return definition, and operational capability development associated with operations planning. Johnson provided technical direction to the Work Package 1 contractor for the design and development of all station subsystems.

Johnson set up the Space Station Freedom Projects Office with the responsibility of managing and directing the various design, development, assembly, and training activities. This office reported to the Space Station Program Office in Reston, Virginia. The projects office at Johnson was to develop the capability to conduct all career flight crew training. The integrated training architecture would include the Space Station Control Center and ultimately the Payload Operations Integration Center when the station became permanently occupied. Johnson established several facilities in support of its various responsibilities: the Space Station Control Center, the Space Systems Automated Integration and Assembly Facility, the Space Station Training Facility, and the Neutral Buoyancy Laboratory.

Goddard Space Flight Center

The Goddard Space Flight Center in Greenbelt, Maryland, had responsibility for the Work Package 3 portion of the Space Station program. It was responsible for developing the free-flying platforms and attached payload accommodations, as well as for planning NASA’s role in servicing accommodations in support of the user payloads and satellites. Goddard was also responsible for developing the Flight Telerobotic Servicer (Figure 3–35), which had been mandated by Congress in the conference report accompanying NASA’s FY 1986 appropriations bill. The Flight Telerobotic Servicer was an outgrowth of the automation and robotics initiative of the station’s definition and preliminary design phase.

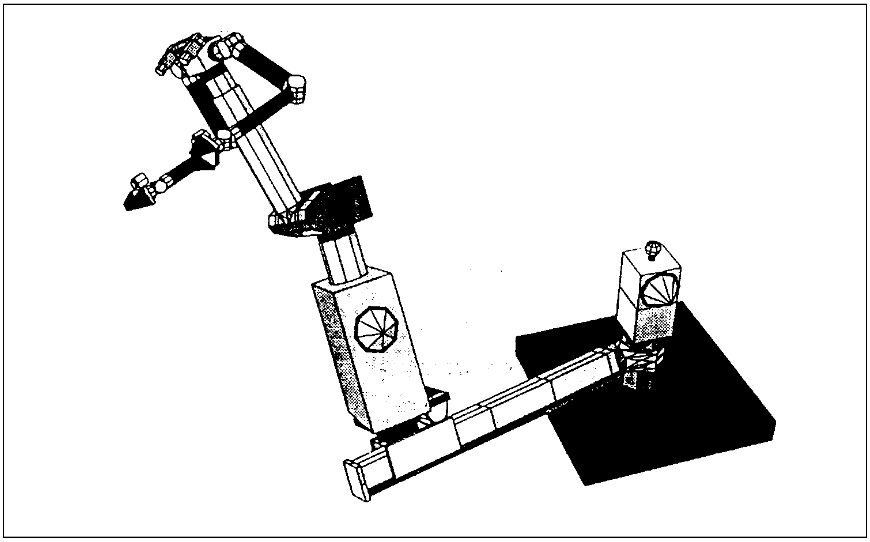

Figure 3–35. Flight Telerobotic Servicer

Lewis Research Center

The Lewis Research Center was responsible for the Work Package 4 portion of the Space Station program. Its station systems directorate was responsible for designing and developing the electric power system. This included responsibility for systems engineering and analysis for the overall electrical power system; all activities associated with the design, development, test, and implementation of the photovoltaic systems (Figure 3–36); hooks and scars activities in solar dynamics and in support of Work Package 2 in resistojet propulsion technology; power management and distribution system development; and activities associated with

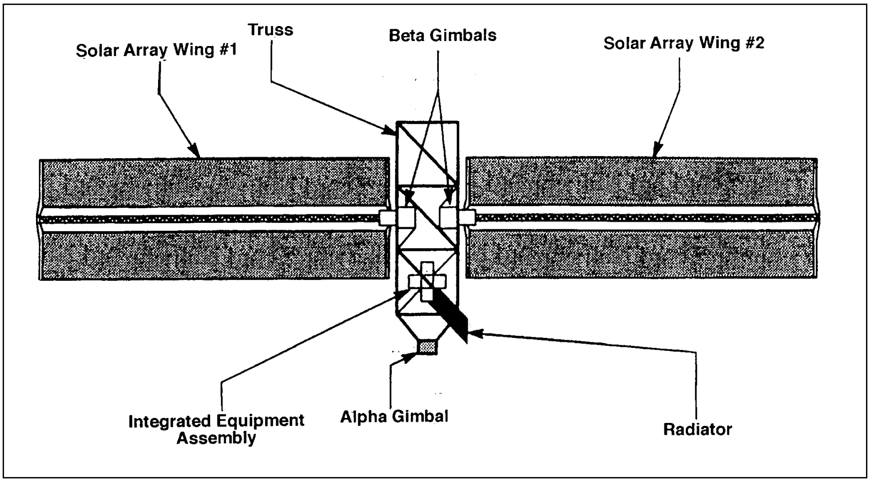

Figure 3–36. Photovoltaic Module

the Lewis station power system facilities and in planning electric power system mission operations.

International Cooperation

Canada

In March 1986, Canadian Prime Minister Brian Mulroney and President Reagan agreed to Canadian participation in the Space Station program. Canada intended to commit $1.2 billion to the program through the year 2000. Canada planned to provide the Mobile Servicing Center for Space Station *Freedom.* Together with a U.S.-provided, rail-mounted, mobile transporter, which would move along the truss, the Mobile Servicing Center and the transporter would comprise the Mobile Servicing System. The Mobile Servicing System was to play the main role in the accomplishing the station's assembly and maintenance, moving equipment and supplies around the station, releasing and capturing satellites, supporting EVAs, and servicing instruments and other payloads attached to the station. It would also be used for docking the Space Shuttle orbiter to the station and then loading and unloading materials from its cargo bay.

NASA considered the Mobile Servicing Center as part of the station's critical path: an indispensable component in the assembly, performance, and operation of the station. In space, Canada would supply the RMS, the Mobile Servicing Center and Maintenance Depot, the special purpose dexterous manipulator, Mobile Servicing System work and control stations, a power management and distribution system, and a data management system (Figure 3–37). On the ground, Canada would build a manipulator development and simulation facility and a mission operations facility. The Canadian Space Agency would provide project management.

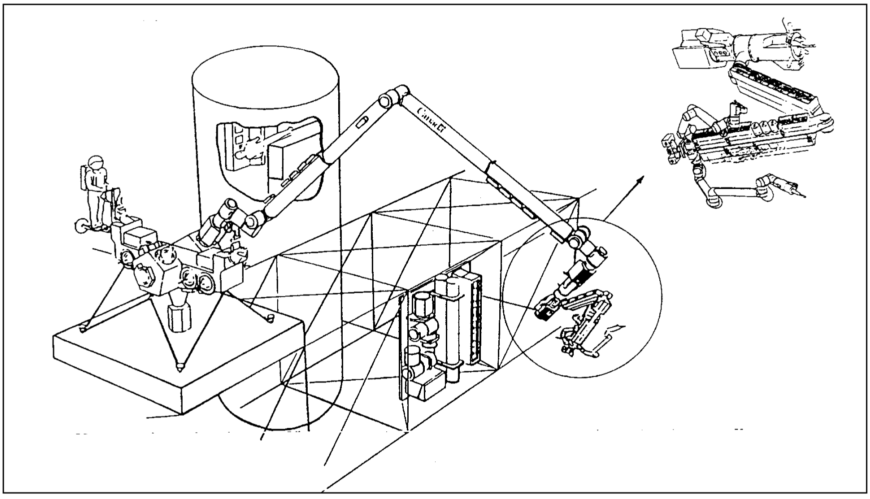

Figure 3–37. Mobile Servicing System and Special Purpose Dexterous Manipulator

European Space Agency

ESA gave the name “Columbus” to its program to develop the three elements that Europe was to contribute to the station: the Columbus Attached Laboratory, the Columbus Free-Flying Laboratory, and the Columbus Polar Platform. Columbus would provide an in-orbit and ground infrastructure compatible with European and international user needs from the mid-1990s onward. The program would also provide Europe with expertise in human, human-assisted, and fully automatic space operations as a basis for future autonomous missions. The program aimed to ensure that Europe establish the key technologies required for these various types of spaceflight.

The concept of Columbus was studied in the early 1980s as a follow-up to the Spacelab. The design, definition, and technology preparation phase was completed at the end of 1987. The development phase was planned to cover 1988–98 and would be completed by the initial launch of Columbus’s three elements

Columbus Attached Laboratory. This laboratory would be permanently attached to the station’s base. It would have a diameter of approximately four meters and would be used primarily for materials sciences, fluid physics, and compatible life sciences missions (Figure 3–38). The attached laboratory would be launched from the Kennedy Space Center on a dedicated Space Shuttle flight, removed from the Shuttle’s payload bay, and berthed at the station’s base.

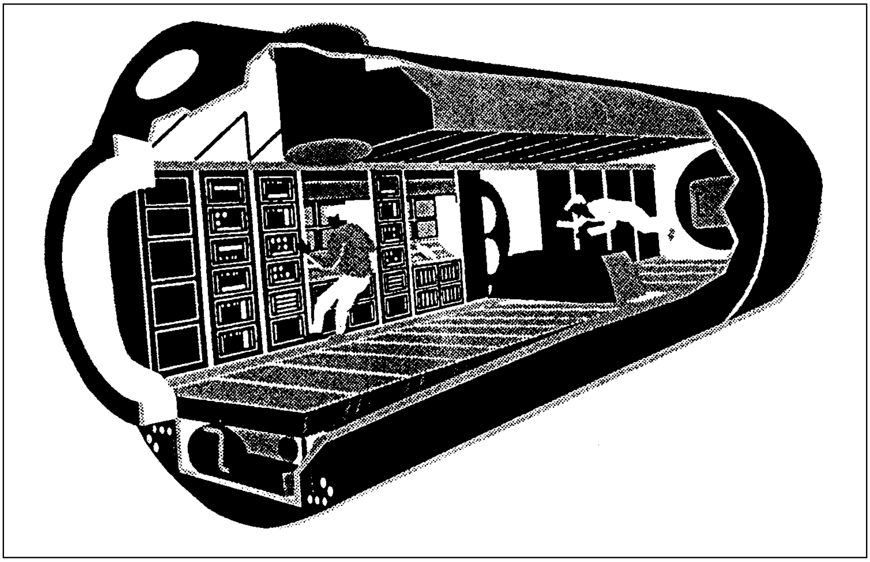

Figure 3–38. Columbus Attached Laboratory

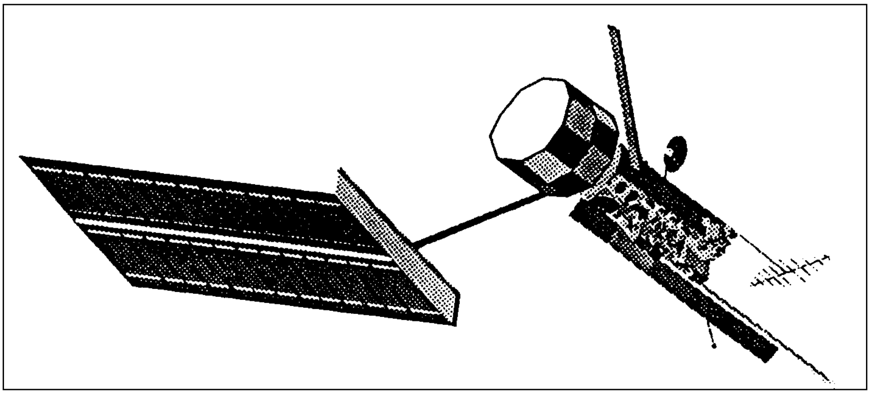

Figure 3–39. Columbus Free-Flying Laboratory

Columbus Free-Flying Laboratory. This free-flying laboratory (the "Free Flyer") would operate in a microgravity optimized orbit with a twenty-eight-and-a-half-degree inclination, centered on the altitude of the station (Figure 3–39). It would accommodate automatic and remotely controlled payloads, primarily from the materials sciences and technology disciplines, together with its initial payload, and would be launched by an Ariane 5 from the Centre Spatial Guyanais in Kourou, French Guiana. The laboratory would be routinely serviced in orbit by a Hermes at approximately six-month intervals. Initially, this servicing would be performed at Space Station *Freedom,* which the Free Flyer would also visit every three to four years for major external maintenance events.

Columbus Polar Platform. This platform would be stationed in a highly inclined Sun-synchronous polar orbit with a morning descending node (Figure 3–40). It would be used primarily for Earth observation missions. The platform was planned to operate in conjunction with one or more additional platforms provided by NASA and/or other international partners and would accommodate European and internationally provided payloads. The platform would not be serviceable and would be designed to operate for a minimum of four years. The platform would accommodate between 1,700 and 2,300 kilograms of ESA and internationally provided payloads.

Japan

Japan initiated its space program in 1985 in response to the U.S. invitation to join the Space Station program. The Space Activities Commission's Ad Hoc Committee on the Space Station concluded that Japan should participate in the Phase B (definition) study of the program with its own experimental module. On the basis of the committee's conclusion, the Science and Technology Agency concluded a Phase B MOU with NASA. Under the supervision of the Science and Technology Agency, the National Space Development Agency of Japan, a quasi-

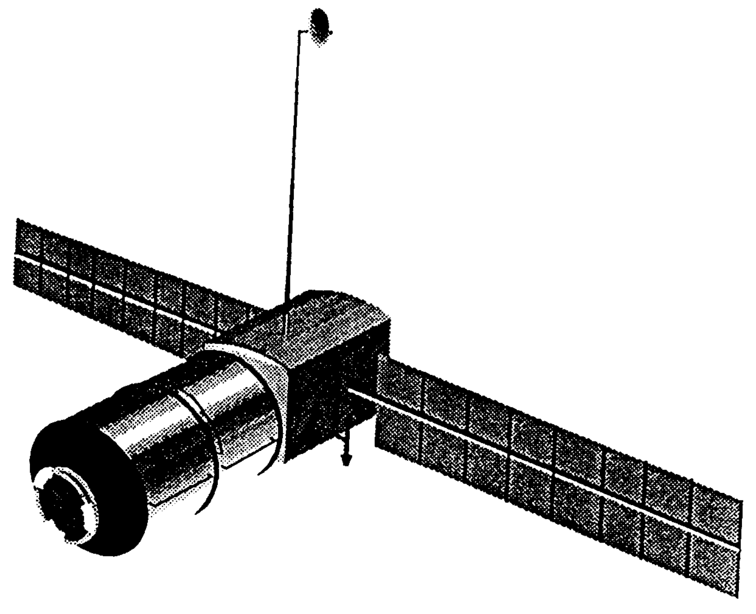

Figure 3–40. Columbus Polar Platform

governmental organization responsible for developing and implementing Japanese space activities, began the detailed definition and the preliminary design of the Japanese Experiment Module (JEM), which is shown in Figure 3–41 and would be attached to the Space Station. The JEM would be a multipurpose laboratory consisting of a pressurized module, an exposed facility, and an experiment logistics module (Table 3–51). The JEM would be launched on two Space Shuttle flights. The first flight

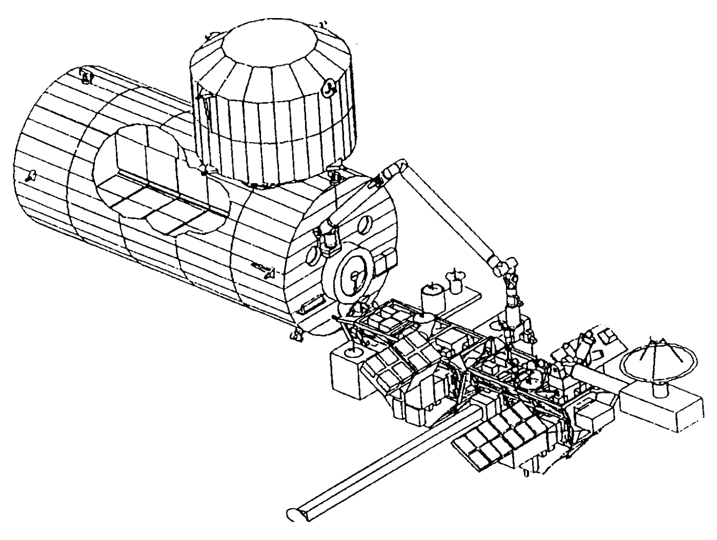

Figure 3–41. Japanese Experiment Module

would transport the pressurized module and the first exposed facility. The second flight would transport the second exposed facility and the experiment logistics module.

Commercial Participation

From its inception, one of the prime goals of the Space Station program was to encourage private-sector, space-based commercial activity. President Reagan's 1984 State of the Union message stated the objective of promoting private-sector investment in space through enhanced U.S. space-based operational capabilities. The station was planned to be highly conducive to commercial space activities by providing extended time in orbit, facilities for research and testing, and the presence of a trained crew for the periodic tending, repair, and handling of unexpected occurrences.

NASA's 1985 "Commercial Space Policy" set forth guidelines for the use of space for commercial enterprises relating to the station and other NASA activities. The guidelines stated that NASA welcomed and encouraged participation in station development and operations by companies that sought to develop station systems and services with private funds. NASA would provide incentives and technical assistance, including access to NASA data and facilities, where appropriate. NASA would protect proprietary rights and would request privately owned data only when necessary to carry outs its responsibilities.[35]

NASA expected the private sector to be a principal user of station capabilities. It also expected the private sector to participate in the program by providing services, both on the ground and in orbit. The private sector would participate in the program through procurements to design and build elements of the station and its related systems. In 1986, NASA's Commercial Advocacy Group conducted workshops to identify and encourage potential commercial use of the station, particularly in the areas of materials processing, Earth and ocean remote sensing, communications satellite delivery, and industrial services. In August 1986, NASA established "Guidelines for United States Commercial Enterprises for Space Station Development and Operations." These guidelines were to encourage U.S. private-sector investment and involvement in developing and operating station systems and services.

In November 1987, NASA issued a series of new program initiatives designed to expand the opportunities for pioneering commercial ventures in space. The initiatives built on earlier commercial development policies and provided for the continued encouragement of private space activities. The 1988 National Space Policy mandated the provision for commercial participation in the Space Station program. Commercial participation would be possible through commercial utilization and commercial

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[35] "NASA Guidelines for United States Commercial Enterprises for Space Station Development and Operations," Office of Space Station, NASA, 1985, NASA Historical Reference Collection, Washington, DC.

infrastructure activities. Commercial utilization activities would involve commercial users of the station who would conduct space-based research and development activities. Commercial infrastructure activities would involve provisions for selected station-related systems and services on a commercial basis to NASA and station users.

In October 1988, NASA published revised policy guidelines for proposals from commercial entities to provide the infrastructure for the station. These guidelines, revised in response to President Reagan's Commercial Space Initiatives, issued in February 1988, were intended to provide a framework to encourage U.S. commercial investment and involvement in the development and operation of Space Station *Freedom.* NASA would use these guidelines to evaluate proposals from industry for participating in the Space Station program.[36]

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[36] "NASA Issues Draft Guidelines on Station Commercial Infrastructure," *NASA News,* Release 88-144, October 25, 1988.

Table 3–1. Total Human Spaceflight Funding History (in thousands of dollars)

Year and Budget Item	Request	Authorization	Appropriation	Programmed (Actual)
1979				
Space Shuttle Program	1,439,300	1,443,300	*a*	1,638,300
Suppl. Appr.	185,000	185,000	185,000	
Space Flight Operations	311, 900	315,900	*b*	299,700
1980			*c*	
Space Shuttle Program	1,586,000	1,586,000		1,871,000
Suppl. Appr.	300,000	—	285,000	
Space Flight Operations	446,604 *d*	463,300	*e*	446,600
1981				
Space Shuttle	1,873,000	1,873,000	1,995,000 *f*	1,995,000
Space Flight Operations	683,700 *g*	779,500	679,200 *h*	679,200
1982				
Space Shuttle	2,194,000 *i*	2,189,000	2,194,000	2,638,350
Space Flight Operations	895,900 *j*	907,900	*k*	466,500
1983				
Space Shuttle	1,718,000	1,798,000	1,769,000	2,144,700
Space Flight Operations	1,452,000 *l*	1,699,000	1,796,000	1,421,700
1984				
Space Transportation Capability Dev. (R&D)	1,927,400	2,009,400	427,400 *m*	484,795
Space Transportation Capability Dev. (SFC&DC)			1,545,000 *n*	1,569,303
Space Transportation Ops. (R&D)	1,452,000 *o*	1,545,600	*p*	41,669
Space Transportation Ops. (SFC&DC)			1,570,600	1,397,638

Table 3–1 continued

Year and Budget Item	**Request**	**Authorization**	**Appropriation**	**Programmed (Actual)**
1985				
Space Transportation Capability Dev.	361,400	351,400	407,400 *q*	391,400
Space Production & Operational Capability (SFC&DC) *r*	1,465,600	1,470,600	1,510,600	1,484,500
Space Transportation Operations	1,339,000	1,319,000	1,339,000	1,314,000
Space Station	150,000	150,000	155,000 *s*	155,500
1986				
Space Transportation Capability Dev.	459,300	437,300	439,300	402,383
Shuttle Production & Operational Capability (SFC&DC) *t*	976,500	961,500	976,500	1,329,390
Space Transportation Operations	1,725,000 *u*	1,710,100	1,725,100	1,573,412
Space Station	205,000 *v*	205,000	205,000	184,702
1987				
Space Transportation Capability Dev.	507, 500 *w*	515,500	507,500	491,100
Shuttle Production & Operational Capability	1,134,400 *x*	1,156,400	2,984,400	3,408,100
Space Transportation Operations	1,847,000 *y*	1,881,700	1,867,700	1,746,000
Space Station	410,000	410,000	410,000	420,000
1988				
Space Transportation Capability Dev.	568,600	553,600	549,600	598,564
Shuttle Production & Operational Capability	1,229,600	1,174,600	1,100,609	1,815,517
Space Transportation Operations	1,838,000 *z*	1,885,800	1,885,800	1,836,352
Space Station	392,300 *aa*	767,000	425,000 *bb*	489,509

a Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

b Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

c Undistributed. Total 1980 R&D appropriation = $4,091,086,000.

Table 3–1 continued

d Amended budget submission. Original budget submission = $467,300,000.

e Undistributed. Total 1980 R&D appropriation = $4,091,086,000.

f Reflects recission.

g Amended budget submission. Original budget submission = $809,500,000.

h Reflects recission.

i Amended budget submission. Original budget submission = $2,230,000,000.

j Amended budget submission. Original budget submission = $1,043,000,000.

k Undistributed. Total 1982 R&D appropriation = $4,973,100,000.

l Amended budget submission. Original budget submission = $1,707,000,000.

m In 1984, funding for most transportation activities moved from the R&D appropriation to the SFC&DC appropriation. The amount of $427,400,000 remained in R&D for upper stages ($143,200,000), Spacelab ($119,600,000), engineering and technology base ($93,100,000), advanced programs ($53,200,000), tethered satellite system ($15,000,000), and teleoperator maneuvering system ($3,300,000) activities.

n Space Transportation & Capability Development included under the SFC&DC appropriation funded Shuttle Production and Capability Development ($1,500,000,000) and a reserve of $45,000,000, which included an allocation of $50,000,000 for orbiter/engine spares and reduced the amount earmarked for Shuttle training aircraft advance payment by $5,000,000.

o Amended budget submission. Original budget submission = $1,570,600,000.

p In 1984, all funds for Space Transportation Operations activities moved to the SFC&DC appropriation.

q Reflects supplemental legislation, which increased appropriation from $367,400,000 to $407,400,000. Accompanying note states that increased appropriation was designated for upper stages and would not be available until March 1, 1986.

r New budget category includes funding for orbiter, launch and mission support, propulsion systems, and changes and systems upgrading.

s Reflects supplemental legislation, which increased appropriation from $150,000,000 to $155,500,000.

t New budget category includes funding for orbiter, launch and mission support, propulsion systems, and changes and systems upgrading.

u Amended budget submission. Original budget submission = $1,725,000,000.

v Amended budget submission. Original budget submission = $230,000,000.

w Amended budget submission. Original budget submission = $465,500,000.

x Amended budget submission. Original budget submission = $745,400,000.

y Amended budget submission. Original budget submission = $1,524,700,000.

z Amended budget submission. Original budget submission = $1,885,800,000.

aa Amended budget submission. Original budget submission = $767,000,000.

bb Reflects transfer of $100,000,000 to FY 1988 for Space Station from FY 1987.

Table 3–2. Programmed Budget by Budget Category (in thousands of dollars)

Budget Category/Year	**1979**	**1980**	**1981**	**1982**	**1983**
Space Shuttle Program	1,638,300	1,871,000	1,995,000	2,638,350	2,144,700
Space Flight Operations Program	299,700	446,600	679.200	466,500	1,421,700
Shuttle Production & Operational Capability	Not a budget category until 1985				
Space Transportation (System) Operations	Not a budget category until 1984				
Space Transportation Capability Development	Not a budget category until 1984				
Space Station Program	Not a budget category until 1984				

Budget Category/Year	**1984**	**1985**	**1986**	**1987**	**1988**
Space Shuttle Program	Not a budget category after 1983				
Space Flight Operations Program	Not a budget category after 1983				
Shuttle Production & Operational Capability	—	1,484,500	1,329,390	3,408,100	1,815,517
Space Transportation (System) Operations	1,439,307 (R&D + SFC&DC)	1,314,000	1,573,412	1,746,000	1,836,352
Space Transportation Capability Development	2,048,098 (R&D + SFC&DC)	391,400	402,383	491,100	598,564
Space Station Program	—	155,500	184,702	420,000	489,509

Table 3–3. Orbiter Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed
1979	DDT&E 536,500	DDT&E 536,500	[b]	DDT&E 727,800
	Production 397,000	Production [a]		Production 264,500
Suppl Appr.	[c]	61,500 [d]	[e]	
1980	DDT&E 560,900 [f]	DDT&E 420,800	[h]	DDT&E 641,900
	Production 572,600 [g]	Production 570,600		Production 572,600
Suppl Appr.	[i]	— [j]	[k]	
1981	DDT&E 521,000 [l]	DDT&E 320,900	DDT&E 521,000 [n]	DDT&E 510,500
	Production 727,500 [m]	Production 768,200	Production 727,500 [o]	Production 779,000
1982	DDT&E 422,000 [p]	DDT&E 372,000	DDT&E 372,000	Production 916,850
	Production 860,000 [q]	Production 832,000	Production 837,000	
1983	904,400 [r]	1,018,500	984,500	903,910
1984	716,300 [s]	[t]		724,900
1985	655,300 [u]	651,800	651,800	674,200
1986	333,600	333,600	333,600	396,400
1987	373,000 [v]	211,000	211,000	448,100 [w]
1988	328,600 [x]	348,200	403,200	321,300

[a] Undistributed. Total 1979 Production authorization = $458,000,000.

[b] Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

[c] Supplemental appropriation submission of $185,000,000 undistributed among functions.

[d] Distribution for supplemental appropriation not specified in budget figures. Distribution indicated in supporting congressional committee documentation.

[e] Supplemental appropriation of $185,000,000 undistributed among functions.

[f] Amended budget submission. Original submission = $420,800,000.

[g] Amended budget submission. Original submission = $570,600,000.

[h] Undistributed. Total 1980 R&D appropriation = $4,091,086,000.

[i] Specific functions for supplemental appropriation not specified. Supporting committee documentation states that the administration requested additional funds for design, development, test, and evaluation of orbiter ($140,100,000), external tank ($11,000,000), solid rocket booster ($3,700,000), launch and landing ($45,200,000), and changes/systems upgrading ($100,000,000) for a total of $300,000,000.

Table 3–3 continued

j House committee introduced and passed supplemental appropriation for $300,000,000, but no further action was taken by the whole House. Senate committee authorized supplemental appropriation of $300,000,000, which was passed by the whole Senate. However, there was no conference committee authorization for a supplemental appropriation.

k Undistributed supplemental appropriation of $285,000,000 approved by conference committee and Congress.

l Amended budget submission. Original submission = $320,900,000. The increase reflects technical problems that delayed the scheduled rollout of the orbiter *Columbia* from the Orbiter Processing Facility and led to the delay in the Orbital Flight Test program and the initial operational capability date.

m Amended budget submission. Original submission = $768,200,000.

n Reflects recission.

o Reflects recission.

p Amended budget submission. Original submission = $372,000,000.

q Amended budget submission. Original submission = $837,000,000.

r Amended budget submission. Original submission = $933,500,000.

s Amended budget submission. Original submission = $729,600,000.

t No authorization or appropriation for orbiter budget category.

u Amended budget submission. Original submission = $606,800,000.

v Amended budget submission. Original budget submission = $211,000,000.

w Amount is for Orbiter Operational Capability.

x Amended budget submission. Original budget submission = $403,200,000.

Table 3–4. Orbiter Replacement Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed
1987	250,000	272,000	2,100,000	2,000,000

Table 3–5. Launch and Mission Support Funding History (in thousands of dollars) [a]

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed
1979	DDT&E 128,100	DDT&E 128,000	[c]	DDT&E 149,600
	Production 11,000	Production [b]		Production 7,000
Suppl. Appr.	[d]	19,500 [e]	[f]	
1980	DDT&E 188,400 [g]	DDT&E 143,200	[i]	DDT&E 188,400
	Production 16,400 [h]	Production 20,000		Production 16,400
Suppl. Appr.	[j]	[k]	[l]	
1981	DDT&E 204,000 [m]	DDT&E 154,400	DDT&E 204,000 [o]	DDT&E 214,500
	Production 34,000 [n]	Production 40,400	Production 34,000 [p]	Production 33,000
1982	DDT&E 260,000 [q]	DDT&E 199,000	DDT&E 199,000	Operations 6,400
	Production 63,000 [r]	Production 57,000	Production 57,000	Production and Capability Dev. 134,900
1983	246,600	67,000 [s]	67,000	246,300
1984	No budget item [t]			277,700
1985	229,800 [u]	219,800	234,800	218,100
1986	169,000 [v]	158,900	163,900	180,000
1987	148,200 [w]	161,000	161,000	151,200
1988	164,800 [x]	249,300	552,100 [y]	167,400

[a] Budget category titled Launch and Landing (Design, Development, Test, and Evaluation) in 1979–1983.

[b] Undistributed. Total 1979 Production authorization = $458,000,000.

[c] Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

[d] Supplemental appropriation submission undistributed functions.

[e] Distribution for supplemental appropriation not specified in budget figures. Distribution indicated in supporting congressional committee documentation.

[f] Supplemental appropriation undistributed among functions.

[g] Amended budget submission. Original submission = $143,200,000.

[h] Amended budget submission. Original submission = $20,000,000.

Table 3–5 continued

[i] Undistributed. Total 1980 R&D appropriation = $4,091,086,000.

[j] Specific functions for supplemental appropriation not specified. Supporting committee documentation states that the administration requested additional funds for design, development, test, and evaluation of orbiter ($140,100,000), external tank ($11,000,000), solid rocket booster ($3,700,000), launch and landing ($45,200,000), and changes/systems upgrading ($100,000,000), for a total of $300,000,000.

[k] House committee introduced and passed supplemental appropriation for $300,000,000, but no further action was taken by the whole House. Senate committee authorized supplemental appropriation of $300,000,000, which was passed by the whole Senate. However, there was no conference committee authorization for a supplemental appropriation.

[l] Undistributed supplemental appropriation of $285,000,000 approved by conference committee and Congress.

[m] Amended budget submission. Original submission = $154,400,000. Increase reflects the compressed effort required to process the Shuttle vehicle for launch, which increased the development and support contractor funding requirements substantially.

[n] Amended budget submission. Original submission = $40,400,000.

[o] Reflects recission.

[p] Reflects recission.

[q] Amended budget submission. Original submission = $199,000,000. Increase reflects growth in requirements related to the support for launch processing operations and for facility and equipment modifications needed to resolve problems experienced during the first two Shuttle launches.

[r] Amended budget submission. Original submission = $57,000,000.

[s] Authorization and appropriation figures reflect amounts for Space Shuttle program only. Mission support figures not provided for Space Flight Operations program.

[t] Amount for Launch and Mission Support included as part of Space Transportation System Capability Development. Request = $1,927,400,000; authorization = $2,009,400,000; and appropriation (SFC&DC) = $1,570,000. Budget submission for Launch and Mission Support per budget submission submission according to NASA Comptroller’s Office = $277,700,000.

[u] Amended budget submission. Original budget submission = $234,800,000.

[v] Amended budget submission. Original budget submission = $163,900,000.

[w] Amended budget submission. Original budget submission = $161,000,000.

[x] Amended budget submission. Original budget submission = $249,300,000.

[y] Reflects $302,000,000 transferred from Propulsion Systems to Launch and Mission Support.

Table 3–6. Launch and Landing Operations Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Authorization**	**Appropriation**	**Programmed**
1984	357,200	*a*	*b*	329,000
1985	275,900 *c*	265,000	265,000	275,500
1986	332,400 *d*	*e*		315,100
1987	353,300 *f*	285,000	300,500	359,800
1988	449,800 *g*	401,600	401,600	452,200

a Undistributed. Total Shuttle Operations authorization = $,495,600,000.

b No budget item. Shuttle Operations transferred to SFC&DC appropriation.

c Amended budget submission. Original budget submission = $265,000,000.

d Amended budget submission. Initial budget submission = $335,900,000.

e No authorization or appropriation for Launch and Landing Operations.

f Amended budget submission. Initial budget submission = $285,000,000.

g Amended budget submission. Initial budget submission = $401,600,000.

Table 3–7. Spaceflight Operations Program Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed
1979	311,900	315,900	[a]	299,700
1980	446,600 [b]	463,300	[c]	446,600
1981	683,700 [d]	779,500	679,200 [e]	679,200
1982	895,900 [f]	907,900	[g]	466,500 [h]
1983	1,453,700 [i]	1,699,000	1,796,000	1,421,700
1984 [j]	1,452,000 [k]	1,545,600	1,570,600	1,452,000
1985	1,339,000	1,319,000	1,339,000	1,314,000
1986	1,725,000 [l]	1,710,000	1,725,000	1,640,200
1987	1,847,000 [m]	1,881,700	1,867,700	1,746,000
1988	1,838,000 [n]	1,885,800	1,885,800	1,833,600

[a] Undistributed. Total 1979 R&D appropriation = $3,477,200,000.

[b] Amended budget submission. Original submission = $467,300,000.

[c] Undistributed. Total 1980 R&D appropriation = $4,091,086,000.

[d] Reflects amended budget submission. Initial budget submission = $809,500,000.

[e] Amended budget submission. Original submission = $767,500,000. Primary reflects rephasing of Shuttle and Spacelab operations. Also reflects recission.

[f] Amended budget submission. Initial budget submission = $1,043,000,000.

[g] Undistributed. Total 1982 R&D appropriation = $4,740,900,000 (reflects effect of Gen. Prov. Sec. 412).

[h] Reduction reflects reordering of budget categories included in Space Flight Operations.

[i] Amended budget submission. Initial budget submission = $1,707,000.

[j] Became Space Transportation Operations in 1984. Appropriation transferred to SFC&DC.

[k] Budget category reconfigured as Space Transportation Operations. Includes Shuttle Operations and Expendable Launch Vehicles programs. Amended budget submission. Original budget submission = $1,570,600,000.

[l] Amended budget submission. Initial budget submission = $1,725,100,000.

[m] Amended budget submission. Initial budget submission = $1,524,700,000.

[n] Amended budget submission. Initial budget submission = $1,885,800,000.

Table 3–8. Flight Operations Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed
1984	315,000	[a]	[b]	333,900
1985	316,000 [c]	316,000	316,000	315,600
1986	435,000 [d]	[e]		434,200
1987	557,700 [f]	360,600	399,000	515,000
1988	583,600 [g]	561,100	561,100	597,100

[a] Undistributed. Total Shuttle Operations authorization = $1,495,600,000.

[b] No budget category for Flight Operations in appropriations activity.

[c] Amended budget submission. Initial budget submission = $315,200,000.

[d] Amended budget submission. Initial budget submission = $425,200,000.

[e] No authorization or appropriation for Flight Operations budget category.

[f] Amended budget submission. Initial budget submission = $360,600,000. Increase reflects increased funding to replace lost reimbursable income and an increase in program requirements that have resulted in increases in support to system design reviews and safety/reliability oversight.

[g] Amended budget submission. Initial budget submission = $561,100,000.

Table 3–9. Spacelab Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed
1979 *a*				26,700
1980 *b*	58,800			58,800
1981	139,700 *c*	144,700	139,700 *d*	138,800
1982	100,800 *e*	*f*	110,700	100,800
1983	121,200 *g*	*h*	113,200	121,200
1984	112,500 *i*	119,600	119,600	111,000
1985	58,300 *j*	69,300	69,300	55,700
1986	92,900 *k*	96,700	96,700	78,000
1987	73,900 *l*	66,700	68,800	72,000
1988	66,500 *m*	73,500	73,500	66,500

a No budget item for Spacelab indicated in 1979 budget submission. Spacelab is mentioned in Space Flight Operations budget category narrative for FY 1979 Senate authorization bill (legislative day: April 24, 1978), which states that Spacelab is being developed and paid for by the European Space Agency (ESA) and that NASA supports ESA’s Spacelab development effort. “This support includes developing a crew transfer tunnel and procurement of necessary mockups, trainers and ground support equipment not provided by ESA. Other activities include procurement of flight and ground hardware, and system activation activities to assure Spacelab compatibility with the orbiter and an operational capability.” Actual programmed amount for Spacelab for FY 1979 = $26,700,000.

b No budget item for Spacelab indicated in FY 1980 budget submission. Only mention of Spacelab in FY 1980 budget submission occurs in narrative accompanying Senate authorization bill, which says that the “principal areas of [Space Flight Operations] activity include the Spacelab, the space transportation upper stages….”

c Amended budget submission. Initial budget submission = $151,700,000.

d Amended budget submission. Initial submission = $149,700,000. Reflects recission.

e Amended budget submission. Initial budget submission = $140,700,000.

f Undistributed. Total 1982 R&D authorization = $4,973,100,000.

g Amended budget submission. Original budget submission = $113,200,000.

h Undistributed. Total Space Flight Operations authorization = $1,699,000,000.

i Amended budget submission. Initial budget submission = $119,600,000.

j Amended budget submission. Initial budget submission = $69,300,000.

k Amended budget submission. Initial budget submission = $96,700,000.

l Amended budget submission. Initial budget submission = $89,700,000.

m Amended budget submission. Initial budget submission = $73,500,000.

Table 3–10. Space Station Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed
1985	150,000	150,000	155,500	155,500
1986	205,000 *a*	205,000	205,000	184,702
1987	410,000	410,000	410,000	420,000
1988	392,300 *b*	767,000	425,000 *c*	489,509

a Amended budget submission. Initial budget submission = $230,000,000.

b Amended budget submission. Initial budget submission = $767,300,000. The reduction reflects deferring the buildup of the prime contractor personnel, limiting supporting development personnel hiring and equipment purchases and constraining supporting engineering development capabilities.

c Reflects transfer of $100,000,000 to FY 1988 for Space Station from FY 1987.

Table 3–11. Orbiter Characteristics

Component	**Characteristics**
Length	37.24
Height	17.25
Vertical Stabilizer	8.01
Wingspan	23.79
Body Flap	
Area (sq m)	12.6
Width	6.1
Aft Fuselage	
Length	5.5
Width	6.7
Height	6.1
Mid-Fuselage	
Length	18.3
Width	5.2
Height	4.0
Airlock (cm)	
Inside Diameter	160
Length	211
Minimum Clearance	91.4
Opening Capacity	46 x 46 x 127
Forward Fuselage Crew Cabin (cu m)	71.5
Payload Bay Doors	
Length	18.3
Diameter	4.6
Surface Area (sq m)	148.6
Weight (kg)	1,480
Wing	
Length	18.3
Maximum Thickness	1.5
Elevons	4.2 and 3.8
Tread Width	6.91
Structure Type	Semimonocoque
Structure Material	Aluminum
Gross Takeoff Weight	Variable
Gross Landing Weight	Variable
Inert Weight (kg) (approx.)	74,844
Main Engines	
Number	3
Average Thrust	1.67M newtons at sea level 2.10M newtons in vacuum
Nominal Burn Time	522 seconds

Table 3–11 continued

Component	**Characteristics**
OMS Engines	
Number	2
Average Thrust	26,688 newtons
Dry Weight (kg)	117.9
Propellant	Monomethyl hydrazine and nitrogen tetroxide
RCS Engines	
Number	38 primary (4 forward, 12 per aft pod) 6 vernier (2 forward, 4 aft)
Average Thrust	3,870 newtons in each primary engine 111.2 newtons in each vernier engine
Propellant	Monomethyl hydrazine and nitrogen tetroxide
Major Systems	Propulsion; Power Generation; Environmental Control and Life Support; Thermal Protection; Communications; Avionics; Data Processing; Purge, Vent, and Drain; Guidance, Navigation, and Control; Dedicated Display; Crew Escape

All measurements are in meters unless otherwise noted.

Table 3–12. Typical Launch Processing/Terminal Count Sequence

Time	**Event**
T-11 hr	Start retraction of rotating service structure (completed by T-7 hr 30 min)
T-5 hr 30 min	Enter 6-hr built-in hold, followed by clearing of pad
T-5 hr	Start countdown, begin chill down of liquid oxygen/liquid hydrogen transfer system
T-4 hr 30 min	Begin liquid oxygen fill of external tank
T-2 hr 50 min	Begin liquid hydrogen fill of external tank
T-2 hr 4 min	1-hr built-in hold, followed by crew entry operations
T-1 hr 5 min	Crew entry complete; cabin hatch closed; start cabin leak check (completed by T-25 min)
T-30 min	Secure white room; ground crew retires to fallback area by T-10 min; range safety activation/Mission Control Center guidance update
T-25 min	Mission Control Center/crew communications checks; crew given landing weather information for contingencies of return-to-abort or abort once around
T-20 min	Load flight program; beginning of terminal count
T-9 min	10-min built-in hold (also a 5-min hold capability between T-9 and T-2 min and a 2-min hold capability between T-2 min and T-27 sec)
T-9 min	Go for launch/start launch processing system ground launch sequencer (automatic sequence)
T-7 min	Start crew access arm retraction
T-5 min	Activate orbiter hydraulic auxiliary power units (APUs)
T-4 min 30 sec	Orbiter goes to internal power
T-3 min	Gimbal main engines to start position
T-2 min 55 sec	External tank oxygen to flight pressure
T-1 min 57 sec	External tank hydrogen to flight pressure
T-31 sec	Onboard computers' automatic launch sequence software enabled by launch processing system command
T-30 sec	Last opportunity for crew to exit by slidewire
T-27 sec	Latest hold point if needed (following any hold below the T-2 min mark, the countdown will be automatically recycled to T-9 min)
T-25 sec	Activate solid rocket booster hydraulic power units; initiative for management of countdown sequence assumed by onboard computers; ground launch sequencer remains on line
T-18 sec	Solid rocket booster nozzle profile conducted
T-3.6 sec	Main propulsion system start commands issued by the onboard GPCs
T-3.46 sec to 3.22 sec	Main engines start
T-0	Main engines at 90 percent thrust
T+2.64 sec	Solid rocket booster fire command/holddown bolts triggered
T+3 sec	LIFTOFF

Table 3–13. Space Shuttle Launch Elements

Event	**Time min:sec**	**Geodetic altitude (km)**	**Inertial velocity (km/hr)**
SSME ignition	–00:03.46	.056	0
Solid rocket booster ignition	00:03	.056	0
Begin pitchover	00:07	.166	0
Maximum dynamic pressure reached	01:09	13.4	6.4
Solid rocket booster separation	02:04	47.3	38.1
Main engine cutoff	08:38	117.5	1,335
External tank separation	08:50	118.3	1,427
OMS-1 ignition	10:39	126	2,221
OMS-1 cutoff	12:24	133.9	2,993
OMS-2 ignition	43:58	279.4	15,731
OMS-2 cutoff	45:34	280.3	16,526

Table 3–14. Mission Command and Control Positions and Responsibilities

Position	Function
Flight Director	Leads the flight control team. The Flight Director is responsible for mission and payload operations and decisions relating to safety and flight conduct.
Spacecraft Communicator	Primary communicator between Mission Command and Control and the Shuttle crew.
Flight Dynamics Office	Plans orbiter maneuvers and follows the Shuttle's flight trajectory along with the Guidance Officer.
Guidance Officer	Responsible for monitoring the orbiter navigation and guidance computer software.
Data Processing Systems Engineer	Keeps track of the orbiter's data processing systems, including the five on-board general purpose computers, the flight-critical and launch data lines, the malfunction display system, mass memories, and systems software.
Flight Surgeon	Monitors crew activities and is for the medical operations flight control team, providing medical consultations with the crew, as required, and keeping the Flight Director informed on the state of the crew's health.
Booster Systems Engineer	Responsible for monitoring and evaluating the main engine, solid rocket booster, and external tank performance before launch and during the ascent phases of a mission.
Propulsion Systems Engineer	Monitors and evaluates performance of the reaction control and orbital maneuvering systems during all flight phases and is charged with management of propellants and other consumables for various orbiter maneuvers.
Guidance, Navigation, and Control Systems Engineer	Monitors all Shuttle guidance, navigation, and control systems. Also keeps the Flight Director and crew notified of possible abort situations, and keeps the crew informed of any guidance problems.
Electrical, Environmental, and Consumables Systems Engineer (EECON)	Responsible for monitoring the cryogenic supplies available for the fuel cells, avionics and cabin cooling systems, and electrical distribution, cabin pressure, and orbiter lighting systems.
Instrumentation and Communication Systems Engineer	Plans and monitors in-flight communications and instrumentation systems.
Ground Control	Responsible for maintenance and operation of Mission Command and Control hardware, software, and support facilities. Also coordinates tracking and data activities with the Goddard Space Flight Center, Greenbelt, Maryland.
Flight Activities Officer	Plans and supports crew activities, checklists, procedures, and schedules.
Payloads Officer	Coordinates the ground and on-board system interfaces between the flight control team and the payload user. Also monitors Spacelab and upper stage systems and their interfaces with payloads.
Maintenance, Mechanical Arm, and Crew Systems Engineer	Monitors operation of the remote manipulator arm and the orbiter's structural and mechanical systems. May also observe crew hardware and in-flight equipment maintenance.
Public Affairs Officer	Provides mission commentary and augments and explains air-to-ground conversations and flight control operations for the news media and public.

Table 3–15. Shuttle Extravehicular Activity

Mission	**Date**	**Astronaut**	**Duration (Hr: Min)**
STS-6	April 8, 1983	Musgrave	3:54
		Peterson	3:54
STS 41-B	February 8, 1984	McCandless	11:37
		Stewart	11:37
STS 41-C	April 11, 1984	Nelson	10:06
		van Hoften	10:06
STS 41-G	October 12, 1984	Leestma	3:29
		Sullivan	3:29
STS 51-A	November 21, 1984	Allen	12:14
		Gardner	12:14
STS 51-D	April 17, 1985	Griggs	3:10
		Hoffman	3:10
STS 51-I	September 1, 1985	van Hoften	4:31
		W. Fisher	4:31
STS 61-B	November 30, 1985	Spring	12:12
	December 1, 1985	Ross	12:12

Table 3–16. STS-1–STS-4 Mission Summary

Mission	Dates	Crew	Payload and Experiments
STS-1	Apr. 12–14, 1981	Cmdr: John W. Young Pilot: Robert L. Crippen	Aerodynamic Coefficient Identification Package Data Flight Instrumentation Package Passive Optical Sample Assembly
STS-2	Nov. 12–14, 1981	Cmdr: Joe H. Engle Pilot: Richard H. Truly	Aerodynamic Coefficient Identification Package Catalytic Surface Experiment Data Flight Instrumentation Dynamic, Acoustic and Thermal Experiment Induced Environment Contamination Monitor Tile Gap Heating Effects Experiment OSTA-1 Payload (Office of Space and Terrestrial Applications) • Feature Identification and Location Experiment • Heflex Bioengineering Test • Measurement of Air Pollution From Satellites • Night-Day Optical Survey of Lightning • Ocean Color Experiment • Shuttle Imaging Radar-A • Shuttle Multispectral Infrared Radiometer
STS-3	Mar. 22–30, 1982	Cmdr: Jack R. Lousma Pilot: C. Gordon Fullerton	Data Flight Instrumentation Aerodynamic Coefficient Identification Package Induced Environment Contamination Monitor Tile Gap Heating Effects Experiment Catalytic Surface Experiment Dynamic, Acoustic and Thermal Experiment Monodisperse Latex Reactor Electrophoresis Test Heflex Bioengineering Test Infrared Imagery of Shuttle OSS-1 Payload (Office of Space Science) • Contamination Monitor • Microabrasion Foil Experiment • Plant Growth Unit • Plasma Diagnostics Package • Shuttle-Spacelab Induced Atmosphere • Solar Flare X-Ray Polarimeter • Solar Ultraviolet Spectral Irradiance Monitor • Thermal Canister Experiment • Vehicle Charging and Potential Experiment

Table 3–16 continued

Mission	Dates	Crew	Payload and Experiments
STS-3 continued			Get-Away Special Canister • Flight Verification Shuttle Student Involvement Project • Insects in Flight
STS-4	June 27, 1982–July 4, 1982	Cmdr: Thomas K. Mattingly Pilot: Henry W. Hartsfield, Jr.	Aerodynamic Coefficient Identification Package Catalytic Surface Experiment Continuous Flow Electrophoresis System Data Flight Instrumentation Department of Defense Payload DOD-82-1 Dynamic, Acoustic and Thermal Experiment Induced Environment Contamination Monitor Infrared Imagery of Shuttle Monodisperse Latex Reactor Night/Day Optical Survey of Lightning Tile Gap Heating Effects Experiment Get-Away Special • G-001 Utah State University Shuttle Student Involvement Project • Effects of Diet, Exercise, Zero Gravity on Lipoprotein Profiles • Effects of Space Travel on Trivalent Chromium in the Body

Table 3–17. STS-1 Mission Characteristics

Crew	Cmdr: John W. Young Pilot Robert L. Crippen
Launch	7:00:03 a.m., EST, April 12, 1981, Kennedy Space Center The launch followed a scrubbed attempt on April 10. The countdown on April 10 proceeded normally until T-20 minutes when the orbiter general purpose computers (GPCs) were scheduled for transition from the vehicle checkout mode to the vehicle flight configuration mode. The launch was held for the maximum time and scrubbed when the four primary GPCs would not provide the correct timing of the backup flight system GPC. Analysis and testing indicated the primary set of GPCs provided incorrect timing to the backup flight system at initialization and caused the launch scrub. The problem resulted from a Primary Ascent Software System (PASS) skew during initialization. The PASS GPCs were reinitialized and dumped to verify that the timing skew problem had cleared. During the second final countdown attempt on April 12, transition of the primary set of orbiter GPCs and the backup flight system GPC occurred normally at T-20 minutes. The Shuttle cleared its 106-meter launch tower in six seconds and reached Earth orbit in about 12 minutes.
Orbital Altitude & Inclination	237 km/40 degrees The crew changed their orbit from its original elliptical 106 km x 245 km by firing their orbital maneuvering system on apogee.
Total Weight in Payload Bay	4,870 kg
Landing & Post-landing Operations	10:27:57 a.m., PST, April 14, 1981, Dry Lakebed Runway 23, Edwards AFB Orbiter was returned to Kennedy April 28, 1981.
Rollout Distance	2,741 m
Rollout Time	60 seconds
Mission Duration	2 days, 6 hours, 20 minutes, and 53 seconds
Landed Revolution No.	37
Mission Support	Spacecraft Tracking and Data Network (STDN)
Deployed Satellites	None
Get-Away Specials	None
Experiments	Data Flight Instrumentation (DFI). This subsystem included special-purpose sensors required to monitor spacecraft conditions and performance parameters not already covered by critical operational systems. The subsystem consisted of transducers, signal conditioning equipment, pulse-code modulation (PCM) encoding equipment, frequency multiplex equipment, PCM recorders, analog recorders, timing equipment, and checkout equipment.

Table 3–17 continued

	Passive Optical Sample Assembly. This assembly consisted of an array of passive samples with various types of surfaces exposed to all STS-1 mission phases. The array was mounted on the DFI pallet in the orbiter payload bay. Ground-based assessments were to evaluate contamination constraints to sensitive payloads to be flown on future missions.
	Aerodynamic Coefficient Identification Package (ACIP). This package consisted of three linear accelerometers, three angular accelerometers, three rate gyros, and signal conditioning and PCM equipment mounted on the wing box carry-through structure near the longitudinal center-of-gravity. The instruments sensed vehicle motions during flight from entry initiation to touchdown to provide data for postflight determination of aerodynamic coefficients, aerocoefficient derivatives, and vehicle-handling qualities.
Mission Success	Successful

Table 3–18. STS-2 Mission Characteristics

Crew	Cmdr: Joe H. Engle Pilot: Richard H. Truly
Launch	10:09:59 a.m., EST, Nov. 12, 1981, Kennedy Space Center Launch set for October 9 was rescheduled when a nitrogen tetroxide spill occurred during loading of forward reaction control system. Launch on November 4 was delayed and then scrubbed when countdown computer called for a hold in count because of an apparent low reading on fuel cell oxygen tank pressures. During hold, high oil pressures were discovered in two of three auxiliary power units (APUs) that operated hydraulic system. APU gear boxes were flushed and filters replaced, forcing launch reschedule. Launch on November 12 was delayed 2 hours, 40 minutes to replace multiplexer/demultiplexer and additional 9 minutes, 59 seconds to review systems status. Modifications to launch platform to overcome solid rocket booster overpressure problem were effective.
Orbital Altitude & Inclination	222 x 230 km/38 degrees
Total Weight in Payload Bay	8,900 kg
Landing & Post-landing Operations	8:40 a.m., PST, November 14, 1981, Dry Lakebed Runway 23, Edwards AFB Orbiter was returned to Kennedy November 25, 1981.
Rollout Distance	2,350 m
Rollout Time	53 seconds
Mission Duration	2 days, 6 hours, 13 minutes, 12 seconds Mission was shortened by approximately 3 days because of number one fuel cell failure.
Landed Revolution No.	36
Mission Support	Spacecraft Tracking and Data Network (STDN)
Deployed Satellites	None
Get-Away Specials	None
Experiments	Data Flight Instrumentation (see STS-1) Aerodynamic Coefficient Identification Package (see STS-1) Induced Environment Contamination Monitor (IECM). This monitor measured and recorded concentration levels of gaseous and particulate contamination near the payload bay during flight. During ascent and entry, the IECM obtained data on relative humidity and temperature, dewpoint temperature, trace quantities of various compounds, and airborne particulate concentration.

Table 3–18 continued

	Tile Gap Heating Effects Experiment. Analysis and ground tests have indicated that the gap between thermal protection system (TPS) tiles will generate turbulent airflow, resulting in increased heating during entry. Analysis and ground tests also showed that this may be reduced significantly by reconfiguring the tiles with a larger edge radius. To test this effect under actual orbiter entry conditions, a panel with various tile gaps and edge radii was carried.
	Catalytic Surface Experiment. Various orbiter tiles were coated with a highly efficient catalytic overlay. The coating was applied to standard instrumented tiles. This experiment provided a better understanding of the effects of catalytic reaction on convective heat transfer, perhaps permitting a weight reduction in the TPS of future orbiters and other reentry vehicles.
	Dynamic, Acoustic and Thermal Experiment (DATE). The DATE program was to develop improved techniques for predicting the dynamic, acoustic, and thermal environments and associated payload response in cargo areas of large reusable vehicles. The first step was to obtain baseline data of the orbiter environment using existing sensors and data systems. These data served as the basis for developing better prediction methods, which would be confirmed and refined on subsequent flights and used to develop payload design criteria and assess flight performance.
	OSTA-1 Payload (Office of Space and Terrestrial Applications) (see Table 5–55)
Mission Success	Successful

Table 3–19. STS-3 Mission Characteristics

Crew	Cmdr: Jack R. Lousma Pilot: C. Gordon Fullerton
Launch	11:00 a.m., EST, March 22, 1982, Kennedy Space Center The launch was delayed by 1 hour because of the failure of a heater on a nitrogen gas ground support line.
Orbital Altitude & Inclination	208 km/38 degrees
Total Weight in Payload Bay	10,220 kg
Landing & Post-landing Operations	9:04:46 a.m., MST, March 30, 1982, Northrup Strip, White Sands, New Mexico Landing site was changed from Edwards AFB to White Sands because of wet conditions on Edwards dry lakebed landing site. High winds at White Sands resulted in a 1-day extension of mission. Some brake damage upon landing and dust storm caused extensive contamination of orbiter. Orbiter was returned to Kennedy April 6, 1982.
Rollout Distance	4,186 m
Rollout Time	83 seconds
Mission Duration	8 days, 0 hours, 4 minutes, 465 seconds
Landed Revolution No.	130
Mission Support	Spacecraft Tracking and Data Network (STDN)
Deployed Satellites	None
Get-Away Specials	Get-Away Special Verification Payload. This test payload, a cylindrical canister 61 centimeters in diameter and 91 centimeters deep, measured the environment in the canister during the flight. Those data were recorded and analyzed for use by Get-Away Special experimenters on future Shuttle missions.
Experiments	Data Flight Instrumentation (see STS-1) Aerodynamic Coefficient Identification Package (see STS-1) Induced Environment Contamination Monitor (see STS-2) Tile Gap Heating Effects Experiment (see STS-2) Catalytic Surface Experiment (see STS-2) Dynamic, Acoustic and Thermal Experiment (see STS-2) Monodisperse Latex Reactor (MLR). This experiment studied the feasibility of making monodisperse (identically sized) polystyrene latex microspheres, which may have major medical and industrial research applications.

Table 3–19 continued

	Electrophoresis Test. This test evaluated the feasibility of separating cells according to their surface electrical charge. It was a forerunner to planned experiments with other equipment that would purify biological materials in the low gravity environment of space. Heflex Bioengineering Test. This preliminary test supported an experiment called Heflex, part of the Spacelab 1 mission. The Heflex experiment would depend on plants grown to a particular height range. The relationship between initial soil moisture content and final height of the plants needed to be determined to maximize the plant growth during the Spacelab mission. Infrared Imagery of Shuttle. This experiment obtained high-resolution infrared imagery of the orbiter lower and side surfaces during reentry from which surface temperatures and hence aerodynamic heating may be inferred. The imagery was obtained using a 91.5 cm telescope mounted in the NASA C-141 Gerard P. Kuiper Airborne Observatory positioned at an altitude of 13,700 m along the entry ground track of the orbiter. OSS-1 Payload (see Table 4–49) Shuttle Student Involvement Project Insects in Flight Motion Study. Investigated two species of insects under uniform conditions of light, temperature, and pressure, the variable being the absence of gravity in space.
Mission Success	Successful

Table 3–20. STS-4 Mission Characteristics

Crew	Cmdr: Thomas K. Mattingly Pilot: Henry W. Hartsfield, Jr.
Launch	June 27, 1982, Kennedy Space Center This was the first Shuttle launch with no delays in schedule. Two solid rocket booster casings were lost when main parachutes failed and they hit the water and sank. Some rainwater penetrated the protective coating of several tiles while the orbiter was on the pad. On orbit, the affected area turned toward the Sun and water evaporation prevented further tile damage from freezing water.
Orbital Altitude & Inclination	258 km/28.5 degrees
Total Weight in Payload Bay	11,021 kg
Landing & Post-landing Operations	July 4, 1982, Runway 22, Edwards AFB This was the first landing on the 15,000-foot-long concrete runway at Edwards AFB. Orbiter was returned to Kennedy July 15, 1982.
Rollout Distance	3,011 m
Rollout Time	73 seconds
Mission Duration	7 days, 1 hour, 9 minutes, 31 seconds
Landed Revolution No.	113
Mission Support	Spacecraft Tracking and Data Network (STDN)
Deployed Satellites	None
Get-Away Specials	G-001 Customer: R. Gilbert Moore Moore, a Morton Thiokol Corporation executive, donated this Get-Away Special to Utah State University. It consisted of 10 experiments dealing with the effects of microgravity on various processes.
Experiments	Aerodynamic Coefficient Identification Package (see STS-1) Catalytic Surface Experiment (see STS-2) Data Flight Investigation (see STS-1) Dynamic, Acoustic and Thermal Experiment (see STS-2) Induced Environment Contamination Monitor (see STS-2) Infrared Imagery of Shuttle (see STS-3) Monodisperse Latex Reactor (see STS-3) Night/Day Optical Survey of Lightning (see STS-2) Tile Gap Heating Experiment (see STS-2)

Table 3–20 continued

	Continuous Flow Electrophoresis System. This experiment obtained flight data on system performance. During operation, a sample of biological material was continuously injected into a flowing medium, which carried the sample through a separating column where it was under the influence of an electric field. The force exerted by the field separated the sample into its constituent types at the point of exit from the column where samples were collected.
	Department of Defense DOD-82-1 (Classified)
	Shuttle Student Involvement Project • Effects of Diet, Exercise, and Zero Gravity on Lipoprotein Profiles. This project documented the diet and exercise program for the astronauts preflight and postflight. The goal of the research was to determine whether any changes occurred in lipoprotein profiles during spaceflight. • Effects of Space Travel on Trivalent Chromium in the Body. This project was to determine whether any changes occurred in chromium metabolism during spaceflight.
Mission Success	Successful

Table 3–21. STS-5–STS-27 Mission Summary

Mission/ Orbiter	Dates	Crew	Payload and Experiments
STS-5 *Columbia*	Nov. 11–16, 1982	Cmdr: Vance D. Brand Plt: Robert F. Overmyer MS: Joseph P. Allen, William B. Lenoir	**Commercial Payloads** • Satellite Business Systems Satellite (SBS-C)/PAM-D • Telesat-E (Anik C-3)/PAM-D **Experiments and Equipment** • Tile Gap Heating Effects Experiment • Catalytic Surface Effects Experiment • Dynamic, Acoustic and Thermal Environment Experiment (DATE) • Oxygen Atom Interaction With Materials Test • Atmospheric Luminosities Investigation (Glow Experiment) • Development Flight Instrumentation (DFI) • Aerodynamic Coefficient Identification Package (ACIP) **Get-Away Special** • G-026 (DFVLR, West Germany) **Shuttle Student Involvement Program** • Formation of Crystals in Weightlessness • Growth of Porifera in Zero-Gravity • Convection in Zero-Gravity
STS-6 *Challenger*	Apr. 4–9, 1983	Cmdr: Paul J. Weitz Plt: Karol J. Bobko MS: F. Story Musgrave, Donald H. Peterson	**NASA Payload** • Tracking and Data Relay Satellite (TDRS-1)/IUS **Experiments and Equipment** • Continuous Flow Electrophoresis System • Monodisperse Latex Reactor • Nighttime/Daytime Optical Survey of Lightning • ACIP **Get-Away Specials** • G-005 (Asahi Shimbun, Japan) • G-049 (Air Force Academy) • G-381 (Park Seed Company, South Carolina)
STS-7 *Challenger*	June 18–24, 1983	Cmdr: Robert L. Crippen Plt: Frederick H. Hauck MS: John M. Fabian, Sally K. Ride, Norman E. Thagard	**Commercial Payloads** • Telesat-F (Anik C-2)/PAM-D • Palapa-B1/PAM-D **NASA Payload** • OSTA-2 (Office of Space and Terrestrial Applications) – Mission Peculiar Equipment Support Structure (MPESS) – Materials Experiment Assembly (MEA) – Liquid Phase Miscibility Gap Materials – Vapor Growth of Alloy-Type Semiconductor Crystals

Table 3–21 continued

Mission/ Orbiter	Dates	Crew	Payload and Experiments
STS-7 continued			– Containerless Processing of Glass Forming Melts – Stability of Metallic Dispersions – Particles at a Solid/Liquid Interface **Detachable Payload** • Shuttle Pallet Satellite (SPAS)-01 **Experiments and Equipment** • Continuous Flow Electrophoresis System (CFES) • Monodisperse Latex Reactor **Get-Away Specials** • G-002 (Kayser Threde, West Germany) • G-009 (Purdue University) • G-012 (RCA/Camden, New Jersey, Schools) • G-033 (California Institute of Technology, Steven Spielberg) • G-088 (Edsyn, Inc.) • G-305 (Air Force/Naval Research Laboratory (NRL), Department of Defense Space Test Program) • G-345 (Goddard Space Flight Center/NRL)
STS-8 *Challenger*	Aug. 30– Sept. 5, 1983	Cmdr: Richard H. Truly Plt: Daniel C. Brandenstein MS: Dale A. Gardner, Guion S. Bluford, Jr., William E. Thornton	**International Payload** • Insat-1B/PAM-D **Detachable Payload** • Payload Flight Test Article **Experiments and Equipment** • Radiation Monitoring Experiment • Development Flight Instrumentation Pallet – Heat Pipe – Oxygen Interaction on Materials • Investigation of STS Atmospheric Luminosities • Animal Enclosure • Continuous Flow Electrophoresis System • Modular Auxiliary Data System (MADS) • ACIP **Get-Away Specials** • G-346 (GSFC/Neupert) • G-347 (GSFC/Adolphsen) • G-348 (GSFC/McIntosh) • G-475 (Asahi/Shimbun, Japan) **Shuttle Student Involvement Program** • SE 81-1 (Biofeedback Mediated Behavioral Training in Physiological Self Regulator: Application in a Near Zero Gravity Environment) **Other** • Postal Covers

Table 3–21 continued

Mission/ Orbiter	Dates	Crew	Payload and Experiments
STS-9 *Columbia*	Nov. 28–Dec. 8, 1983	Cmdr: John W. Young Plt: Brewster H. Shaw MS: Owen K. Garriott, Robert A.R. Parker PS: Byron K. Lichtenberg, Ulf Merbold (ESA)	**International Payload (NASA/ESA)** • Spacelab-1 (long module and pallet —ESA) • Spacelab Attach Hardware, TK, set, Misc.
STS 41-B *Challenger*	Feb. 3–11 1984	Cmdr: Vance D. Brand Plt: Robert L. Gibson MS: Robert L. Stewart, Bruce McCandless, II, Ronald E. McNair	**Commercial Payloads** • Westar VI/PAM-D • Palapa-B2/PAM-D **Attached Payload** • Shuttle Pallet Satellite (SPAS)-01A **Experiments and Equipment** • Integrated Rendezvous Target • Acoustic Containerless Experiment System • Isoelectric Focusing • Radiation Monitoring Experiment • Monodisperse Latex Reactor • Cinema 360 • Manned Maneuvering Unit (MMU) • Manipulation Foot Restraint • Cargo Bay Storage Assembly **Get-Away Specials** • G-004 (Utah State Univ./Aberdeen Univ.) • G-008 (AIAA/Utah State Univ./ Brighton High School) • G-051 (GTE Laboratories, Inc.) • G-309 (Air Force Space Test Program) • G-349 (Goddard Space Flight Center) **Shuttle Student Involvement Program** • SE 81-40 (Arthritis, Dan Weber-Pfizer/GD)
STS 41-C *Challenger*	April 6–13, 1984	Cmdr: Robert L. Crippen Plt: Francis R. Scobee MS: Terry J. Hart, James D.A. van Hoften, George D. Nelson	**NASA Payloads** • Long Duration Exposure Facility (LDEF) • Solar Max Mission Flight Support System **Experiments and Equipment:** • Manned Maneuvering Unit Flight Support System • Manned Foot Restraint • Cinema 360 • IMAX • Radiation Monitoring Experiment **Shuttle Student Involvement Program** • Honeycomb construction by bee colony
STS 41-D *Discovery*	Aug. 30–Sept. 5, 1984	Cmdr: Henry W. Hartsfield, Jr. Plt: Michael L. Coats MS: Richard M. Mullane, Steven A. Hawley,	**Commercial Payload** • SBS-4/PAM-D • Syncom IV-2/Unique Upper Stage (Leasat-2) • Telstar 3-C/PAM-D

Table 3–21 continued

Mission/ Orbiter	Dates	Crew	Payload and Experiments
STS 41-D continued		Judith A. Resnik PS: Charles D. Walker	**NASA Payload** • OAST-1/MPESS **Experiments and Equipment** • CFES III • IMAX • Radiation Monitoring Experiment • Clouds Logic to Optimize Use of Defense Systems (CLOUDS) • Vehicle Glow Experiment **Shuttle Student Involvement Program** • SE 82-14 (Purification and Growth of Single Crystal Gallium by the Float Zone Technique in a Zero Gravity Environment, Shawn Murphy/Rockwell International)
STS 41-G *Challenger*	Oct. 5–13, 1984	Cmdr: Robert L Crippen Plt: Jon A. McBride MS: Sally K. Ride, Kathryn D. Sullivan, David C. Leestma PS: Marc D. Garneau, Paul D. Scully-Power	**NASA Payloads** • Earth Radiation Budget Satellite (ERBS) **Experiments and Equipment:** • OSTA-3/Pallet • Large Format Camera (LFC)/CRS/MPESS • IMAX • Radiation Monitoring Experiment • Auroral Photography Experiment • Thermoluminescent Dosimeter • Canadian Experiment (CANEX) **Get-Away Specials** • G-007 (Student Experiment, Radio Transmission Experiment, Alabama Space and Rocket Center) • G-013 (Halogen Lamp Experiment (HALEX), Kayser-Threde/ESA) • G-032 (Physics of Solids and Liquids, International Space Corp., Asahi Nat. Broadcasting Corp., Japan) • G-038 (Vapor Deposition, McShane/Marshall Space Flight Center) • G-074 (Fuel System Test, MDAC) • G-306 (Trapped Ions in Space, NRL/Navy) • G-469 (Cosmic Ray Upset Experiment, NASA/Goddard/IBM) • G-518 (Physics and Materials Processing, Utah State Univ.)
STS 51-A *Discovery*	Nov. 8–16, 1984	Cmdr: Frederick H. Hauck Plt: David M. Walker MS: Joseph P. Allen, Anna L. Fisher, Dale A. Gardner	**Commercial Payloads** • Telesat-H/PAM-D (Anik D2) • Syncom IV-1/Unique Upper Stage (Leasat-1) • Satellite Retrieval Pallets (2) (Palapa B-2, Westar-6)

Table 3–21 continued

Mission/ Orbiter	Dates	Crew	Payload and Experiments
STS 51-A continued			**Experiments and Equipment** • MMU/Fixed Service Structure (FSS) (2) • Diffuse Mixing of Organic Solids • Radiation Monitoring Experiment • Manual Foot Restraint
STS 51-C *Discovery*	Jan. 24–27, 1985	Cmdr: Thomas K. Mattingly, II Plt: Loren J. Shriver MS: Ellison S. Onizuka, James F. Buchli PS: Gary E. Payton	**NASA Payloads** • DOD 85-1/IUS **Experiments and Equipment** • Aggregation of Red Blood Cells, Middeck Experiment—University of Sydney
STS 51-D *Discovery*	April 12–19, 1985	Cmdr: Karol J. Bobko Plt: Donald E. Williams MS: M. Rhea Seddon, S. David Griggs, Jeffrey A. Hoffman PS: Charles D. Walker, Sen. E.J. Garn	**Commercial Payloads** • Telesat-I/PAM-D (Anik C-1) • Syncom IV-3/Unique Upper Stage (UUS) (Leasat-3) **Experiments and Equipment** • Office of Space Science and Applications Middeck Experiments: – American Flight Echocardiograph – Phase Partitioning Experiment – Protein Crystal Growth (PCG) • CFES III • Image Intensifier Investigation • Informal Science Study (Toys in Space) • Medical Experiments **Get Away Specials** • G-035 (Physics of Solids and Liquids, Asahi, Japan) • G-471 (Capillary Pumped Loop Experiment, Goddard Space Flight Center) **Shuttle Student Involvement Program** • SE 82-03 (Statoliths in Corn Root Caps-Amberg/Martin Marietta) • SE 83-03 (Effect of Weightlessness on Aging of Brain Cells-A. Fras/ USC/Los Angeles Orthopedic Hospital) **Other** • Statue of Liberty Replicas (2)
STS 51-B *Challenger*	April 29– May 6, 1985	Cmdr: R.F. Overmyer Plt: F.D. Gregory MS: Don L. Lind, Norman E Thagard, William Thornton PS: Lodewijk van den Berg, Taylor Wang	**International Payload (NASA/ESA)** • Spacelab 3 (long module and MPESS) **Get-Away Specials (Deployable)** • NUSAT • GLOMR (not deployed)
STS 51-G *Discovery*	June 17–24, 1985	Cmdr: Daniel Brandenstein Plt: John O. Creighton MS: John M. Fabian, Steven R. Nagel, Shannon W. Lucid	**Commercial Payloads** • Morelos-A/PAM-D • Arabsat-A/PAM-D • Telstar 3-D/PAM-D

Table 3–21 continued

Mission/ Orbiter	Dates	Crew	Payload and Experiments
STS 51-G continued		PS: Patrick Baudry (CNES), Prince Sultan Salman Al-Saud	**Deployable** • Spartan-1/MPESS **Experiments and Equipment** • French Echocardiograph Experiment • French Postural Experiment • Automated Directional Solidification Furnace • High-Precision Tracking Experiment **Get-Away Specials** • G-025 (Dynamic Behavior of Liquid Properties, ERNO, West Germany) • G-027 (Slipcasting Under Microgravity, DFVLR, West Germany) • G-028 (Functional Study of MnBi, DFVLR, West Germany) • G-034 (Biological/Physical Science Experiment, El Paso/ Dickshire Coors, Ysleta, Texas) • G-314 (Space Ultraviolet Radiation Environment (SURE), Air Force/NRL) • G-471 (Capillary Pumped Loop Experiment, Goddard)
STS 51-F *Challenger*	July 29– Aug. 6, 1985	Cmdr: C. Gordon Fullerton Plt: Roy Bridges, Jr. MS: F. Story Musgrave, Anthony W. England, Karl G. Henize PS: Loren W. Acton, John-David Bartoe	**International Payload (NASA/ESA)** • Spacelab 2 **Experiments and Equipment** • Shuttle Amateur Radio Experiment • Protein Crystal Growth in a Microgravity Environment **Deployable** • Plasma Diagnostics Package (part of Spacelab 2)
STS 51-I *Discovery*	Aug. 27– Sept. 3, 1985	Cmdr: Joe H. Engle Plt: Richard O. Covey MS: James D.A. van Hoften, John M. Lounge, William F. Fisher	**Commercial Payload** • Aussat-1/PAM-D • ASC-1/PAM-D • Syncom IV-4/Unique Upper Stage (Leasat-4) **Experiments and Equipment** • Physical Vapor Transport of Organic Solids • Syncom IV-3 Repair Equipment
STS 51-J *Atlantis*	Oct. 3–7, 1985	Cmdr: Karl Bobko Plt: Ronald J. Grabe MS: Robert L. Stewart, David C. Hilmers PS: William A. Pailes	DOD Mission

Table 3–21 continued

Mission/ Orbiter	Dates	Crew	Payload and Experiments
STS 61-A *Challenger*	Oct. 30–Nov. 6, 1985	Cmdr: Henry Hartsfield, Jr. Plt: Steven Nagel MS: Bonnie Dunbar, James Buchli, Guion Bluford PS: Ernst Messerschmid, Reinhard Furrer, Wubbo Ockels (ESA)	**International Payload (Germany)** • German Spacelab D-1 (Long Module + Unique Support Structure) **Get-Away Special (Deployed)** • G-308 (GLOMR—DOD) **Experiments and Equipment** • MEA
STS 61-B *Atlantis*	Nov. 26–Dec. 3, 1985	Cmdr: Brewster H. Shaw, Jr. Plt: Bryan D. O’Connor MS: Mary L. Cleave, Sherwood C. Spring, Jerry L. Ross PS: Rodolfo Neri Vela, Charles Walker	**Commercial Payloads** • Morelos B/PAM-D • Aussat-2/PAM-D • Satcom KU-2/PAM-DII **Experiments and Equipment** • EASE/ACCESS/MPESS • IMAX Payload Bay Camera • CFES III • Diffusive Mixing of Organic Solutions • Protein Crystal Growth (PCG) • Morelos Payload Specialist Experiments **Get-Away Special** • G-479 (Primary Surface Mirrors and Metallic Crystals, Telesat, Canada)
STS 61-C *Columbia*	Jan. 12–18, 1986	Cmdr: Robert L. Gibson Plt: C.F. Bolden, Jr. MS: F.R. Chang-Diaz, George D. Nelson, Steven A. Hawley PS: Robert J. Cenker, Congressman Bill Nelson	**Commercial Payloads** • Satcom KU-1/PAM-D2 **Experiments and Equipment** • Materials Science Lab (MSL-2) • Hitchhiker G-1 • Infrared Imaging Experiment • Initial Blood Storage Experiment • Comet Halley Active Monitoring Program • GAS Bridge Assembly (includes 12 GAS cans) **Get-Away Specials** • G-007 (Alabama Space and Rocket Center) • G-062 (Pennsylvania State Univ./General Electric Co. Space Div.) • G-310 (Air Force Academy/DOD Space Test Program) • G-332 (Booker T. Washington High School, Houston, Texas) • G-446 (High Performance Liquid Chromatography/Alltech Associates Inc.) • G-449 (Joint Utilization of Laser Integrated Experiments/St. Mary’s Hospital, Milwaukee)

Table 3–21 continued

Mission/ Orbiter	Dates	Crew	Payload and Experiments
STS 61-C continued			Experiment, NASA OSSA) • G-470 (Dept. of Agriculture/ Goddard) • G-481 (Vertical Horizons) • G-494 (Photometric Thermospheric Oxygen Nightglow Study/National Research Council of Canada) • Unnumbered (Environmental Monitoring Package, Goddard) **Shuttle Student Involvement Program** • Argon Injection as an Alternative to Honeycombing • Formation of Paper in Microgravity • Measurement of Auxin Levels and Starch Grains in Plant Roots
STS 51-L *Challenger*	Jan. 28–28, 1986	Cmdr: Francis R. Scobee Plt: Michael J. Smith MS: Judith A. Resnik, Ellison S. Onizuka, Ronald E. McNair PS: Gregory Jarvis, S. Christa McAuliffe	**NASA Payload (Planned)** • TDRS-B/IUS-NASA/Spacecom **Experiments and Equipment (Planned)** • Spartan-Halley/MPESS • Comet Halley Active Monitoring Program • Fluid Dynamics Experiment • Radiation Monitoring Experiment • Phase Partitioning Experiment • Teacher in Space Project **Shuttle Student Involvement Program (Planned)** • Utilizing a Semi-Permeable Membrane to Direct Crystal Growth • Effects of Weightlessness on Grain Formation and Strength in Metals • Chicken Embryo Development in Space
STS-26 *Discovery*	Sept. 29– Oct. 3, 1988	Cmdr: Frederick H. Hauck Plt: Richard O. Covey MS: John M. Lounge, David C. Hilmers, George D. Nelson	**NASA Payload** • TDRS-3/IUS **Experiments and Equipment** • Orbiter Experiments Autonomous Supporting Instrumentation System (OASIS) • Automated Directional Solidification Furnace • Aggregation of Red Blood Cells • Earth Limb Radiance Experiment • Isoelectric Focusing Experiment • Infrared Communication Flight Experiment • Mesoscale Lightning Experiment • Protein Crystal Growth (PCG) • Phased Partitioning Experiment • Physical Vapor Transport of Organic Solids

Table 3–21 continued

Mission/ Orbiter	**Dates**	**Crew**	**Payload and Experiments**
STS-26 continued			**Shuttle Student Involvement Program** • 82-4 (Utilizing a Semi-Permeable Membrane to Direct Crystal Growth, MDAC/Lloyd Bruce) • 82-5 (Effects of Weightlessness on Grain Formation and Strengthening Metals, Union College/R. Caboli)
STS-27 *Atlantis*	Dec. 2–6, 1988	Cmdr: Robert L. Gibson Plt: Guy S. Gardner MS: Jerry L. Ross, Richard M. Mullane, William M. Shepherd	DOD Payload

Table 3–22. STS-5 Mission Characteristics

Vehicle	*Columbia* (OV-102)
Crew	Cmdr: Vance D. Brand Pilot: Robert F. Overmyer MS: Joseph P. Allen, William B. Lenoir
Launch	November 11, 1982, 7:19:00 a.m., EST, Kennedy Space Center The launch proceeded as scheduled with no delays.
Orbital Altitude & Inclination	298.172 km/28.5 degrees
Launch Weight[a]	112,090.4 kg
Landing & Post-landing Operations	November 16, 1982, 6:33:26 am PST, Runway 22, Edwards AFB Orbiter was returned to Kennedy November 22, 1982.
Rollout Distance	2,911.8 m
Rollout Time	63 seconds
Mission Duration	5 days, 2 hours, 14 minutes, 26 seconds
Landed Revolution No.	82
Mission Support	Spaceflight Tracking and Data Network (STDN)
Deployed Satellites	SBS-C/PAM-D Telesat-E 3/PAM-D (Anik C-3)
Get-Away Specials	G-026 Customer: DFVLR, the German Aerospace Research Establishment This GAS was the first in a series of 25 GAS payloads managed by DFVLR. It was part of the German material science program, Project MAUS. Investigators used their knowledge that several combinations of two metals can be dissolved together in their liquid state above a certain temperature (consolute temperature), but not below this temperature. They used a combination of gallium and mercury to investigate the dissolution process above the consolute temperature. X-ray recordings provided real-time data of the different states of the experiment sequence.
Experiments	Tile Gap Heating Effects Experiment. This investigated the heat generated by gaps between the tiles of the thermal protection system on the Shuttle. Catalytic Surface Effects Experiment. This investigated the chemical reaction caused by impingement of atomic oxygen on the Shuttle thermal protection system, which was designed with the assumption that the atomic oxygen would recombine at the thermal protection system wall. Dynamic, Acoustic and Thermal Environment (DATE) Experiment. This collected data for use in making credible predictions of cargo bay environments. These environments were neither constant nor consistent throughout the bay and were influenced by interactions between cargo elements.

Table 3–22 continued

	Atmospheric Luminosities Investigation (Glow Experiment). This experiment was to determine the spectral content of the STS-induced atmospheric luminosities that had relevance for scientific and engineering aspects of payload operations. Oxygen Atom Interaction With Materials Test. This was conducted to obtain quantitative reaction rates of low-Earth orbit oxygen atoms with various materials used on payloads. Data obtained on STS-2 through 4 indicated that some payloads might be severely limited in life because of oxygen effect. The STS-5 test provided data for assessment of oxygen effects and possible fixes. Development Flight Instrumentation. This was a data collection and recording package, located in the aft areas of the payload bay, consisting of three magnetic tape recorders, wideband frequency division multiplexers, a pulse code modulation master unit, and signal conditioners. Aerodynamic Coefficient Identification Package (ACIP). This package, which has flown on STS-1 through 4, continued to collect aerodynamic data during the launch, entry, and landing phases of the Shuttle; establish an extensive aerodynamic database for verification of the Shuttle's aerodynamic performance and the verification and correlation with ground-based data, including assessments of the uncertainties of such data; and provide flight dynamics data in support of other technology areas, such as aerothermal and structural dynamics. Shuttle Student Involvement Program: 1. Growth of Porifera in Zero-Gravity studied the effect of zero gravity on sponge, Porifera, in relation to its regeneration of structure, shape, and spicule formation following separation of the sponge. 2. Convection in Zero-Gravity studied surface tension convection in zero gravity and the effects of boundary layer conditions and geometries on the onset and character of the convection. 3. Formation of Crystals in Weightlessness compared crystal growth in zero gravity to that in one-g to determine whether weightlessness eliminates the causes of malformation of crystals.
Mission Success	Successful

a Weight includes all cargo but does not include consumables.

Table 3–23. STS-6 Mission Characteristics

Vehicle	*Challenger* (OV-099)
Crew	Cmdr: Paul J. Weitz Pilot: Karol J. Bobko MS: Donald H. Peterson, F. Story Musgrave
Launch	April 4, 1983, 1:30:00 p.m., EST, Kennedy Space Center The launch set for January 20, 1983, was postponed because of a hydrogen leak into the number one main engine aft compartment, which was discovered during the 20-second Flight Readiness Firing (FRF) on December 18. Cracks in the number one main engine were confirmed to be the cause of the leak during the second FRF performed January 25, 1983. All three main engines were removed while the Shuttle was on the pad, and fuel line cracks were repaired. Main engines two and three were reinstalled following extensive failure analysis and testing. The number one main engine was replaced. An additional delay was caused by contamination to the Tracking and Data Relay Satellite (TDRS-1) during a severe storm. The launch on April 4 proceeded as scheduled.
Orbital Altitude & Inclination	284.5 km/28.45 degrees
Launch Weight	116,459 kg
Landing & Post-landing Operations	April 9, 1983, 10:53:42 a.m., PST, Runway 22, Edwards AFB Orbiter was returned to Kennedy April 16, 1983.
Rollout Distance	2,208 m
Rollout Time	49 seconds
Mission Duration	5 days, 0 hours, 23 minutes, 42 seconds
Landed Revolution No.	81
Mission Support	Spaceflight Tracking and Data Network (STDN)
Deployed Satellites	Tracking and Data Relay Satellite-1/IUS
Get-Away Specials	G-005 Customer: The Asahi Shimbun This experiment was proposed by two Japanese high school students to make artificial snowflakes in the weightlessness of space. The experiment was to contribute to crystallography, especially the crystal growth of semiconductors or other materials from a vapor source.

Table 3–23 continued

	G-049 Customer: Air Force Academy Academy cadets conducted six experiments: 1. Metal Beam Joiner demonstrated that soldering of beams can be accomplished in space. 2. Metal Alloy determined whether tin and lead will combine more uniformly in a zero-gravity environment. 3. Foam Metal generated foam metal in zero-gravity forming a metallic sponge. 4. Metal Purification tested the effectiveness of the zone-refining methods of purification in a zero-gravity environment. 5. Electroplating determined how evenly a copper rod can be plated in a zero-gravity environment. 6. Microbiology tested the effects of weightlessness and space radiation on microorganism development. G-381 Customer: George W. Park Seed Company, Inc. This payload consisted of 46 varieties of flower, herb, and vegetable seeds. It studied the impact of temperature fluctuations, vacuum, gravity forces, and radiation on germination rate, seed vigor, induced dormancy, and varietal purity. An objective was to determine how seeds should be packaged to withstand spaceflight.
Experiments	Continuous Flow Electrophoresis System (CFES). A sample of biological material was continuously injected into a flowing medium, which carried the sample through a separating column where it was under the influences of an electric field. The force exerted by the field separated the sample into its constituent types at the point of exit from the column where samples were collected. Monodisperse Latex Reactor. This materials processing experiment continued the development of uniformly sized (monodisperse) latex beads in a low-gravity environment, where the effects of buoyancy and sedimentation were minimized. The particles may have major medical and industrial research applications. Night/Day Optical Survey of Lightning. This studied lightning and thunderstorms from orbit for a better understanding of the evolution of lightning in severe storms. Aerodynamic Coefficient Identification Package (ACIP) (see STS-5)
Mission Success	Successful

Table 3–24. STS-7 Mission Characteristics

Vehicle	*Challenger* (OV-099)
Crew	Cmdr: Robert L. Crippen Pilot: Frederick H. Hauck MS: John M. Fabian, Sally K. Ride, Norman E. Thagard
Launch	June 18, 1983, 7:33:00 a.m., EDT, Kennedy Space Center The launch proceeded as scheduled.
Orbital Altitude & Inclination	296.3 km/28.45 degrees
Launch Weight	113,027.1 kg
Landing & Post-landing Operations	June 24, 1983, 6:56:59 a.m., PDT, Runway 15, Edwards AFB The planned landing at Kennedy was scrubbed because of poor weather conditions, and the mission was extended two revolutions to facilitate landing at Edwards. Orbiter was returned to Kennedy June 29, 1983.
Rollout Distance	3,185 m
Rollout Time	75 seconds
Mission Duration	6 days, 2 hours, 23 minutes, 59 seconds
Landed Revolution No.	98
Mission Support	Spaceflight Tracking and Data Network (STDN)
Deployed Satellites	Telesat-F/PAM-D (Anik C-2), Palapa-B1/PAM-D
Get-Away Specials	G-002 Customer: Kayser-Threde GMBH German high school students provided the experiments for this GAS. Their five experiments studied crystal growth, nickel catalysts, plant contamination by heavy metals, microprocessor controlled sequencers, and a biostack studying the influence of cosmic radiation on plant seeds. G-305 Customer: Department of Defense Space Test Program The Space Ultraviolet Radiation Environment (SURE) instrument, developed by the U.S. Naval Research Laboratory (NRL) Space Science Division, marked the debut of the GAS motorized door assembly (MDA). The MDA allowed the payload's spectrometer to measure the natural radiation in the upper atmosphere at extreme ultraviolet wavelengths. SURE was the first in a series of experiments planned by the NRL that ultimately would provide global pictures of "ionospheric weather." G-033 Customer: Steven Speilberg Movie director Steven Speilberg donated this GAS to the California Institute of Technology after receiving the payload as a gift. Caltech students designed and built one experiment, which examined oil and water separation in microgravity, and a second, which grew radish seeds, testing the theory that roots grow downward because gravity forces dense structures (amyloplasts) to settle to the bottom of root cells.

Table 3–24 continued

	G-009 Customer: Purdue University Purdue University students conducted three experiments: 1. Seeds were germinated in microgravity on a spinning disk. 2. Nuclear Particle Detection Experiment traced and recorded the paths of nuclear particles encountered in the near-Earth space environment. 3. Fluid Dynamics Experiment measured the bulk oscillations of a drop of mercury immersed in a clear liquid.
	G-088 Customer: Edsyn, Inc. Edsyn ran more than 60 experiments on soldering and de-soldering equipment. Passive experiments determined how soldering gear would function in space. Powered experiments investigated the physics of soldering in microgravity and a vacuum.
	G-345 Customer: Goddard Space Flight Center The Ultraviolet Photographic Test Package exposed film samples to the space environment.
	G-012 Customer: RCA High school students from Camden, New Jersey, with the backing of RCA Corporation and Temple University, investigated whether weightlessness would affect the social structure of an ant colony.
Detachable Payload	Shuttle Pallet Satellite (SPAS)-01. Ten experiments mounted on SPAS-01 performed research in forming metal alloys in microgravity and using a remote-sensing scanner. The orbiter's small control rockets fired while SPAS-01 was held by the RMS to test movement on the extended arm.
Experiments	OSTA-2 Payload (see Chapter 5, "Space Applications") Continuous Flow Electrophoresis System (CFES) (see STS-6) Monodisperse Latex Reaction (see STS-6)
Mission Success	Successful

Table 3–25. STS-8 Mission Characteristics

Vehicle	*Challenger* (OV-99)
Crew	Cmdr: Richard H. Truly Pilot: Daniel C. Brandenstein MS: Dale A. Gardner, Guion S. Bluford, Jr., William E. Thornton
Launch	August 30, 1983, 2:32:00 a.m., EDT, Kennedy Space Center Launch was delayed 17 minutes because of weather.
Orbital Altitude & Inclination	296.3 km/28.45 degrees
Launch Weight	110,107.8 kg
Landing & Post-landing Operations	September 5, 1983, 12:40:43 a.m. PDT, Runway 22, Edwards AFB Orbiter was returned to Kennedy September 9, 1983.
Rollout Distance	2,856.3 m
Rollout Time	50 seconds
Mission Duration	6 days, 1 hour, 8 minutes, 43 seconds
Landed Revolution No.	98
Mission Support	Spaceflight Tracking and Data Network (STDN)
Deployed Satellites	Insat 1B/PAM-D
Get-Away Specials	G-346 Customer: Goddard Space Flight Center The Cosmic Ray Upset Experiment attempted to resolve many of the questions concerning upsets caused by single particles. An upset, or change in logic state, of a memory cell can result from a single, highly energetic particle passing through a sensitive volume in a memory cell. G-347 Customer: Goddard Space Flight Center The Ultraviolet-Sensitive Photographic Emulsion Experiment evaluated the effect of the orbiter's gaseous environment on ultraviolet-sensitive photographic emulsions. G-475 Customer: The Asahi Shimbun The Japanese Snow Crystal Experiment attempted to create the first snowflakes in space, which had been attempted unsuccessfully on STS-6. G-348 Customer: Goddard Space Flight Center The Contamination Monitor Package measured the changes in outer coatings and thermal blanket coverings on the Shuttle that were caused by atomic oxygen erosion.
Experiments	Development Flight Instrumentation Pallet (DFI Pallet): • High Capacity Heat Pipe Demonstration (DSO 0101) provided an in-orbit demonstration of the thermal performance of a high-capacity heat pipe designed for future spacecraft heat rejection systems. • Evaluation of Oxygen Interaction with Materials (DSO 0301) obtained quantitative rates of oxygen interaction with materials used on the orbiter and advanced payloads.

Table 3–25 continued

	Biofeedback Experiments. Six rats were flown in the Animal Enclosure Module to observe animal reactions in space and to demonstrate that the module was capable of supporting six healthy rats in orbit without compromising the health and comfort of either the astronaut crew or the rats. Continuous Flow Electrophoresis System (CFES) (see STS-6) Aerodynamic Coefficient Identification Package (ACIP) (see STS-5) Radiation Monitoring Experiment. This consisted of hand-held and pocket-sized monitors, which measured the level of background radiation present at various times in orbit. The two devices were self-contained and powered by 9-volt batteries. At appointed times, the crew took and recorded measurements of any radiation that penetrated the cabin. Investigation of STS Atmospheric Luminosities (see STS-5) Shuttle Student Involvement Program: Biofeedback Mediated Behavioral Training in Physiological Self Regulator: Application in Near Zero Gravity Environment. This aimed to determine whether biofeedback training learned in a one-g environment can be successfully implemented at zero-g.
Mission Success	Successful

Table 3–26. STS-9 Mission Characteristics

Vehicle	*Columbia* (OV-102)
Crew	Cmdr: John W. Young Pilot: Brewster H. Shaw MS: Owen K. Garriott, Robert A.R. Parker PS: Byron K. Lichtenberg, Ulf Merbold (ESA)
Launch	November 28, 1983, 11:00:00 a.m., EST, Kennedy Space Center Launch set for September 30, 1983, was delayed 28 days because of a suspect exhaust nozzle on the right solid rocket booster. The problem was discovered while the Shuttle was on the launch pad. The Shuttle was returned to the Vehicle Assembly Building and demated. The suspect nozzle was replaced, and the vehicle was restacked. The countdown on November 28 proceeded as scheduled. During launch and ascent, verification flight instrumentation (VFI) operated the Spacelab and the Spacelab interfaces with the orbiter. This instrumentation monitored Spacelab subsystem performance and Spacelab-to-orbiter interfaces. Data were recorded during launch and ascent on the VFI tape recorder and played back to receiving stations on Earth during acquisition of signal periods using the Tracking and Data Relay Satellite System (TDRSS).
Orbital Altitude & Inclination	287.1 km/57.0 degrees
Launch Weight	112,320 kg
Landing & Post-landing Operations	December 8, 1983, 3:47:24 p.m., PST, Runway 17, Edwards AFB Landing was delayed approximately 8 hours to analyze problems when general purpose computers one and two failed and inertial measurement unit one failed. During landing, two of the three auxiliary power units caught fire. During descent and landing, the VFI continued to monitor and record selected Spacelab parameters within the payload bay. One hour after touchdown, power to the induced environment contamination monitor was removed. Orbiter was returned to Kennedy December 15, 1983.
Rollout Distance	2,577.4 m
Rollout Time	53 seconds
Mission Duration	10 days, 7 hours, 47 minutes, 24 seconds
Landed Revolution No.	167
Mission Support	Spaceflight Tracking and Data Network (STDN)/Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	INSAT-1B/PAM-D
Get-Away Specials	None
Experiments	See Table 4–45, Spacelab 1 Experiments
Mission Success	Successful

Table 3–27. STS 41-B Mission Characteristics

Vehicle	*Challenger* (OV-099)
Crew	Cmdr: Vance D. Brand Pilot: Robert L. Gibson MS: Bruce McCandless II, Ronald E. McNair, Robert L. Stewart
Launch	February 3, 1984, 8:00:00 a.m., EST, Kennedy Space Center The launch, set for January 29, was postponed for 5 days while the orbiter was still in the Orbiter Processing Facility to allow changeout of all three auxiliary power units (APUs), a precautionary measure in response to APU failures on the STS-9 mission.
Orbital Altitude & Inclination	350 km/28.5 degrees
Launch Weight	113,605 kg
Landing & Post-landing Operations	February 11, 1984, 7:15:55 a.m., EST, Runway 15, Kennedy This was the first end-of-mission landing at Kennedy.
Rollout Distance	3,294 m
Rollout Time	67 seconds
Mission Duration	7 days, 23 hours, 15 minutes, 55 seconds
Landed Revolution No.	128
Mission Support	Spaceflight Tracking and Data Network (STDN)
Deployed Satellites	Westar-VI/PAM-D, Palapa-B2/PAM-D
Get-Away Specials	G-004 Customer: Utah State University Students at the University of Aberdeen in Scotland used one of Utah State's spacepaks on this payload. Aberdeen students flew experiments on spore growth, three-dimensional Brownian motion, and dimensional stability. Two other spacepaks contained experiments on capillary action in the absence of gravity. G-008 Customer: Utah State University This payload was purchased by the Utah Section of the American Institute of Aeronautics and Astronautics and donated to Utah State University: 1. In the experiment conducted by students from Brighton High School, Salt Lake City, radish seeds sprouted in a zero-g environment. About one-half of the germinated seeds had flown earlier in an STS-6 experiment. 2. Students from Utah State University attempted to crystallize proteins in a controlled-temperature environment under zero-g conditions. The crystallization of proteins was necessary for studies in x-ray crystallography. 3. Two Utah State students devised this payload. The first experiment reran a soldering experiment flown on GAS G-001. The second tested an experimental concept for creating a flow system for electophoresis experiments.

Table 3–27 continued

	G-349 Customer: Goddard Space Flight Center Contamination Monitor Package (flown on STS-8) measured the flow of atomic oxygen by determining the mass loss of carbon and osmium, known to readily oxidize. The mass loss indicated the atomic oxygen flux as a function of time, which was correlated to altitude, attitude, and direction. This experiment exposed the Shuttle’s outer coatings and thermal blanket coverings to normal orbit conditions.
	G-051 Customer: GTE Laboratories, Inc. Arc Lamp Research studied the configuration of an arc lamp in gravity-free surroundings. Scientists hoped the experiment would pave the way for the development of a more energy-efficient commercial lamp.
	G-309 Customer: U.S. Air Force Cosmic Ray Upset Experiment (CRUX) was a repeat of G-346 initially flown by Goddard on STS-8. This experiment investigated upsets or changes in the logic state of a memory cell caused by highly active energetic particles passing through a sensitive volume in the memory cell.
Experiments	Acoustic Containerless Experiment (ACES). This materials processing furnace experiment was enclosed in two airtight canisters in the orbiter middeck. Activated at 23 hours mission elapsed time, ACES ran a preprogrammed sequence of operations and shut itself off after 2 hours.
	Monodisperse Latex Reaction (see STS-6)
	Radiation Monitoring Experiment (see STS-8)
	Isoelectric Focusing Experiment. This self-contained experiment package in the middeck lockers was activated by the crew at the same time as ACES. It evaluated the effect of electro-osmosis on an array of eight columns of electrolyte solutions as DC power was applied and pH levels between anodes and cathodes increased.

Table 3–27 continued

	Cinema 360 Camera. Two Cinema 360 cameras were carried on board to provide a test for motion picture photography in a unique format designed especially for planetarium viewing. One camera was located in the crew cabin area and the other in a GAS canister in the payload bay. The primary objective was to test the equipment and concept. Film footage taken by the two systems was also of considerable value. Arriflex 35mm Type 3 motion picture cameras with an 8mm/f2.8 “fisheye” lens were used. The Cinema 360 camera, including an accessory handle and lens guard/support, weighed about 5 kilograms.
	A system power supply weighed an additional 7.7 kilograms. Filming inside the orbiter focused on activities on the flight deck. The camera system located in the GAS canister in the payload bay provided film on exterior activities, including EVA/MMU operations, satellite deployment, and RMS operations. Lens focus, diaphragm setting, and frame speed were preset, thus requiring no light level readings or exposure calculations by the crew. Each camera carried a 122-meter film magazine. Filming done on this flight and subsequent missions was used in the production of a motion picture about the Space Shuttle program.
	Shuttle Student Involvement Program: This experiment tested the hypothesis that arthritis may be affected by gravity.
Mission Success	Successful

Table 3–28. STS 41-C Mission Characteristics

Vehicle	*Challenger* (OV-099)
Crew	Cmdr: Robert L. Crippen Pilot: Francis R. Scobee MS: George D. Nelson, James D. A. van Hoften, Terry J. Hart
Launch	April 6, 1984 8:58:00 a.m., EST, Kennedy Space Center The launch proceeded as scheduled with no delays.
Orbital Altitude & Inclination	579.7 km/28.5 degrees
Launch Weight	115,329.6 kg
Landing & Post-landing Operations	April 13, 1984, 5:38:07 a.m., PST, Runway 17, Edwards AFB The mission was extended 1 day when astronauts were initially unable to grapple the Solar Maximum Mission spacecraft. The planned landing at Kennedy was scrubbed and the mission extended one revolution to facilitate landing at Edwards. Orbiter was returned to Kennedy April 18, 1984.
Rollout Distance	2,656.6 m
Rollout Time	49 seconds
Mission Duration	6 days, 23 hours, 40 minutes, 7 seconds
Landed Revolution No.	108
Mission Support	Spaceflight Tracking and Data Network (STDN)
Deployed Satellites	Long Duration Exposure Facility-1 (LDEF-1)
Get-Away Specials	None
Experiments	The experiments carried aboard the reusable LDEF fell into four major groups: material structures, power and propulsion, electronics and optics, and science. The 57 separate experiments involved more that 200 investigators from the United States and eight other countries and were furnished by government laboratories, private companies, and universities. They are described in Chapter 4, “Space Science.” Radiation Monitoring Experiment (see STS-8) Cinema 360 (see STS 41-B) IMAX. The IMAX camera made the first of three scheduled trips into space on this mission. Footage from the flight was assembled into a film called *The Dream Is Alive*. The IMAX camera was part of a joint project among NASA, the National Air and Space Museum, IMAX Systems Corporation of Toronto, Canada, and the Lockheed Corporation. Shuttle Student Involvement Program: This experiment studied the honeycomb structure built by bees in zero gravity, compared to the structure built by bees on Earth.
Mission Success	Successful

Table 3–29. STS 41-D Mission Characteristics

Vehicle	*Discovery* (OV-103)
Crew	Cmdr: Henry W. Hartsfield, Jr. Pilot: Michael L. Coats MS: Judith A. Resnik, Richard M. Mullane, Steven A. Hawley PS: Charles D. Walker
Launch	August 30, 1984, 8:41:50 a.m., EDT, Kennedy Space Center The launch attempt on June 25 was scrubbed during a T-9 minute hold because of failure of the orbiter's back-up general purpose computer (GPC). The launch attempt on June 26 aborted at T-4 seconds when the GPC detected an anomaly in the orbiter's number three main engine. *Discovery* was returned to the Orbiter Processing Facility and the number three main engine replaced. (To preserve the launch schedule of future missions, the 41-D cargo was remanifested to include payload elements from both the 41-D and 41-F flights, and the 41-F mission was canceled.) After replacement of the engine, the Shuttle was restacked and returned to the pad. The third launch attempt on August 29 was delayed when a discrepancy was noted in flight software of *Discovery*'s master events controller relating to solid rocket booster fire commands. A software patch was verified and implemented to assure all three booster fire commands were issued in the proper time interval. The launch on August 30 was delayed 6 minutes, 50 seconds when a private aircraft intruded into the warning area off the coast of Cape Canaveral.
Orbital Altitude & Inclination	340.8 km/28.5 degrees
Launch Weight	119,513.2 kg
Landing & Post-landing Operations	September 5, 1984, 6:37:54 a.m. PDT, Runway 17, Edwards AFB Orbiter was returned to Kennedy September 10, 1984.
Rollout Distance	3,131.8 m
Rollout Time	60 seconds
Mission Duration	6 days, 0 hours, 56 minutes, 4 seconds
Landed Revolution No.	97
Mission Support	Spaceflight Tracking and Data Network (STDN)
Deployed Satellites	SBS-4/PAM-D, Syncom IV-2/UUS (Leasat-2), and Telstar 3-C/PAM-D
Get-Away Specials	None
Experiments	Cloud Logic to Optimize Use of Defense Systems (CLOUDS). Sponsored by the Air Force, this payload consisted of two 250-exposure camera assemblies with battery-powered motor drives, which were used at the aft flight deck station for cloud photography data collection.

Table 3–29 continued

	Vehicle Glow Experiment. This experiment characterized surface-originated vehicle glow on strips of material that were attached to the robot arm. Observations made during previous Shuttle flights indicated that optical emissions originated on spacecraft surfaces facing the direction of orbital motion. These emissions showed differing spectral distribution and intensity of the glow for different materials and spacecraft altitude. These results had significance for observations made from the space telescope and space station. CFES-III (see STS-6) Radiation Monitoring Experiment (see STS-8) IMAX (see STS 41-C) Shuttle Student Involvement Program: Purification and Growth of Single Crystal Gallium by the Float Zone Technique in a Zero Gravity Environment, Shawn Murphy/Rockwell International. This experiment compared a crystal grown by the "Flat Zone" technique in a low-gravity environment with one grown in an identical manner on Earth.
Mission Success	Successful

Table 3–30. STS 41-G Mission Characteristics

Vehicle	*Challenger* (OV-099)
Crew	Cmdr: Robert L. Crippen Pilot: Jon A. McBride MS: David C. Leestma, Sally K. Ride, Kathryn D. Sullivan PS: Paul D. Scully-Power, Marc Garneau (Canadian Space Agency)
Launch	October 5, 1984 7:03:00 a.m., EDT, Kennedy Space Center Launch proceeded as scheduled with no delays.
Orbital Altitude & Inclination	403.7 km/57.0 degrees
Launch Weight	110,125 kg
Landing & Post-landing Operations	October 13, 1984, 12:26:38 p.m., EDT, Runway 33, Kennedy
Rollout Distance	3,220 m
Rollout Time	54 seconds
Mission Duration	8 days, 5 hours, 23 minutes, 38 seconds
Landed Revolution No.	133
Mission Support	Spaceflight Tracking and Data Network (STDN)/Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	Earth Radiation Budget Satellite (ERBS)
Get-Away Specials	G-013 Customer: Kayser-Threde GMBH The Halogen Lamp Experiment (HALEX) tested the performance of halogen lamps during periods of microgravity. The flight was financed by ESA. G-007 Customer: Alabama Space and Rocket Center Project Explorer Payload: 1. This experiment attempted to transmit radio-frequency measurements to ground-based radio hams around the world. This experiment was built by the Marshall Space Flight Center Amateur Radio Club. 2. Alabama university students investigated the growth of a complex inorganic compound with exceptional conductive properties, the solidification of an alloy with superplastic properties, and the germination and growth of radish seeds in space. The payload did not operate, and a reflight was scheduled for STS 61-C. G-032 Customer: International Space Corp. This experiment studied the strength of surface tension in the absence of gravity by firing BBs at free-standing spheres of water in microgravity. A second experiment on this GAS used five small electrical furnaces to produce new materials.

Table 3–30 continued

G-306
Customer: Department of Defense Space Test Program
The Trapped Ions in Space experiment recorded the tiny radiation damage tracks left by heavy ions as they passed through a stack of track-detecting plastic sheets during flight. Upon return to Earth, the tracks were etched chemically, revealing cone-shaped pits where particles had passed. Investigators then studied the pits to deduce the energies and arrival direction of the different types of ions that were collected.

G-038
Customer: Marshall—McShane
The investigator used vacuum deposition techniques to coat glass spheres with gold, platinum, and other metals to create lustrous space sculptures. The process was similar to that used on Earth to coat lenses, glass, and mirrors, but the vacuum and weightlessness of space allowed a highly uniform coating only a few microns thick. A control sphere was evacuated to the natural vacuum level of space and sealed. Back on Earth, the investigator took measurements of it to determine the vacuum level at which the depositions had occurred.

G-518
Customer: Utah State University
Four experiments flown on STS 41-B were reflown. The experiments explored basic physical processes in a microgravity environment: capillary waves caused when water is excited, separation of flux and solder, thermocapillary convection, and a fluid flow system in a heat pipe.

G-074
Customer: McDonnell Douglas Astronautics Co.
This experiment demonstrated two methods of delivering partially full tanks of liquid fuel, free of gas bubbles, to engines that control and direct orbiting spacecraft.

G-469
Customer: Goddard Space Flight Center
The Cosmic Ray Upset Experiment (CRUX) III evolved from experiments flown on STS-8 and STS 41-B. It tested fur types of advanced, state-of-the-art microcircuits, totaling more than 12 megabytes. This environment for this experiment was harsher by orders of magnitude than for previous CRUX payloads carried at lower latitudes.

Table 3–30 continued

Experiments	Aurora Photography Experiment. This was conducted for the U.S. Air Force. Orbital Refueling System. This developed and demonstrated the equipment and techniques for refueling existing satellites in orbit. Four fuel transfers, controlled by the crew from within the crew cabin, were performed during the mission, in addition to a spacewalk designed to connect a servicing tool to valves that simulated existing satellites not originally designed for on-orbit refueling. Radiation Monitoring Experiment (see STS-8) IMAX (see STS 41-C) Canadian Experiment (CANEX). Mark Garneau, the Canadian payload specialist, conducted ten experiments for the National Research Council of Canada. They fell into the categories of space technology, space science, and life sciences. Thermoluminescent Dosimeter (TLD). The Central Research Institute for Physics in Budapest, Hungary, developed a small portable dosimetry system that was carried in a cabin locker. It received doses of cosmic radiation during spaceflight for comparison with the currently used dosimetry systems.
Mission Success	Successful, with the exception of the Shuttle Imaging Radar (SIR)-B. *Challenger*'s Ku-band antenna problems severely affected the SIR-B. A reflight of SIR-B was requested and manifested on STS 72-A, at that time scheduled for launch in February 1987.

Table 3–31. STS 51-A Mission Characteristics

Vehicle	*Discovery* (OV-103)
Crew	Cmdr: Frederick H. Hauck Pilot: David M. Walker MS: Anna L. Fisher, Dale A. Gardner, Joseph P. Allen
Launch	November 8, 1984, 7:15:00 a.m., EST, Kennedy Space Center Launch attempt on November 7 was scrubbed during a built-in hold at T-20 minutes because of wind shears in the upper atmosphere. The countdown on November 8 proceeded as scheduled.
Orbital Altitude & Inclination	342.6 km/28.5 degrees
Launch Weight	119,443.7 kg
Landing & Post-landing Operations	November 16, 1984, 6:59:56 a.m., EST, Runway 15, Kennedy
Rollout Distance	2,881.6 m
Rollout Time	58 seconds
Mission Duration	7 days, 23 hours, 44 minutes, 56 seconds
Landed Revolution No.	127
Mission Support	Spaceflight Tracking and Data Network (STDN)/ Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	Telesat-H/PAM-D (Anik D2), Syncom IV-1/PAM-D (Leasat-1)
Get-Away Specials	None
Experiments	The Diffusive Mixing of Organic Solutions (DMOS) experiment, a collaboration between 3M and NASA, was the first attempt to grow organic crystals in the microgravity environment of the orbiter. The program's ultimate goal was to produce commercially valuable products in the fields of organic and polymer chemistry. The experiment studied the physical processes that govern the crystal growth and evaluated the diffusive mixing method of crystal growth. It also evaluated the type of apparatus used for its suitability for crystal growth in the weightless environment of low-Earth orbit. Radiation Monitoring Experiment (see STS-8)
Mission Success	Successful

Table 3–32. STS 51-C Mission Characteristics

Vehicle	*Discovery* (OV-103)
Crew	Cmdr: Thomas K. Mattingly II Pilot: Loren J. Shriver MS: James F. Buchli, Ellison S. Onizuka PS: Gary E. Payton
Launch	January 24, 1985, 2:50:00 p.m., EST, Kennedy Space Center The January 23 launch was scrubbed because of freezing weather conditions. (*Challenger* was scheduled for STS 51-C, but thermal tile problems forced the substitution of *Discovery*.)
Orbital Altitude & Inclination	407.4 km/28.5 degrees
Launch Weight	113,804.2 kg
Landing & Post-landing Operations	January 27, 1985, 4:23:23 p.m., EST, Runway 15, Kennedy
Rollout Distance	2,240.9 m
Rollout Time	50 seconds
Mission Duration	3 days, 1 hour, 33 minutes, 23 seconds
Landed Revolution No.	49
Mission Support	Spaceflight Tracking and Data Network (STDN)/ Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	DOD 85-1/IUS
Get-Away Specials	None
Experiments	Aggregation of Red Blood Cells. This tested the capability of the apparatus to study in weightlessness some of the various characteristics of blood, such as viscosity, and their disease dependencies. Preliminary results indicated that: • It was possible to obtain perfect microphotographs of blood cells in space under conditions of heavy vibration. • Cells form aggregates that grow with time, analogous to patterns on Earth. • The internal organization and structure of aggregates seem to be different under zero gravity. • Individual red cells do not show abnormal shapes under zero gravity; notwithstanding the origin of the blood samples, they looked normal. • Because there was no sludging under weightlessness, studies on interactions between cells should be much easier. • Changes in shape of red cells in astronauts (as reported by Johnson Space Center) must be caused by a change of calcium metabolism.
Mission Success	Successful

Table 3–33. STS 51-D Mission Characteristics

Vehicle	*Discovery* (OV-103)
Crew	Cmdr: Karol J. Bobko Pilot: Donald E. Williams MS: M. Rhea Seddon, S. David Griggs, Jeffrey A. Hoffman PS: Charles D. Walker, Sen. E.J. Garn
Launch	April 12, 1985, 8:59:05 a.m., EST, Kennedy Space Center The launch set for March 19 was rescheduled to March 28 because of remanifesting of payloads from canceled mission 51-E. The launch was delayed further because of damage to the orbiter's payload bay door when the facility access platform dropped. The April 12 launch was delayed 55 minutes when a ship entered the restricted solid rocket booster recovery area.
Orbital Altitude & Inclination	527.8 km/28.5 degrees
Launch Weight	113,804.2 kg
Landing & Post-landing Operations	April 19, 1985, 8:54:28 a.m. EST, Runway 33, Kennedy Extensive brake damage and a blown tire during landing prompted the landing of future flights at Edwards AFB until the implementation of nose wheel steering.
Rollout Distance	3,138.8 m
Rollout Time	63 seconds
Mission Duration	6 days, 23 hours, 55 minutes, 23 seconds
Landed Revolution No.	110
Mission Support	Spaceflight Tracking and Data Network (STDN)/Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	Telesat-I/PAM-D (Anik C-1), Syncom IV-3/UUS (Leasat-3)
Get-Away Specials	G-035 Customer: The Asahi Shimbun Physics of Solids and Liquids in Zero Gravity was designed to determine what happened when a metal or plastic (solid) was allowed to collide with a water ball (liquid) in weightlessness. The behavior of the metal or plastic ball and the water ball after collision was observed on video systems. G-471 Customer: Goddard Space Flight Center Capillary Pump Loop Experiment investigated whether a capillary pump system could transfer waste heat from a spacecraft out into space. The experiment consisted of two capillary pump evaporators with heaters and was designed to demonstrate that such a system can be used under zero-gravity conditions of spaceflight to provide thermal control of scientific instruments, advanced orbiting spacecraft, and space station components.

Table 3–33 continued

Experiments	Phase Partitioning Experiment. Phase partitioning is a selective, yet gentle and inexpensive technique used to separate biomedical materials, such as cells and proteins. It establishes a two-phase system by adding various polymers to a water solution containing the materials to be separated. Theoretically, phase partitioning should separate cells with significantly higher resolution than was presently obtained in the laboratory. Investigators believed that when the phases are emulsified on Earth, the rapid, gravity-driven fluid movements occurring as the phases coalesce tended to randomize the separation process. They expected that the theoretical capabilities of phase partitioning systems could be more closely approached in the weightlessness of orbital spaceflight, where gravitational effects of buoyancy and sedimentation were minimized.
	American Flight Echocardiograph. This experiment studied the effects of weightlessness on the cardiovascular system of astronauts, which was important for both personal and operational safety reasons. The newly available instrument gathered in-flight data on these effects during space adaptation to develop optimal countermeasures to crew cardiovascular changes (particularly during reentry) and to ensure long-term safety to people living in weightlessness.
	Protein Crystal Growth (PCG). This experiment studied the composition and structure of proteins, extremely important to the understanding of their nature and chemistry and the ability to manufacture them for medical purposes. However, for most complex proteins, it had not been possible to grow, on Earth, crystals large enough to permit x-ray or neutron diffraction analyses to obtain this information. A key objective of the overall PCG program was to enable drug design without the present empirical approach to enzyme engineering and the manufacture of chemotherapeutic agents.
	Toys in Space. The crew demonstrated the behavior of simple toys in a weightless environment. The results, recorded and videotaped, became part of a curriculum package for elementary and junior high students through the Houston Museum of Natural Science. Studies showed that students could learn physics concepts by watching mechanical systems in action. In an Earth-based classroom, the gravitational field has a constant value of 1-g. Although the gravity force varied greatly throughout the universe and in noninertial reference frames, students could only experiment in a constant 1-g environment. The filming of simple generic-motion toys in the zero-g environment enabled students to discover how the different toy mechanical systems work without gravity.

Table 3–33 continued

	Image Intensifier Investigation. This tested low-light-level photographic equipment, in preparation for the visit by Halley's Comet. Astronaut Hoffman examined an image intensifier coupled with a Nikon camera, a combination that intensified usable light by a factor of about 10,000. It was believed that the equipment could be used to observe objects of astronomical interest through the Shuttle's window, including Halley's Comet. Hoffman photographed objects at various distances from the Sun when it was below the horizon, similar to lighting conditions when the comet appeared. Continuous Flow Electrophoresis System (CFES) III (see STS-8) Shuttle Student Involvement Program: 1. Statoliths in Corn Root Caps examined the effect of weightlessness on the formation of statoliths (gravity-sensing organs) in plants and was tested by exposing plants with capped and uncapped roots to spaceflight. The root caps of the flight and control plants were examined postflight by an electron microscope for statolith changes. 2. Effect of Weightlessness on the Aging of Brain Cells used houseflies and was expected to show accelerated aging in their brain cells based on an increased accumulation of age pigment in, and deterioration of, the neurons.
Medical Experiments	Utah Senator E.J. "Jake" Garn was the first public official to fly aboard the Space Shuttle. Garn was a payload specialist and congressional observer. As payload specialist, he conducted medical physiological tests and measurements. Tests on Garn detected and recorded changes the body underwent in weightlessness, an ongoing program that began with astronauts on the fourth Shuttle flight. Garn accomplished the following: • During launch, Garn wore a waist belt with two stethoscope microphones fastened to an elastic bandage. At main engine cutoff, about 8.5 minutes into the flight, the belt was plugged into a portable tape recorder stored in the seat flight bag and began recording bowel sounds to evaluate early in-flight changes in gastric mobility. • An electrocardiogram recorded electrical heart rhythm in the event of space motion sickness in orbit. • Garn was wore a leg plethysmography stocking to measure leg volume. It recorded the shifting of fluids during adaptation to weightlessness. • Blood pressure and heart rate were recorded in orbit and during reentry. • Another test measured Garn's height and girth in space to determine the amount of growth and change in body shape associated with weightlessness. Space travelers may grow up to 2 inches while weightless. • Tests determined whether a medication dosage on Earth was adequate in space with acetaminophen. Garn's saliva was collected for analysis after each dose.
Mission Success	Successful

Table 3–34. STS 51-B Mission Characteristics

Vehicle	*Challenger* (OS-099)
Crew	Cmdr: Robert F. Overmyer Pilot: Frederick D. Gregory MS: Don L. Lind, Norman E. Thagard, William E. Thornton PS: Lodewijk van den Berg, Taylor G. Wang
Launch	April 29, 1985, 12:02:18 p.m., EDT, Kennedy Space Center This flight was first manifested as 51-E. It was rolled back from the pad because of a timing problem with the TDRS-B payload. Mission 51-E was canceled, and the orbiter was remanifested with 51-B payloads. The launch on April 29 was delayed 2 minutes, 18 seconds because of a launch processing system failure.
Orbital Altitude & Inclination	411.1 km/57.0 degrees
Launch Weight	111,984.8 kg
Landing & Post-landing Operations	May 6, 1985, 9:11:04 a.m. PDT, Runway 17, Edwards AFB Orbiter was returned to Kennedy May 11, 1985.
Rollout Distance	2,535 m
Rollout Time	59 seconds
Mission Duration	7 days, 0 hours, 8 minutes, 46 seconds
Landed Revolution No.	111
Mission Support	Spaceflight Tracking and Data Network (STDN)/ Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	NUSAT (Get-Away Special); GLOMR was scheduled for deployment but was rescheduled on STS 61-A
Get-Away Specials	G-010 Customer: R. Gilbert Moore Northern Utah Satellite (NUSAT) was a cooperative effort among the Federal Aviation Administration (FAA), Weber State College, Utah State University, New Mexico State University, Goddard, the U.S. Air Force, and more than 26 private corporations. It was deployed into a 20-month orbit. It was an air traffic control radar calibration system that measured antenna patterns for ground-based radar operated in the United States and in member countries of the International Civil Aviation Organization. G-308 Customer: Department of Defense Space Test Program The Global Low Orbiting Message Relay (GLOMR) satellite was planned to pick up digital data streams from ground users, store the data, and deliver the messages in these data streams to customers' computer terminals upon command. It was designed to remain in orbit for 1 year. However, because of a malfunction in the Motorized Door Assembly, GLOMR was not deployed on this mission.
Experiments	See Table 4–46, Spacelab 3 Experiments
Mission Success	Successful

Table 3–35. STS 51-G Mission Characteristics

Vehicle	*Discovery* (OV-103)
Crew	Cmdr: Daniel C. Brandenstein Pilot: John O. Creighton MS: Shannon W. Lucid, Steven R. Nagel, John M. Fabian PS: Patrick Baudry (CNES), Sultan Salman Al-Saud
Launch	June 17, 1985, 7:33:00 a.m., EDT, Kennedy Space Center The launch proceeded as scheduled with no delays.
Orbital Altitude & Inclination	405.6 km/28.5 degrees
Launch Weight	116,363.8 kg
Landing & Post-landing Operations	June 24, 1985, 6:11:52 a.m., PDT, Runway 23, Edwards AFB Orbiter was returned to Kennedy June 28, 1985.
Rollout Distance	2,265.6 m
Rollout Time	42 seconds
Mission Duration	7 days, 1 hour, 38 minutes, 52 seconds
Landed Revolution No.	112
Mission Support	Spaceflight Tracking and Data Network (STDN)/Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	Morelos-A/PAM-D, Telstar-3D/PAM-D, Arabsat-A/PAM-D, Spartan-1 (deployed and retrieved)
Get-Away Specials	G-025 Customer: ERNO-Raumfahrttechnik GMBH Liquid Sloshing Behavior in Microgravity examined the behavior of liquid in a tank in microgravity. It was representative of phenomena occurring in satellite tanks with liquid propellants. The results were expected to validate and refine mathematical models describing the dynamic characteristics of tank-fluid systems. This in turn would support the development of future spacecraft tanks, in particular the design of propellant management devices for surface-tension tanks. G-027 Customer: DFVLR Slipcasting Under Microgravity Conditions was performed by Germany’s material research project, MAUS. Its goal was to demonstrate with model materials the possibility of slipcasting in microgravity, even with unstabilized suspensions using mixtures of powders with different density, grain size, and concentration. G-028 Customer: DFVLR Fundamental Studies in Manganese-Bismuth produced manganese-bismuth specimens with possibly better magnetic properties than currently was possible under Earth gravity.

Table 3–35 continued

	G-034 Customer: Dickshire Coors Texas Student Experiments featured twelve different biological and physical science experiments designed by high school students from El Paso and Ysleta, Texas. The microgravity experiments studied the growth of lettuce seeds, barley seed germination, the growth of brine shrimp, germination of turnip seeds, the regeneration of the flat work planeria, the wicking of fuels, the effectiveness of antibiotics on bacteria, the growth of soil mold, crystallization in zero gravity, the symbiotic growth of the unicellular algae chlorella and the milk product kefir, the operation of liquid lasers, and the effectiveness of dynamic random access memory computer chips without ozone protection. G-314 Customer: DOD Space Test Program Space Ultraviolet Radiation Environment (SURE) measured the natural radiation field in the upper atmosphere at extreme ultraviolet wavelengths, between 50 and 100 nanometers. These measurements provided a way of remotely sensing the ionosphere and upper atmosphere. G-471 Customer: Goddard Space Flight Center Capillary Pumped Loop investigated the thermal control capability of a capillary-pumped system under zero-gravity conditions for ultimate use in large scientific instruments, advanced orbiting spacecraft, and space station components.
Experiments	Spartan 1. This was the first in a series of Shuttle-launched, short-duration free-flyers designed to extend the capabilities of sounding rocket class experiments. Its primary mission was to perform medium-resolution mapping of the x-ray emission from extended sources and regions, specifically the hot (10,000 degrees Celsius) gas pervading a large cluster of galaxies in the constellation Perseus and in the galactic center and Scorpius-X-2. In addition, it mapped the x-ray emissions from the nuclear region of the Milky Way galaxy. French Echocardiograph Experiment. This measured and studied the evolution of the fundamental parameters that characterized cardiac function, blood vessel circulation, and cardiovascular adaptation. After reviewing the data, the principal investigator observed a decrease of cardiac volume, stroke volume, and left ventricular diastolic volume, a decrease in cerebral circulatory resistance, and noted variations in peripheral resistance and vascular stiffness of the lower limbs.

Table 3–35 continued

	French Posture Experiment. This had five general objectives: a study of the adaptive mechanisms of postural control, the influence of vision in adaptations, the role of the otoliths in the oculomotor stabilization reflexes, their role in the coordination of eye and head movements, and mental representation of space. After reviewing the data, the principal investigator observed a change in vertical optokinetic nystagmus, which included an asymmetry reversal and a downward shift in beating field of the nystagmus, as well as a decrease in the gain of the vestibular ocular reflex. Automated Directional Solidification Furnace. Experiments carried out in the furnace demonstrated the capability of the furnace equipment and provided preliminary scientific results on magnetic composites. Future missions would demonstrate the feasibility of producing improved magnetic composite materials for commercial use. These materials could eventually lead to smaller, lighter, stronger and longer lasting magnets for electrical motors used in aircraft and guidance systems, surgical instruments, and transponders. High-Precision Tracking Experiment. Flown by the Strategic Defense Initiative Organization, this tested the ability of a ground laser beam director to accurately track an object in low-Earth orbit.
Mission Success	Successful

Table 3–36. STS 51-F Mission Characteristics

Vehicle	*Challenger* (OV-099)
Crew	Cmdr: C. Gordon Fullerton Pilot: Roy D. Bridges, Jr. MS: F. Story Musgrave, Karl G. Henize, Anthony W. England PS: Loren W. Acton, John-David F. Bartoe
Launch	July 29, 1985, 5:00:00 p.m., EDT, Kennedy Space Center The launch countdown on July 12 was halted at T-3 seconds when a malfunction of the number two main engine coolant valve caused a shutdown of all three main engines. Launch countdown was initiated on July 27 and continued to about T-9 minutes on July 29. At that time, launch was delayed 1 hour, 37 minutes because of a problem with the table maintenance block update uplink. In addition, ascent was hampered when at 5 minutes, 45 seconds into ascent, the number one main engine shut down prematurely, resulting in an abort-to-orbit trajectory. The abort-to-orbit trajectory resulted in the orbiter's insertion orbit altitude being approximately 108 x 143 nautical miles. A final orbit if 314.84 x 316.69 kilometers was achieved to meet science payload requirements. During launch and ascent, verification flight instrumentation (VFI) operated. The VFI was strategically located throughout Spacelab and at the Spacelab interfaces with the orbiter. The VFI monitored Spacelab subsystem performance and Spacelab/orbiter interfaces. Data were recorded during launch and ascent on the VFI tape recorder and played back to ground receiving stations during acquisition of signal periods utilizing the Tracking and Data Relay Satellite System (TDRSS).
Orbital Altitude & Inclination	314.84 km/49.5 degrees
Launch Weight	114,695 kg
Landing & Post-landing Operations	August 6, 1985, 12:45:26 p.m., PDT, Runway 23, Edwards AFB The VFI continued to monitor and record selected Spacelab parameters on the VFI tape recorder and the orbiter payload recorder during descent and landing. Approximately 25 minutes after landing, orbiter power was removed from Spacelab. The mission was extended 17 revolutions for additional payload activities because of the abort-to-orbit. Orbiter was returned to Kennedy August 11, 1985.
Rollout Distance	2,611.8 m
Rollout Time	55 seconds
Mission Duration	7 days, 22 hours, 45 minutes, 26 seconds
Landed Revolution No.	127
Mission Support	Spaceflight Tracking and Data Network (STDN)/ Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	Plasma Diagnostics Package (PDP) (see experiments below)
Get-Away Specials	None

Table 3–36 continued

Experiments	Spacelab 2 (see Table 4–47, Spacelab 2 Experiments) Plasma Diagnostics Package. The instrument package was extended and released by the RMS to take measurements after the orbiter maneuvered to selected attitudes. After taking measurements, the manipulator arm recaptured the PDP and returned it to the vicinity of the payload bay. Before landing, it was locked back in place on the aft pallet. Instruments mounted within the PDP included a quadrispherical low-energy proton and electron differential analyzer, a plasma wave analyzer and electric dipole and magnetic search coil sensors, a direct current electric field meter, a triaxial flux-gate magnetometer, a Langmuir probe, a retarding potential analyzer and differential flux analyzer, an ion mass spectrometer, and a cold cathode vacuum gauge. (See Chapter 4 for further data on the PDP.) Protein Crystal Growth in a Microgravity Environment. The purpose was to develop hardware and procedures for growing proteins and other organic crystals by two methods in the orbiter during the low-gravity portion of the mission. Generally, hardware for both methods worked as planned. Postflight analysis showed that minor modification in the flight hardware was needed and a means of holding the hardware during activation, crystal growth, deactivation, and photography was desirable. The dialysis method produced three large tetragonal lysozyme crystals with average dimensions of 1.3 mm x 0.65 mm x 0.65 mm. The solution growth methods produced small crystals of lysozyme, alpha-2 interferon, and bacterial purine nucleoside phosphorylase. (See also STS 51-D.) Gravity-Influenced Lignification in Higher Plants/Plant Growth Unit. Mung beans and pine seedlings, planted in the Plant Growth Unit before flight, were flown to monitor the production of lignin, a structural rigidity tissue found in plants. Shuttle Amateur Radio Experiment (SAREX). Astronauts England and Bartoe conversed from *Challenger* with amateur radio operators through a handheld radio.
Mission Success	Successful

Table 3–37. STS 51-I Mission Characteristics

Vehicle	*Discovery* (OV-103)
Crew	Cmdr: Joseph H. Engle Pilot: Richard O. Covey MS: James D.A. van Hoften, John M. Lounge, William F. Fisher
Launch	August 27, 1985, 6:58:01 a.m., EDT, Kennedy Space Center The August 24 launch was scrubbed at T-5 minutes because of thunderstorms in the vicinity. The launch on August 25 was delayed when the orbiter's number five on-board general purpose computer failed. The launch on August 27 was delayed 3 minutes, 1 second because of a combination of weather and an unauthorized ship entering the restricted solid rocket booster recovery area.
Orbital Altitude & Inclination	514.9 km/28.5 degrees
Launch Weight	118,983.4 kg
Landing & Post-landing Operations	September 3, 1985, 6:15:43 a.m., PDT, Runway 23, Edwards AFB The mission was shortened 1 day when the Aussat sunshield hung up on the Remote Manipulator System camera and Aussat had to be deployed before scheduled. Orbiter was returned to Kennedy September 8, 1985.
Rollout Distance	1,859.3 m
Rollout Time	47 seconds
Mission Duration	7 days, 2 hours, 17 minutes, 42 seconds
Landed Revolution No.	112
Mission Support	Spaceflight Tracking and Data Network (STDN)/Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	ASC-1/PAM-D; Aussat-1/PAM-D, Syncom IV-4/UUS (Leasat-4); Syncom IV-4 failed to function after reaching correct geosynchronous orbit
Get-Away Specials	None
Experiments	Physical Vapor Transport Organic Solid Experiment (PVTOS). In this second of some 70 experiments the 3M Corporation planned to conduct by 1995, solid materials were vaporized into a gaseous state to form thick crystalline films on selected substrates of sublimable organics. 3M researchers studied the crystals produced by PVTOS for their optical properties and other characteristics that might ultimately have important applications to 3M's businesses in the areas of electronics, imaging, and health care.
Mission Success	Successful

Table 3–38. STS 51-J Mission Characteristics

Vehicle	*Atlantis* (OV-104)
Crew	Cmdr: Karol J. Bobko Pilot: Ronald J. Grabe MS: Robert L. Stewart, David C. Hilmers PS: William A. Pailes
Launch	October 3, 1985, 11:15:30 a.m., EDT, Kennedy Space Center The launch was delayed 22 minutes, 30 seconds because of the main engine liquid hydrogen prevalve close remote power controller showing a faulty "on" indication.
Orbital Altitude & Inclination	590.8 km/28.5 degrees
Launch Weight	classified
Landing & Post-landing Operations	October 7, 1985, 10:00:08 a.m., PDT, Runway 23, Edwards AFB Orbiter returned to Kennedy October 11, 1985.
Rollout Distance	2,455.5 m
Rollout Time	65 seconds
Mission Duration	4 days, 1 hour, 44 minutes, 38 seconds
Landed Revolution No.	64
Mission Support	Spaceflight Tracking and Data Network (STDN)
Deployed Satellites	Not available
Get-Away Specials	None
Experiments	Not available
Mission Success	Successful

Table 3–39. STS 61-A Mission Characteristics

Vehicle	*Challenger* (OV-099)
Crew	Cmdr: Henry W. Hartsfield, Jr. Pilot: Steven R. Nagel MS: James F. Buchli, Guion S. Bluford, Jr., Bonnie J. Dunbar PS: Reinhard Furrer, Ernst Messerschmid, Wubbo J. Ockels (ESA)
Launch	October 30, 1985, 12:00:00 noon, EST, Kennedy Space Center Launch proceeded as scheduled with no delays.
Orbital Altitude & Inclination	383.4 km/57.0 degrees
Launch Weight	110,570.4 kg
Landing & Post-landing Operations	November 6, 1985, 9:44:53 a.m., PST, Runway 17, Edwards AFB Orbiter was returned to Kennedy November 11, 1985.
Rollout Distance	2,531.1 m
Rollout Time	45 seconds
Mission Duration	7 days, 0 hours, 44 minutes, 53 seconds
Landed Revolution No.	112
Mission Support	Spaceflight Tracking and Data Network (STDN)/Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	Global Low Orbiting Message Relay (GLOMR) deployed from G-308
Get-Away Specials	G-308 Customer: Department of Defense Space Test Program GLOMR, originally planned for deployment on STS 51-B, was successfully deployed and remained in orbit for 14 months. The GLOMR satellite, a 68-kilogram, 62-side polyhedron, was a data-relay, communications spacecraft. Its purpose was to demonstrate the ability to read signals and command oceanographic sensors, locate oceanographic and other ground sensors, and relay data from them to customers. The satellite could pick up digital data streams from ground users, store the data, and deliver the streams to customers’ computer terminals upon command.
Experiments	Spacelab D-1 (see Table 4–48, Spacelab D-1 Experiments)
Mission Success	Successful

Table 3–40. STS 61-B Mission Characteristics

Vehicle	*Atlantis* (OV-104)
Crew	Cmdr: Brewster H. Shaw, Jr. Pilot: Bryan D. O'Connor MS: Mary L. Cleave, Sherwood C. Spring, Jerry L. Ross PS: Rodolfo Neri Vela, Charles D. Walker
Launch	November 26, 1985, 7:29:00 p.m., EST, Kennedy Space Center The launch proceeded as scheduled with no delays.
Orbital Altitude & Inclination	416.7 km/28.5 degrees
Launch Weight	118,596 kg
Landing & Post-landing Operations	December 3, 1985, 1:33:49 p.m., PST, Runway 22, Edwards AFB The mission was shortened one revolution because of lightning conditions at Edwards. *Atlantis* landed on a concrete runway because the lakebed was wet. Orbiter was returned to Kennedy December 7, 1985.
Rollout Distance	3,279.3 m
Rollout Time	78 seconds
Mission Duration	6 days, 21 hours, 4 minutes, 49 seconds
Landed Revolution No.	109
Mission Support	Spaceflight Tracking and Data Network (STDN)/ Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	Morelos-B/PAM-D, AUSSAT-2/PAM-D, Satcom Ku-2/PAM-DII
Get-Away Specials	G-479 Customer: Telesat Canada Telesat, Canada's domestic satellite carrier, sponsored a national competition soliciting science experiments from Canadian high school students. The selected experiment, called Towards a Better Mirror, proposed to fabricate mirrors in space that would provide higher performance than similar mirrors made on Earth.
Experiments	Orbiter Experiments (OEX). An onboard experimental digital autopilot software package was tested. The autopilot software could be used with the orbiter, another space vehicle, such as the Orbital Transfer Vehicle, which was under development, or the space station. OEX was designed to provide precise stationkeeping capabilities between various vehicles operating in space. Protein Crystal Growth Experiment (PCG). This experiment studied the possibility of crystallizing biological materials, such as hormones, enzymes, and other proteins. Successful crystallization of these materials, which were very difficult to crystallize on Earth, would allow their three-dimensional atomic structure to be determined by x-ray crystallography. IMAX Cargo Bay Camera. The IMAX camera was used to document payload bay activities associated with the EASE/ACCESS assembly during the two spacewalks. Experimental Assembly of Structures in Extravehicular Activity (EASE). This experiment studied EVA dynamics and human factors in the construction of structures in space.

Table 3–40 continued

	Assembly Concept for Construction of Erectable Space Structures (ACCESS). This experiment validated ground-based timelines based on the neutral buoyancy water simulator at the Marshall Space Flight Center, Huntsville, Alabama. Crew members manually assembled and disassembled a 45-foot truss to evaluate concepts for assembling larger structures in space.
	Morelos Payload Specialist Experiments. Rodolfo Neri Vela performed a series of mid-deck cabin experiments and took photographs of Mexico: 1. Effects of Spatial Environment on the Reproduction and Growing of Bacteria. Cultures of *Escherichia coli* B-strain were mixed in orbit with different bacteriophages that attack the *E. coli* and were observed for possible changes and photographed as required. 2. Transportation of Nutrients in a Weightless Environment. Ten plant specimens were planted in containers that allowed a radioactive tracer to be released in orbit for absorption by the plants. At selected intervals, each plant was sectioned and the segments retained for postflight analysis to determine the rate and extent of absorption. 3. Electropuncture and Biocybernetics in Space. This experiment validated electropuncture theories, which stated that disequilibrium in the behavior of human organs could be monitored and stimulated using electric direct current in specified zones. The experiment was performed by measuring the conductance of electricity in a predetermined zone. If a disequilibrium was detected, exercises or stimulus would be applied for a certain period until the value of the conductance fell into the normal range. 4. Effects of Weightlessness and Light on Seed Germination. Seed specimens of amaranth, lentil, and wheat were planted in orbit in two identical containers. One container was exposed to illumination and the other to constant darkness. Photographs of the resulting sprouts were taken every 24 hours. One day prior to landing, the sprouts were submitted to a metabolical detection process for subsequent histological examination on Earth to determine the presence and localization of starch granules. 5. Photography of Mexico. Postearthquake photos were taken of Mexico and Mexico City.
	Diffusive Mixing of Organic Solutions. This experiment grew organic crystals in near-zero gravity. 3M scientists hoped to produce single crystals that are more pure and larger than those available on Earth to study their optical and electrical properties.
	Continuous Flow Electrophoresis System (CFES) (see STS-6)
Mission Success	Successful

Table 3–41. STS 61-C Mission Characteristics

Vehicle	*Columbia* (OV-102)
Crew	Cmdr: Robert L. Gibson Pilot: Charles F. Bolden, Jr. MS: Franklin R. Chang-Diaz, Steven A. Hawley, George D. Nelson PS: Robert J. Cenker, Congressman Bill Nelson
Launch	January 12, 1986, 6:55:00 a.m., EST, Kennedy Space Center The launch set for December 18, 1985, was delayed 1 day when additional time was needed to close out the orbiter aft compartment. The December 19 launch attempt was scrubbed at T-14 seconds because of an indication that the right solid rocket booster hydraulic power unit was exceeding RPM red-line speed limits. (This was later determined to be a false reading.) After an 18-day delay, a launch attempt on January 6, 1986, was halted at T-31 seconds because of the accidental draining of liquid oxygen from the external tank. The January 7 launch attempt was scrubbed at T-9 minutes because of bad weather at both transoceanic landing sites (Moron, Spain, and Dakar, Senegal). After a 2-day delay, the launch set for January 9 was delayed because of a launch pad liquid oxygen sensor breaking off and lodging in the number two main engine prevalve. The launch set for January 10 was delayed for 2 days because of heavy rains. The launch countdown on January 12 proceeded with no delays.
Orbital Altitude & Inclination	392.6 km/28.5 degrees
Launch Weight	116,123 kg
Landing & Post-landing Operations	January 18, 1986, 5:58:51 a.m. PST, Runway 22, Edwards AFB The planned landing at Kennedy, originally scheduled for January 17, was moved to January 16 to save orbiter turn-around time. The landing attempts on January 16 and 17 were abandoned because of unacceptable weather at Kennedy. A landing was set for January 18 at Kennedy, but persisting bad weather forced a one-revolution extension of mission and landing at Edwards AFB. Orbiter was returned to Kennedy January 23, 1986.
Rollout Distance	3,110 m
Rollout Time	59 seconds
Mission Duration	6 days, 2 hours, 3 minutes, 51 seconds
Landed Revolution No.	98
Mission Support	Spaceflight Tracking and Data Network (STDN)/ Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	Satcom KU-1/PAM-DII
Get-Away Specials	The Environmental Monitoring Package was contributed by Goddard to measure the effects of launch and landing forces on the bridge and, hence, on the internal environment of the GAS containers. Sound levels, vibrations, and temperature were measured by attaching acoustical pickups, accelerometers, strain gauges, and thermocouples to the bridge. These instruments were connected to a GAS container with equipment that controlled the instruments and recorded their data.

Table 3–41 continued

The GAS Bridge Assembly was flown for the first time on this mission. It contained the 12 GAS canisters.

G-310
The objective of this Air Force Academy–sponsored payload was to measure the dynamics of a vibrating beam in a zero-g environment.

G-463, G-464, G-462
Customer: NASA Office of Space Science and Applications
Ultraviolet Experiment was a group of get-away specials designed to measure diffuse ultraviolet background radiation. The two ultraviolet spectrometers were to look into distant space to observe the high-energy spectrum thought to be associated with the origin of the universe. Other observational targets included galaxies, dust areas, Halley's Comet, and selected stars. It was the only set of GAS experiments to fly as a group of three electrically interconnected containers.

G-062
Customer: General Electric Company Space Division
Four student experiments from Pennsylvania State University and sponsored by the General Electric Co. made up this payload. The liquid droplet heat radiator experiment tested an alternative method of heat transfer, which investigated how moving droplets can radiate heat into space. The second experiment studied the effect of microgravity on the surface tension of a fluid. The third experiment studied the effect of convection on heat flow in a liquid by submersing a heat source in a container of liquid.

G-332
Customer: Booker T. Washington High School
This canister contained two contributions from Houston, Texas. The Brine Shrimp Artemia experiment from Booker T. Washington High School determined the behavioral and physiological effects of microgravity on eggs hatched in space. The High School for Engineering provided the Fluid Physics Experiment, which examined the behavior of fluid when heated in microgravity.

G-446
Customer: Alltech Associates, Inc.
This experiment investigated the effect of gravity on particle dispersion of packing material in high-performance liquid chromatography analytical columns. The investigators expected that by reducing gravity, a more efficient column would be produced.

Table 3–41 continued

G-470
Customer: Goddard Space Flight Center
A joint investigation by Goddard and the U.S. Department of Agriculture examined the effects of weightlessness on gypsy moth eggs and engorged female American dog ticks. It was hoped that the data obtained would lead to new means of controlling these insect pests.

G-007
Customer: Alabama Space and Rocket Center
This canister housed four specific payloads that were originally scheduled to fly on STS 41-G. However, it was not turned on during that mission. Postflight investigation determined that the experiments were not at fault, and they were rescheduled for STS 61-C. The experiment included:

1. A study of the solidification of lead-antimony and aluminum-copper alloys
2. A comparative morphological and anatomical study of the primary root system of radish seeds
3. Examination of the growth of metallic-appearing needle crystals in an aqueous solution of potassium tetracyanoplatinate
4. A half-wave dipole antenna installed on the canister’s top cover plate that was sponsored by the Marshall Amateur Radio Club

G-449
Customer: St. Mary’s Hospital, Milwaukee
The Laser Laboratory at St. Mary’s Hospital in Milwaukee sponsored this four-part experiment:

1. The BMJ experiment studied the biological effects of neodymium and helium-neon laser light upon desiccated human tissue undergoing cosmic ray bombardment. Medications also were exposed to laser light and cosmic radiation.
2. LEDAJO was to determine cosmic radiation effects on medications and medical/surgical materials using Lexan detectors.
3. BLOTY analyzed contingencies that develop because of zero-gravity in blood typing. In Earth-bound blood typing, gravity was essential to produce clumping.
4. CROLO evaluated laser optical protective eyewear materials following exposure to cosmic radiation.

G-481
Customer: Vertical Horizons
This payload transported samples of painted linen canvases and other artistic materials into space. The investigators evaluated how unprimed canvas, prepared linen canvas, and portions of oil painted canvas reacted to space travel.

Table 3–41 continued

	G-494 Customer: National Research Council of Canada This payload was co-sponsored by the Canada Centre for Space Science and the National Research Council of Canada. The experiment consisted of seven filtered photometers that measured oxygen, oxide, and continuum emissions in the terrestrial night glow and in the Shuttle night glow.
Experiments	Materials Science Laboratory-2 (MSL-2). Primary mission objectives were the engineering verification of the MSL payload carrier and of the three materials processing facilities. Secondary objectives were the acquisition of flight specimens and experimental data for scientific evaluation. The MSL-2 held the following experiments: 1. Electromagnetic Levitator. This experiment studied the effects of material flow during solidification of a melted material in the microgravity environment. 2. Automated Directional Solidification Furnace. This experiment investigated the melting and solidification process of four materials. 3. Three-Axis Acoustic Levitator. Twelve liquid samples were suspended in sound pressure waves, and rotated and oscillated in a low-gravity, nitrogen atmosphere. Investigators studied the degree of sphericity attainable and small bubble migration similar to that found in the refining of glass. Comet Halley Active Monitoring Program. This was supposed to investigate the dynamical/morphological behavior as well as the chemical structure of Comet Halley. The 35mm camera that was to photograph Comet Halley did not function properly because of battery problems. Infrared Imaging Experiment. This acquired radiometric pictures/information of selected terrestrial and celestial targets. Initial Blood Storage Experiment. This experiment investigated the factors that limit the storage of human blood. The experiment attempted to isolate factors such as sedimentation that occurred under standard blood bank conditions. A comparison was made of changes in whole blood and blood components that had experienced weightless conditions in orbit with similar samples stored in otherwise comparable conditions on the ground.

Table 3–41 continued

	Hitchhiker G-1.This was the first of a generic class of small payloads under the Small Payload Accommodation program. These payloads were located in the orbiter bay on the starboard side and used specially designed carriers, which attached to the existing GAS attach fittings. This supported three instruments: 1. Particle Analysis Cameras for the Shuttle provided film images of particle contamination around the Shuttle in support of future DOD infrared telescope operations. 2. Capillary Pump Loop provided a zero-g test of a new heat transport system. 3. Shuttle Environment Effects on Coated Mirrors was a passive witness mirror-type experiment that determined the effects of contamination and atomic oxygen on ultraviolet optics material.
	Shuttle Student Involvement Program: 1. Argon Injection as an Alternative to Honeycombing was a material processing experiment that examined the ability to produce a lightweight, honeycomb structure superior to the Earth-produced structures. 2. Formation of Paper in Microgravity studied the formation of cellulose fibers in a fiber mat under weightless conditions. 3. Measurement of Auxin Levels and Starch Grains in Plant Roots investigated the geotropism of a corn root growth in microgravity and determined whether starch grains in the root cap were actually involved with auxin production and transport.
Mission Success	Successful

Table 3–42. STS 51-L Mission Characteristics

Vehicle	*Challenger* (OV-099)
Crew	Cmdr: Francis R. Scobee Pilot: Michael J. Smith MS: Judith A. Resnik, Ellison S. Onizuka, Ronald E. McNair PS: Gregory B. Jarvis Teacher in Space Project: Sharon Christa McAuliffe
Launch	January 28, 1986, 11:38:00, EST, Kennedy Space Center The first Shuttle liftoff scheduled for January 22 was slipped to January 23, then January 24, because of delays in STS 61-C. The launch was reset for January 25 because of bad weather at the transoceanic abort landing site in Dakar, Senegal. To use Casablanca (not equipped for night landings) as an alternate transoceanic abort landing site, T-zero was moved to a morning liftoff time. The launch was postponed 1 day when launch processing was unable to meet the new morning liftoff time. A prediction of unacceptable weather at Kennedy led to the launch being rescheduled for 9:37 a.m., EST, January 27. The launch was delayed 24 hours when the ground-servicing equipment hatch-closing fixture could not be removed from the orbiter hatch. The fixture was sawed off and the attaching bolt drilled out before closeout was completed. During the delay, cross winds exceeded return-to-launch-site limits at Kennedy's Shuttle Landing Facility. The January 28 launch was delayed 2 hours when the hardware interface module in the launch processing system, which monitors the fire detection system, failed during liquid hydrogen tanking procedures. An explosion 73 seconds after liftoff claimed the crew and vehicle.
Orbital Altitude & Inclination	2,778.8 km (planned)/28.5 degrees (planned)
Launch Weight	121,778.4 kg
Landing & Post-landing Operations	No landing
Rollout Distance	N/A
Rollout Time	N/A
Mission Duration	73 seconds
Landed Revolution No.	N/A
Mission Support	Spaceflight Tracking and Data Network (STDN)/ Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	None
Get-Away Specials	None
Experiments	None
Mission Success	Unsuccessful

Table 3–43. STS-26 Mission Characteristics

Vehicle	*Discovery* (OV-103)
Crew	Cmdr: Frederick H. Hauck Pilot: Richard O. Covey MS: John M. Lounge, David C. Hilmers, George D. Nelson
Launch	September 29, 1988, 11:37:00 a.m., EDT, Kennedy Space Center The launch was delayed 1 hour, 38 minutes to replace the fuses in the cooling systems of two of the crew's flight pressure suits and because of lighter than expected upper atmospheric winds. Suit repairs were successful, and the countdown continued after a waiver of a wind condition constraint.
Orbital Altitude & Inclination	376 km/28.5 degrees
Launch Weight	115,489.3 kg
Landing & Post-landing Operations	October 3, 1988, 9:37:11 a.m., PDT, Runway 17, Edwards AFB Orbiter was returned to Kennedy October 8, 1988.
Rollout Distance	2,271.1 m
Rollout Time	46 seconds
Mission Duration	4 days, 1 hour, 0 minutes, 11 seconds
Landed Revolution No.	64
Mission Support	Spaceflight Tracking and Data Network (STDN)/ Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	TDRS-3/IUS
Get-Away Specials	None
Experiments	Physical Vapor Transport of Organic Solids. This experiment by 3M scientists produced organic thin films with ordered crystalline structures to study their optical, electrical, and chemical properties. The results could eventually be applied to the production of specialized thin films on Earth or in space. Protein Crystal Growth (PCG) experiments. A team of industry, university, and government research investigators explored the potential advantages of using protein crystals grown in space to determine the complex, three-dimensional structure of specific protein molecules. Knowing the precise structure of these complex molecules would aid in understanding their biological function and could lead to methods of altering or controlling the function in ways that may result in new drugs. Infrared Communications Flight Experiment. Using the same kind of invisible light that remotely controls home TV sets and VCRs, mission specialist Nelson conducted experimental voice communications with his crewmates via infrared, rather than standard radio-frequency, waves. One major objective of the experiment was to demonstrate the feasibility of the secure transmission of information via infrared light. Unlike radio-frequency signals, infrared waves will not pass through the orbiter's windows; thus, a secure voice environment would be created if infrared waves were used as the sole means of communications within the orbiter. Infrared waves can also carry data as well as voice (such as biomedical information).

Table 3–43 continued

Automated Directional Solidification Furnace. This special space furnace developed and managed by Marshall Space Flight Center demonstrated the possibility of producing lighter, stronger, and better performing magnetic composite materials in a microgravity environment.

Aggregation of Red Blood Cells. Blood samples from donors with such medial conditions as heart disease, hypertension, diabetes, and cancer flew in this experiment developed by Australia and managed by Marshall. The experiment provided information on the formation rate, structure, and organization of red cell clumps and on the thickness of whole blood cell aggregates at high and low flow rates. It helped determine whether microgravity could play a beneficial role in new and existing clinical research and medical diagnostic tests. Results obtained in the Shuttle microgravity environment were compared with results from a ground-based experiment to determine what effects gravity had on the kinetics and morphology of the sampled blood.

Isoelectric Focusing. This was a type of electrophoresis experiment that separated proteins in an electric field according to their surface electrical charge.

Mesoscale Lightning Experiment. This obtained nighttime images of lightning to better understand the effects of lightning discharges on each other, on nearby storm systems, and on storm microbursts and wind patterns and to determine interrelationships over an extremely large area.

Phase Partitioning Experiment. This investigated the role gravity and other physical forces played in separating—that is, partitioning—biological substances between two unmixable liquid phases.

OASIS Instrumentation. This collected and recorded a variety of environmental measurements during various in-flight phases of the orbiter. The information was used to study the effects on the orbiter of temperature, pressure, vibration, sound, acceleration, stress, and strain. It also was used to assist in the design of future payloads and upper stages.

Earth-Limb Radiance Experiment. Developed by the Barnes Engineering Co., this photographed Earth's "horizon twilight glow" near sunrise and sunset. The experiment provided photographs of Earth's horizon that allowed scientists to measure the radiance of the twilight sky as a function of the Sun's position below the horizon. This information allowed designers to develop better, more accurate horizon sensors for geosynchronous communications satellites.

Table 3–43 continued

	Shuttle Student Involvement Program: 1. Utilizing a Semi-Permeable Membrane to Direct Crystal Growth attempted to control crystal growth through the use of a semi-permeable membrane. Lead iodide crystals were formed as a result of a double replacement reaction. Lead acetate and potassium iodide reacted to form insoluble lead iodide crystals, potassium ions, and acetate ions. As the ions traveled across a semi-permeable membrane, the lead and iodide ions collided, forming the lead iodide crystal. 2. Effects of Weightlessness on Grain Formation and Strengthening Metals heated a titanium alloy metal filament to near the melting point to observe the effect of weightlessness on crystal reorganization within the metal. It was expected that heating in microgravity would produce larger crystal grains and thereby increase the inherent strength of the metal filament.
Mission Success	Successful

Table 3–44. STS-27 Mission Characteristics

Vehicle	*Atlantis* (OV-104)
Crew	Cmdr: Robert L. Gibson Pilot: Guy S. Gardner MS: Richard M. Mullane, Jerry L. Ross, William M. Shepherd
Launch	December 2, 1988, 9:30:34 a.m., EST, Kennedy Space Center The launch, set for December 1, 1988, during a classified window lying within a launch period between 6:32 a.m. and 9:32 a.m., was postponed because of unacceptable cloud cover and wind conditions and reset for the same launch period on December 2.
Orbital Altitude & Inclination	Altitude classified/57.0 degrees
Launch Weight	Classified
Landing & Post-landing Operations	December 6, 1988, 3:36:11 p.m., PST, Runway 17, Edwards AFB Orbiter was returned to Kennedy December 13, 1988
Rollout Distance	2,171.1 m
Rollout Time	43 seconds
Mission Duration	4 days, 9 hours, 5 minutes, 37 seconds
Landed Revolution No.	Not available
Mission Support	Spaceflight Tracking and Data Network (STDN)/ Tracking and Data Relay Satellite System (TDRSS)
Deployed Satellites	Not available
Get-Away Specials	None
Experiments	Not available
Mission Success	Successful

Table 3–45. Return to Flight Chronology

Date	Event
January 28, 1986	Moments after the *Challenger* (STS 51-L) explosion, all mission data, flight records, and launch facilities are impounded. Within an hour, Associate Administrator for Space Flight Jesse Moore names an expert panel to investigate.
January 29	Interim Mishap Investigation Board is named and approved by NASA Acting Administrator William R. Graham.
February 3	President Ronald Reagan announces the formation of a presidential commission to investigate the *Challenger* accident. Commission is to be headed by former Secretary of State William Rogers.
February 5	Acting Administrator Graham establishes the 51-L Data and Design Analysis Task Force to assist the Rogers Commission, designating the Associate Administrator for Space Flight as chairperson.
February 18	U.S. Senate holds first of a series of hearings on the *Challenger* accident.
February 20	Rear Admiral Richard H. Truly is appointed Associate Administrator for Space Flight.
February 25	Administrator James M. Beggs, on leave since December 4, 1985, pending disposition of indictment, resigns. Indictment is later dismissed, and Beggs receives apology from Attorney General Edwin Meese.
March 5	First Program Management Review for Space Shuttle program is held at Marshall. Reviews are planned for every 6 weeks.
March 13	NASA begins review of Failure Modes Effects Analysis and Critical Items Lists.
March 24	Admiral Truly, in NASA Headquarters Office of Space Flight memorandum “Strategy for Safely Returning Space Shuttle to Flight Status,” outlines actions required prior to next flight, first flight/first year operations, and development of sustainable flight rate. Truly directs Marshall to form solid rocket motor joint redesign team with National Research Council (NRC) oversight. Truly initiates review of National Space Transportation System (NSTS) management structure. First system design review is conducted to identify changes to improve flight safety.
March 28	Arnold D. Aldrich, manager of NSTS, initiates review of all items on Critical Items List.
March	NASA Flight Rate Capability Working Group is established.
April 7	NASA initiates Shuttle crew egress and escape review.
May 12	James C. Fletcher is sworn in as NASA Administrator.
June 6	*Report to the President by the Presidential Commission on the Space Shuttle Challenger Accident* (Rogers Commission) is released. It recommends: • Redesign faulty joint seal (either eliminate joint or redesign seal to more stringent standards) • Provide independent redesign oversight by NRC • Review Shuttle management to redefine the program manager's responsibility, place astronauts in management positions, and establish an STS Safety Advisory Panel • Improve criticality review and hazard analysis (An audit panel from NRC should verify the adequacy of the effort.)

Table 3–45 continued

Date	Event
June 6 cont.	• Establish a safety office headed by a NASA associate administrator to oversee safety, reliability, maintainability, and quality assurance functions with viable problem reporting, documentation, and resolution • Improve communication, especially from Marshall, develop launch constraints policy, and record Flight Readiness Review (FRR) and Mission Management Team meetings (Flight crew commander should attend FRR.) • Improve landing safety, including tire brake and nosewheel steering, and conditions for Kennedy landing, with landing area weather forecasts more than an hour in advance, and create crew escape system for controlled gliding flight and launch abort possibilities in case of main engine failures early in ascent • Establish flight rate to be consistent with NASA resources, and create firm payload assignment policy • Implement maintenance safeguards, especially for Criticality I items
June 11	Admiral Truly testifies before the House Committee on Science and Technology on status of work in response to Rogers Commission recommendations and announces small group to examine overall Space Shuttle program management, to be headed by astronaut Robert L. Crippen.
June 13	President Reagan writes to NASA requesting the implementation of Rogers Commission recommendations.
June 19	Centaur upper stage is terminated because of safety concerns.
June 25	Astronaut Robert L. Crippen is directed to form a fact-finding group to assess Shuttle management structure and implement effective management and communications.
June 30	Andrew J. Stofan is appointed Associate Administrator of the Office of Space Station at NASA Headquarters.
July 8	NASA establishes an Office of Safety, Reliability, Maintainability, and Quality Assurance and appoints George A. Rodney Associate Administrator.
July 11	NASA Report to the President, *Actions to Implement Recommendations of the Presidential Commission on the Space Shuttle Challenger*, announces return to flight for first quarter of 1988. Fletcher states NASA has responded favorably to the Rogers Commission recommendations in every area and promises another report in 1 year.
July 24	NASA announces abandonment of lead center concept for space station.
August 15	President Reagan issues statement announcing intent to build a fourth Shuttle orbiter as a replacement and that NASA will no longer launch private satellites.
September 10	Astronaut Brian D. O’Connor is appointed chair of the Space Flight Safety Panel.
September 29	James R. Thompson is appointed Director of Marshall Space Flight Center.
October 1	Lt. Gen. Forrest S. McCartney is appointed Director of Kennedy Space Center.

Table 3–45 continued

Date	Event
October 3	Revised NASA manifest is published incorporating president's new policy on commercialization of space and changes in priorities for flying on the Shuttle.
October 6	Dale D. Myers is appointed Deputy Administrator of NASA.
October 12	Aaron Cohen is appointed Director of Johnson Space Center.
October 14	Astronaut Frederick D. Gregory is appointed Chief, Operational Safety Branch, Safety Division, Office of Safety, Reliability, Maintainability, and Quality Assurance at NASA Headquarters.
October 29	U.S. House of Representatives Committee on Science and Technology releases its report: *Investigation of the Challenger Accident*.
November 11	Shuttle management is reorganized. NSTS manager Aldrich is appointed Director of NSTS in the Office of Space Flight at NASA Headquarters. Two NSTS deputy director positions are established: Richard H. Kohrs as Deputy Director for NSTS program and Robert L. Crippen as Deputy Director of NSTS operations. Shuttle project office manager at Marshall is to report directly to the deputy director for NSTS program.
December 30	Former Apollo program manager Brig. Gen. Samuel C. Phillip's study of NASA management is presented to the NASA administrator.
January 7, 1987	Administrator Fletcher issues "State of NASA" memorandum and reestablishes Project Approval Document as a management tool.
January 9	Flight crew is selected for first Space Shuttle mission (STS-26, *Discovery*) after accident: commander—Frederick H. Hauck; pilot—Richard O. Covey; and mission specialists—John M. Lounge, George D. Nelson, and David C. Himmers.
January 25	Public Opinion Laboratory publishes *The Impact of the Challenger Accident on Public Attitudes Toward the Space Program: A Report to the National Science Foundation*. Findings include: • Accident increased an already strong national pride in the Shuttle program. Public responded to the deaths of the *Challenger* astronauts with a sense of personal loss. • Public viewed accident as a minor setback, with universal expectation of a return to flight. • Cost-benefit assessment increased significantly as a result of the accident. • There was a willingness to support increased federal funds for space. • Rogers Commission discussion and criticism did not erode positive views of NASA held by public. • Net effect of accident was a more positive attitude toward the space program.
February 25	NASA publishes *Responses to the Recommendations of the House of Representatives Committee on Science and Technology Report of the Investigation of the Challenger Accident*, which includes a summary of activities undertaken in response to the Rogers Commission investigation.
February	Crew begins training for STS-26 mission.
March 9	Former NASA Deputy Associate Administrator (1965–1975) Willis H. Shapley is appointed Associate Deputy Administrator (Policy).

Table 3–45 continued

Date	Event
May 29	John M. Klineberg is appointed Director of Lewis Research Center.
June 22	Noel W. Hinners is appointed Associate Deputy Administrator (Institution).
June 22	John W. Townsend is appointed Director of Goddard Space Flight Center.
June 30	Administrator Fletcher submits report to the president on status of NASA's work to implement Rogers Commission recommendations. Report details changes to solid rocket motor design, management structure and communications, criticality review and hazards analysis, safety organization, landing safety, launch abort and crew escape, flight rate maintenance safeguards, and related return to flight safeguards.
July 22	Second interim progress report of NRC's Committee on Shuttle Criticality Review and Hazard Analysis Audit is issued.
July 31	Replacement orbiter contract is awarded to Rockwell International, and production of OV-105 is initiated.
August 4	STS-26 begins power-up.
August 17	*Leadership and America's Future in Space* (Ride Report) is released.
August 30	First major test occurs on redesigned solid rocket motor.
August	Advanced solid rocket motor design and definition study contracts are awarded to five aerospace firms by Marshall.
October 22	NASA issues first mixed fleet manifest for Space Shuttle missions and expendable launch vehicles.
October 29	Vice President Bush, in speech at Marshall, pledges to reestablish the National Space Council if elected president.
November 19	Testing begins on escape system that could be activated during controlled gliding flight.
February 11, 1988	White House issues the *President's Space Policy Directive and Commercial Space Initiative*, declaring it is the president's policy to establish long-range goals to expand the human presence and activity beyond Earth orbit into the solar system, to create opportunities for U.S. commerce in space, and to continue the national commitment to a permanently manned space station.
September 29	Successful launch of STS-26, *Discovery*, signals NASA's "return to flight." Mission launches TDRS-C, lasts 4 days, 1 hour, 57 seconds, and orbits Earth 64 times.

Table 3–46. Sequence of Major Events of the Challenger *Accident*

Mission Time (GMT, in hr:min:sec)	**Event**	**Elapsed Time (sec.)**	**Source**
16:37:53.444	ME 3 Ignition Command	6.566	GPC
37:53.564	ME 2 Ignition Command	6.446	GPC
37:53.684	ME 1 Ignition Command	6.326	GPC
38:00.010	SRM Ignition Command (T=0)	0.000	GPC
38:00.018	Holddown Post 2 PIC firing	0.008	E8 Camera
38:00.260	First continuous vertical motion	0.250	E9 Camera
38:00.688	Confirmed smoke above field joint on RH solid rocket motor	0.678	E60 Camera
38:00.846	Eight puffs of smoke (from 0.836 through 2.500 sec MET)	0.836	E63 Camera
38:02.743	Last positive evidence of smoke above right aft solid rocket booster/ external tank attach ring	2.733	CZR-1 Camera
38:03.385	Last positive visual indication of smoke	3.375	E60 Camera
38:04.349	SSME 104% Command	4.339	E41M2076D
38:05.684	RH solid rocket motor pressure 11.8 psi above nominal	5.674	B47P2302C
38:07.734	Roll maneuver initiated	7.724	V90R5301C
38:19.869	SSME 94% Command	19.859	E41M2076D
38:21.134	Roll maneuver completed	21.124	VP0R5301C
38:35.389	SSME 65% Command	35.379	E41M2076D
38:37.000	Roll and yaw attitude response to wind (36.990 to 62.990 sec)	36.990	V95H352nC
38:51.870	SSME 104% Command	51.860	E41M2076D
38:58.798	First evidence of flame on RH solid rocket motor	58.788	E207 Camera
38:59.010	Reconstructed Max Q (720 psf)	59.000	BET
38:59.272	Continuous well-defined plume on RH solid rocket motor	59.262	E207 Camera
38:59.763	Flame from RH solid rocket motor in +Z direction (seen from south side of vehicle)	59.753	E204 Camera
39:00.014	SRM pressure divergence (RH vs. LH)	60.004	B47P2302
39:00.248	First evidence of plume deflection, intermittent	60.238	E207 Camera
39:00.258	First evidence of solid rocket booster plume attaching to external tank ring frame	60.248	E203 Camera
39:00.998	First evidence of plume deflection, continuous	60.988	E207 Camera
39:01.734	Peak roll rate response to wind	61.724	V90R5301C
39:02.094	Peak TVC response to wind	62.084	B58H1150C
39:02.414	Peak yaw response to wind	62.404	V90R5341C
39:02.494	RH outboard elevon actuator hinge moment spike	62.484	V58P0966C
39:03.934	RH outboard elevon actuator delta pressure change	63.924	V58P0966C
39:03.974	Start of planned pitch rate maneuver	63.964	V90R5321C

Table 3–46 continued

Mission Time (GMT, in hr:min:sec)	Event	Elapsed Time (sec.)	Source
39:04.670	Change in anomalous plume shape (LH_2 tank leak near 2058 ring frame)	64.660	E204 Camera
39:04.715	Bright sustained glow on sides of external tank	64.705	E204 Camera
39:04.947	Start of SSME gimbal angle large pitch variations	64.937	V58H1100A
39:05.174	Beginning of transient motion from changes in aero forces due to plume	65.164	V90R5321C
39:06.774	Start of external tank LH_2 ullage pressure deviations	66.764	T41P1700C
39:12.214	Start of divergent yaw rates (RH vs. LH solid rocket booster)	72.204	V90R2528C
39:12.294	Start of divergent pitch rates (RH vs. LH solid rocket booster)	72.284	V90R2525C
39:12.488	SRB major high rate actuator command	72.478	V79H2111A
39:12.507	SSME roll gimbal rate 5 deg/sec	72.497	V58H1100A
39:12.535	Vehicle max +Y lateral acceleration (+.227 g)	72.525	V98A1581C
39:12.574	SRB major high rate actuator motion	72.564	B58H1151C
39:12.574	Start of H_2 tank pressure decrease with two flow control valves open	72.564	T41P1700C
39:12.634	Last state vector downlinked	72.624	Data reduction
39:12.974	Start of sharp MPS LOX inlet pressure drop	72.964	V41P1330C
39:13.020	Last full computer frame of TDRS data	73.010	Data reduction
39:13.054	Start of sharp MPS LH_2 inlet pressure drop	73.044	V41P1100C
39:13.055	Vehicle max; Y lateral acceleration (.254 g)	73.045	V98A1581C
39:13.134	Circumferential white pattern on external tank aft dome (LH_2 tank failure)	73.124	E204 Camera
39:13.134	RH solid rocket motor pressure 19 psi lower than LH solid rocket motor	73.124	B47P2302C
39:13.147	First hint of vapor at intertank	73.137	E207 Camera
39:13.153	All engine systems start responding to loss of fuel and LOX inlet pressure	73.143	SSME team
39:13.172	Sudden cloud along external tank between intertank and aft dome	73.162	E207 Camera
39:13.201	Flash between orbiter and LH_2 tank	73.191	E204 Camera
39:13.221	SSME telemetry data interference from 73.211 to 73.303	73.211	
39:13.223	Flash near solid rocket booster forward attach and brightening of flash between orbiter and external tank	73.213	E204 Camera
39:13.292	First indication of intense white flash at solid rocket booster forward attach point	73.282	E204 Camera

Table 3–46 continued

Mission Time (GMT, in hr:min:sec)	Event	Elapsed Time (sec.)	Source
39:13.337	Greatly increased intensity of white flash	73.327	E204 Camera
39:13.387	Start of RCS jet chamber pressure fluctuations	73.377	V42P1552A
39:13.393	All engines approaching HPFT discharge temp redline limits	73.383	E41Tn010D
39:13.492	ME 2 HPFT discharge temp Chan. A vote for shutdown; two strikes on Chan.	B73.482	MEC data
39:13.492	ME 2 controller last time word update	73.482	MEC data
39:13.513	ME 3 in shutdown from HPFT discharge temperature redline exceedance	73.503	MEC data
39:13.513	ME 3 controller last time word update	73.503	MEC data
39:13.533	ME 1 in shutdown from HPFT discharge temperature redline exceedance	73.523	Calculation
39:13.553	ME 1 last telemetered data point	73.543	Calculation
39:13.628	Last validated orbiter telemetry measurement	73.618	V46P0120A
39:13.641	End of last reconstructed data frame with valid synchronization and frame count	73.631	Data reduction
39:14.140	Last radio-frequency signal from orbiter	74.130	Data reduction
39:14.597	Bright flash in vicinity of orbiter nose	74.587	E204 Camera
39:16.447	RH solid rocket booster nose cap separation/chute deployment	76.437	E207 Camera
39:50.260	RH solid rocket booster RSS destruct	110.250	E202 Camera
39:50.262	LH solid rocket booster RSS destruct	110.252	E230 Camera

Table 3–47. Chronology of Events Prior to Launch of Challenger *(STS 51-L) Related to Temperature Concerns*

Date and Time (EST)	Key Participants	Event
Jan. 27, 1986 12:36 p.m.	*NASA project managers and contractor support personnel (including Morton Thiokol)*	*Launch Scrub.* Decision made to scrub because of high crosswinds at launch site.
Jan. 27 1:00 p.m.	*Same as above*	*Postscrub Discussion.* All appropriate personnel are polled as to feasibility to launch again with 24-hour cycle. Result in no solid rocket booster constraints for launch at 9:38 a.m., January 28: • Request is made for all participants to report any constraints.
Jan. 27 1:00 p.m.	*At Kennedy Space Center:* Boyd C. Brinton, manager, space booster project, Thiokol; Lawrence O. Wear, manager, solid rocket motor project office, Marshall Space Flight Center *At Morton Thiokol, Utah:* Arnold R. Thompson, supervisor, rocket motor cases; Robert Ebeling, manager, ignition system and final assembly, solid rocket motor project	*Conversation.* Wear asks Brinton if Thiokol had any concerns about predicted low temperatures and above what Thiokol had said about cold temperature effects following January 1985 flight 51-C: • Brinton telephones Thompson and other Thiokol personnel to ask them to determine whether there were concerns based on predicted weather conditions. Ebeling and other engineers are notified and asked for evaluation.
Jan. 27 2:00 p.m.	*NASA Level I and Level II management. At Kennedy:* Jesse W. Moore, associate administrator for space flight, NASA Headquarters; Arnold D. Aldrich, manager, space transportation programs, Johnson Space Center; Larry Mulloy, manager, solid rocket booster projects office, Marshall; William Lucas, director, Marshall	*Mission Management Team Meeting.* Discussion includes temperature at the launch facility and weather conditions predicted for launch at 9:38 a.m. on Jan. 28, 1986.

Table 3–47 continued

Date and Time (EST)	Key Participants	Event
Jan. 27 2:30 p.m.	*At Thiokol, Utah:* R. Boisjoly, seal task force, Morton Thiokol, Utah; Robert Ebeling, manager, ignition system and final assembly, solid rocket motor project	Boisjoly learns of cold temperatures at Cape at meeting convened by Ebeling.
Jan. 27 4:00 p.m.	*At Kennedy:* A.J. McDonald, manager, solid rocket motor project, Morton Thiokol; Carver Kennedy, vice president, space services, at Kennedy for Morton Thiokol *At Thiokol, Utah:* Robert Ebeling, manager solid rocket motor project office, igniter and final assembly, Thiokol, Utah	*Telephone Conversation.* McDonald receives call from Ebeling expressing concern about performance of solid rocket booster field joints at low temperature: • McDonald indicates he will call back latest temperature predictions up to launch time. • Carver Kennedy calls Launch Operations Center and receives latest temperature information. • McDonald transmits data to Utah and indicates he will set up telecon and asks engineering to prepare.
Jan. 27 5:15 p.m.	*At Kennedy:* Al McDonald, manager, solid rocket motor project, Morton Thiokol; Cecil Houston, manager, Marshall resident office at Kennedy	Telephone Conversion. McDonald calls Houston informing him that Morton Thiokol engineering had concerns regarding O-ring temperatures: • Houston indicates he will set up teleconference with Marshall and Morton Thiokol.

Table 3–47 continued

Date and Time (EST)	**Key Participants**	**Event**
Jan. 27 5:25 p.m.	*At Kennedy:* Cecil Houston, manager, Marshall resident office at Kennedy *At Marshall:* Judson A. Lovingood, deputy manager, Shuttle projects office, at Marshall	*Telephone Conversation:* Houston calls Lovingood informing him of the concerns about temperature effects on the O-rings and asks him to establish a telecon with: Stanley R. Reinartz, manager, Shuttle projects office, Marshall at Kennedy; Lawrence B. Mulloy, manager, solid rocket booster project, Marshall at Kennedy; George Hardy, deputy director, science and engineering, at Marshall; and Thiokol personnel.
Jan. 27 5:30 p.m.	*At Kennedy:* Stanley R. Reinartz, manager, Shuttle projects office, Marshall *At Marshall:* Jud Lovingood, deputy manager, Shuttle projects office, Marshall	*Telephone Conversation.* Lovingood calls Reinartz to inform him of planned 5:45 p.m. teleconference. Lovingood proposes that Kingsbury (director of science and engineering, Marshall) participate in teleconference.
Jan. 27 5:45 p.m.	*At Kennedy:* Stan Reinartz, manager, Shuttle projects, Marshall *At Marshall:* Jud Lovingood, deputy manager, Shuttle projects office, Marshall *Plus Thiokol and other personnel*	*Teleconference*. The discussion addresses Thiokol concerns regarding the temperature effects on the O-ring seals: • Thiokol is of the opinion launch should be delayed until noon or afternoon. • A decision was made to transmit the relevant data to all of the parties and set up another teleconference for 8:15 p.m. • Lovingood recommends to Reinartz to include Lucas, director, Marshall, and Kingsbury in 8:45 p.m. conference and to plan to go to Level II if Thiokol recommends not launching.

Table 3–47 continued

Date and Time (EST)	Key Participants	Event
Jan. 27 6:30 p.m.	*At Marshall:* Jud Lovingood, deputy manager, Shuttle projects office, Marshall *At Kennedy:* Stan Reinartz, manager, Shuttle projects office, Marshall	*Telephone Conversation.* Lovingood calls Reinartz and tells him that if Thiokol persists, they should not launch: • Lovingood also suggests advising Aldrich, manager, NSTS (Level II), of teleconference to prepare him for Level I meeting to inform of possible recommendation to delay.
Jan. 27 7:00 p.m.	*At Kennedy:* Larry Mulloy, manager, solid rocket booster projects office, Marshall; Stan Reinartz, manager, Shuttle projects office, Marshall; William Lucas, director, Marshall; Vim Kingsbury, director of engineering, Marshall	*Conversion.* Reinartz and Mulloy visit Lucas and Kingsbury in their motel rooms to inform them of Thiokol concern and planned teleconference.
Jan. 27 8:45 p.m.	*Teleconference Participants:* *At Kennedy:* Stan Reinartz, manager, Shuttle projects office, Marshall; Larry Mulloy, manager, solid rocket booster projects office, Marshall; Al McDonald, manager, solid rocket motor project, Morton Thiokol *At Marshall:* Jud Lovingood, deputy manager, Shuttle project office, Marshall; George Hardy, deputy director, science and engineering, Marshall *At Thiokol, Utah:* Jerry Mason, senior vice president, Thiokol, Wasatch; Joe Kilminster, vice president/manager, Shuttle projects, Thiokol, Wasatch; Robert Lund, vice president, engineering, Thiokol; Roger Boisjoly, seal task force—structures, Thiokol; Arnie Thompson, supervisor, structures, Thiokol *Plus other personnel*	*Teleconference.* Telefaxes of charts presenting history of O-ring erosion and blow-by for the primary seal in the solid rocket booster field joints from previous flights, as well as results of subscale tests and static tests of solid rocket motors: • The data show that the timing function of the O-rings would be slower from lower temperatures and that the worst blow-by occurred on solid rocket motor 15 (STS 51-C) in January 1985 with O-ring temperatures of 53 degrees F. • Recommendation by Thiokol was not to launch *Challenger* (STS 51-L) until the temperature of the O-ring reached 53 degrees F, which was the lowest O-ring temperature of any previous flight.

Table 3–47 continued

Date and Time (EST)	Key Participants	Event
Jan. 27 8:45 p.m. cont.		• Mulloy asks for recommendation from Kilminster. • Kilminster states that based upon the recommendation, he can not recommend launch. • Hardy is reported by both McDonald and Boisjoly to have said he is "appalled" by Thiokol's recommendation. • Reinartz comments that he is under the impression that solid rocket motor is qualified from 40 degrees F to 90 degrees F. • NASA personnel challenge conclusions and recommendations. • Kilminster asks for 5 minutes off-line to caucus with Thiokol personnel.
Jan. 27 10:30 p.m.	*Thiokol personnel:* Jerry Mason, senior vice president; Joe Kilminster, vice president manager, Shuttle projects; Cal Wiggins, vice president, Space Division; Robert Lund, vice president, engineering; Arnie Thompson, supervisor, structures; Roger Boisjoly, seal task force—structures *Plus other personnel*	*Thiokol Caucus.* Caucus lasts for about 30 minutes at Thiokol, Wasatch, Utah: • Major issues are (1) temperature effects on O-ring and (2) erosion of the O-ring. • Thompson and Boisjoly voice objections to launch, and indication is that Lund also is reluctant to launch. • A final management review is conducted with only Mason, Lund, Kilminster, and Wiggins. • Lund is asked to put on "management hat" by Mason. • Final agreement is: (1) there is a substantial margin to erode the primary O-ring by a factor of three times the previous worst case, and (2) even if the primary O-ring does not seal, the secondary is in position and will.

Table 3–47 continued

Date and Time (EST)	Key Participants	Event
Jan. 27 10:30–11:00 p.m.	*At Kennedy:* Allan J. McDonald, manager, space booster project Morton Thiokol; Lawrence B. Mulloy, manager, solid rocket booster projects, Marshall; Stan Reinartz, manager, shuttle projects, Marshall; Jack Buchanan, manager, Kennedy operations, for Thiokol; Cecil Houston, Marshall resident manager at Kennedy	*Conversation.* McDonald continues to argue for delay: • McDonald challenges Reinartz's rationale that solid rocket motor is qualified at 40 degrees F to 90 degrees F and Mulloy's explanation that propellant mean bulk temperatures are within specifications.
Jan. 27 11:00 p.m.	*Same Kennedy, Marshall, and Thiokol participants as earlier 8:45 p.m. teleconference*	*Teleconference.* Thiokol indicates it had reassessed; temperature effects are a concern, but data are inconclusive: • Kilminster reads the rationale for recommending launch. • Thiokol recommends launch. • Hardy requests that Thiokol puts its recommendation in writing and send it by fax to both Kennedy and Marshall.
Jan. 27 11:15–11:30 p.m.	*At Kennedy:* Allan J. McDonald, manager, space booster project, Lawrence Mulloy, Thiokol; manager, solid rocket booster projects office, Marshall; Stan Reinartz, manager, shuttle projects office, Marshall; Jack Buchanan, manager, Kennedy operations, for Thiokol; Cecil Houston, manager, Marshall resident office at Kennedy	*Conversation:* McDonald argues again for delay, asking how NASA could rationalize launching below qualification temperature: • McDonald indicates if anything happens, he would not want to have to explain it to a board of inquiry. • McDonald indicates he would cancel launch because of the (1) O-ring problem at low temperatures, (2) booster recovery ships heading into wind toward shore because of high seas, and (3) icing conditions on the launch pad. • McDonald is told it is not his concern and that his stated concerns will be passed on in an advisory capacity.

Table 3–47 continued

Date and Time (EST)	Key Participants	Event
Jan. 27 11:30 p.m.	*At Kennedy:* Larry Mulloy, manager, solid rocket booster projects office, Marshall; Stan Reinartz, manager, Shuttle projects, Marshall at Kennedy; Arnold Aldrich, manager, NSTS program office, Johnson Space Center	*Teleconference.* Discussion centers around the recovery hips' activities and brief discussion of the ice condition at the launch complex area: • Discussion does not include concerns about temperature effects on O-rings. • Reinartz and Mulloy place call to Aldrich. • McDonald delivers fax to Jack Buchanan's office at Kennedy and overhears part of conversation. • Aldrich is apparently not informed of the O-ring concerns.
Jan. 27 11:45 p.m.		*Telefax*. Kilminster telefaxes Thiokol's recommendation to launch: • Fax is signed by Kilminster. • McDonald retrieves fax at Kennedy.
Jan. 28 12:01 a.m.		Kennedy meeting breaks up.
Jan. 28 1:30–3:00 a.m.	*At Kennedy:* Charles Stevenson, supervisor of ice crew, Kennedy; B.K. Davis, ice team member, Marshall	*Ice Crew Inspection of Launch Pad B.* Ice crew finds large quantity of ice on fixed service structure, mobile launch platform, and pad apron and reports conditions.
Jan. 28 5:00 a.m.	*At Kennedy:* Larry Mulloy, manager, solid rocket booster projects office, Marshall; William Lucas, director, Marshall; Jim Kingsbury, director of engineering, Marshall	*Conversation.* Mulloy tells Lucas of Thiokol's concerns over temperature effects on O-rings and final resolution: • Lucas is shown copy of Thiokol fax.

Table 3–47 continued

Date and Time (EST)	Key Participants	Event
Jan. 28 7:00–9:00 a.m.	*At Kennedy:* Charles Stevenson, supervisor of ice crew, Kennedy; B.K. David, ice crew member, Kennedy	*Ice Crew Inspection of Launch Pad B.* Ice crew inspects Launch Pad B and *Challenger* for ice formation: • Davis measures temperature on solid rocket boosters, external tank, orbiter, and launch pad with infrared pyrometer. • Left-hand solid rocket booster seems to be about 25 degrees F, and right-hand solid rocket booster seems to be about 8 degrees F near the aft region. • Ice crew is not concerned because there is no Launch Commit Criteria on surface temperatures and does not report. • Crew reports patches of sheet ice on lower segment and skirt of left solid rocket booster.
Jan. 28 8:00 a.m.	*At Marshall:* Jud Lovingood, deputy manager, shuttle projects office, Marshall; Jack Lee, deputy director, Marshall	*Conversation:* Lovingood informs Lee of previous night's discussions: • He indicates that Thiokol had at first recommended not launching and, then after Wasatch conference, recommended launching. • He also informs Lee that Thiokol is providing in writing its recommendation for launch.

Table 3–47 continued

Date and Time (EST)	Key Participants	Event
Jan. 28 9:00 a.m.	*Nominally NASA Level I and Level II Management*	*Mission Management Team Meeting.* Discussion of ice conditions at launch complex. There is no apparent discussion of temperature effects on O-ring seal.
Jan. 28 10:30 a.m.	*At Kennedy:* Charles Stevenson, supervisor of ice crew; B.K. Davis, ice team member	*Ice Crew Inspection of Launch Pad B.* Ice crew inspects Launch Pad B for third time: • Crew removes ice from water troughs, returns to Launch Control Center at T-20 minutes, and reports conditions to Mission Management Team, including fact that ice remains on left solid rocket booster.
Jan. 28 11:38 a.m.		*Launch. Challenger* (STS 51-L) is launched.

Table 3–48. Schedule for Implementation of Recommendations (as of July 14, 1986)

Date of Action/ Target Date	Action	Recommendation
March 1986	Maintenance Safeguards Team is established.	IX - Maintenance Safeguards
March 1986	NASA establishes a Flight Rate Capability Working Group.	VIII - Flight Rate
March 13, 1986	NASA initiates review of all Shuttle program Failure Modes and Effects Analyses and associated Critical Items Lists.	III - Critical Item Review and Hazard Analysis
March 24, 1986	Marshall is directed to form a solid rocket motor joint redesign team.	I - Solid Rocket Motor
April 7, 1986	NASA initiates a Shuttle crew egress and escape review.	VII - Launch Abort and Crew Escape
May 5–6, 1986	Formal Program Management Review for Space Shuttle program with managers of all Shuttle program activities is held at Marshall.	Related investigation
June 19, 1986	Termination of Centaur upper stage development is announced.	Related investigation
June 25, 1986	Second formal Program Management Review for Space Shuttle program with managers of all Shuttle program activities is held at Kennedy.	Related investigation
June 25, 1986	Astronaut Robert Crippen is directed to form a fact-finding group to assess the Space Shuttle management structure and communications procedures.	II & IV - Shuttle Management Structure and Communications
July 8, 1986	George Rodney is appointed Associate Administrator for Safety, Reliability, Maintainability, and Quality Assurance.	IV - Safety Organization
Aug. 15, 1986	Flight Rate Capability Working Group recommendations are due to the Office of Space Flight.	VIII - Flight Rate
Aug. 15, 1986	Management and communications fact-finding group is to report to the associate administrator for space flight.	II & IV - Shuttle Management Structure and Communications
Sept. 1986	Solid Rocket Motor Preliminary Design Review is conducted.	I - Solid Rocket Motor
Sept. 1, 1986	Deadline arrives for establishment of a Shuttle Safety Panel.	II - Shuttle Management Structure
Sept. 30, 1986	Maintenance plan is completed.	IX - Maintenance Safeguards

Table 3–48 continued

Date of Action/ Target Date	Action	Recommendation
Oct. 1, 1986	Decision on implementation of recommendations of management fact-finding group is due.	II - Shuttle Management Structure
Oct. 1, 1986	Crew escape and launch abort studies are to be completed.	VII - Launch Abort and Crew Escape
Dec. 1986	Decision on implementation on crew escape and launch aborts is due.	VII - Launch Abort and Crew Escape
March 1987	Final review occurs with NASA Headquarters of Failure Modes and Effects Analyses and Critical Items Lists.	III - Critical Item Review and Hazard Analysis
July 1987	Landing aid implementation is completed.	VI - Landing Safety
Aug. 1987	Interim brake system is delivered.	VI - Landing Safety

Table 3–49. Revised Shuttle Manifest (as of October 3, 1986)

Date	**Mission**	**Purpose**	**Vehicle**
Feb. 18, 1988	STS-26/TDRS-C	NASA tracking and communications satellite	*Discovery*
May 30, 1988	STS-27/DOD	Classified	*Atlantis*
July 15, 1988	STS-28/DOD	Classified	*Columbia*
Sept. 15, 1988	STS-29/TDRS/D	NASA tracking and communications satellite	*Discovery*
Nov. 15, 1988	STS-30/HST	NASA program to observe the universe to gain information about its origin, evolution, and disposition of stars, galaxies, etc., dedicated mission, serviceable on later missions	*Atlantis*
Jan. 15, 1989	STS-31/Astro	Three-mission NASA program designed to obtain ultraviolet data on astronomical objects; igloo plus two pallets	*Columbia*
March 1, 1989	STS-32/DOD	Classified	*Discovery*
May 1, 1989	STS-33/Magellan	NASA mission to acquire radar map of the surface of Venus; planetary probe using IUS	*Atlantis*
June 1, 1989	STS-34/DOD Spacelab	Spacelab mission for Strategic Defense Initiative	*Discovery*
July 1, 1989	STS-35/MSL-3, GPS-1, GPS-2	MSL—NASA mission performs materials processing experiments in low gravity; uses MPESS cross-bay; weighs approximately 3,175 kilograms GPS—DOD navigation and position system; uses PAM-D2 upper stage	*Columbia*
July 15, 1989	STS-36/DOD	Classified	*Atlantis*
Aug. 30, 1989	STS-37/DOD	Classified	*Discovery*
Sept. 15, 1989	STS-38/GPS-3, GPS-4, MSL-4	See STS-35	*Columbia*
Oct. 15, 1989	STS-39/Planetary	Assignments for Galileo and Ulysses to be determined; use IUS	*Atlantis*
Dec. 1, 1989	STS-40/SLS-1	NASA Spacelab module mission to investigate the effects of weightlessness exposure using human and animal specimens	*Discovery*

Table 3–49 continued

Date	Mission	Purpose	Vehicle
Jan. 15, 1990	STS-41/GRO	NASA mission to investigate extraterrestrial gamma-ray sources; free-flyer mounts to Shuttle fittings and provides own propulsion; an ELV candidate	*Columbia*
Feb. 1, 1990	STS-42/DOD	Classified	*Atlantis*
April 1, 1990	STS-43/IML	Commercial maritime communications services; uses PAM-D	*Discovery*
April 15, 1990	STS-44/GPS-5, EOS-1, SHARE	EOS—Commercial mission to produce pharmaceuticals for large-scale tests leading to FDA approval and commercial production; special crossbay structure; weighs approximately 2,722 kilograms SHARE—NASA mission to evaluate on-orbit thermal performance of a heat pipe radiator element designed for Space Station heat rejection system application; 50-foot elements mounts on longeron	*Columbia*
May 30, 1990	STS-45/DOD	Classified	*Atlantis*
July 1, 1990	STS-46/DOD	Classified	*Discovery*
July 15, 1990	STS-47/GPS-6, Skynet-4, MSL-5	Skynet—United Kingdom military communications satellite; uses PAM-D2 upper stage	*Columbia*
Aug. 15, 1990	STS-48/DOD	Classified	*Atlantis*
Sept. 30, 1990	STS-49/Planetary	Assignments for Galileo and Ulysses to be determined; uses IUS	*Discovery*
Oct. 15, 1990	STS-50/GPS-7, INSAT-1D, TSS-1	INSAT—Indian communications and meteorological satellite; uses PAM-D TSS—NASA/Italy cooperative mission to demonstrate system capabilities by deploying and retrieving tethered satellite and measuring engineering data from payload on satellite; pallet	*Columbia*

Table 3–49 continued

Date	**Mission**	**Purpose**	**Vehicle**
Nov. 15, 1990	STS-51/ LDEF RETR, Syncom	LDEF RETR—NASA mission to retrieve and return the LDEF to Earth so results may be analyzed; purpose to avoid uncontrolled reentry; will occupy about half of payload bay; weighs approximately 9,980 kilograms Syncom—Commercial mission to provide communications services under lease to the U.S. Navy (Leasat); weighs 7,711 kilograms with own perigee stage	*Atlantis*
Jan. 15, 1991	STS-52, ATLAS-1, COFS-1	ATLAS—NASA mission to measure long-term variability in the total energy radiated by the Sun and determine the variability in the solar spectrum; igloo plus two pallets COFS—NASA mission to demonstrate structural integrity through deployment, retraction, and restowage and develop techniques for distributed control and adaptive control methods; pallet	*Discovery*
Feb. 1, 1991	STS-53/GPS-8, GPS-9, MSL-6, SSBUV-1	SSBUV—NASA mission to measure ozone characteristics of the atmosphere; mounts on longeron; weighs approximately 453.6 kilograms	*Columbia*
March 1, 1991	STS-54/DOD	Classified	OV-105
March 30, 1991	STS-55/ EURECA, Skynet-4, GPS-10	EURECA—ESA platform placed in orbit for 6 months offering conventional services to experiments; releasable, retrievable cross-bay structure; weighs approximately 3,856 kilograms	*Atlantis*

Table 3–50. Space Station Work Packages

	Work Package 1	**Work Package 2**	**Work Package 3**	**Work Package 4**
Lead Center	**Marshall**	**Johnson**	**Goddard**	**Lewis**
Contractors	Boeing Aerospace Co.; Martin Marietta Aerospace	McDonnell Douglas Astronautics Co.; Rockwell International	RCA Astro Electronics; General Electric Co.	Rocketdyne Div., Rockwell International; TRW Federal Systems Div. (contract terminated April 1986)
Responsibilities	Lab Module Hab Module Node Structure Logistics Carriers Environmental Control & Life Support Systems Certain Module Outfitting & Distributed Systems	Truss Structure & Utility Runs Propulsion System Data Management Thermal Control Communication & Tracking Attitude Control Extra Vehicular System	Polar Platform Payload Attach Points & Pointing Systems Flight Telerobotic Servicer	Power Generation Power Management and Distribution

Table 3–51. Japanese Space Station Components

		Experiments Logistics Module		
	Pressurized Module	**Pressurized Section**	**Exposed Section**	**Exposed Facility**
Shape	Cylinder	Cylinder	Box	Box 2 unit
Size	4m diameter	4m diameter	4m x 4m	2.5m (h) x 1.4m (w)
Length	10m	4m	2m	4m
Number of mission payloads	Payload rack 10	Rack 8		Payload 10
Average power		Housekeeping 5 kW, Mission 20 kW		Exchange of experimental equipment and materials and construction of large structures; scientific observations; and communications, scientific/engineering, and materials experiments
Data transfer rate		32 Mbps (Max., Optical LAN)		
Type of activity	Materials processing and life sciences experiments	On-orbit storage and transport logistics support		