CHAPTER TWO

LAUNCH SYSTEMS

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Introduction

Launch systems provide access to space, obviously a necessary component of all spaceflights. The elements of launch systems include the various vehicles, engines, boosters, and other propulsive and launch devices that help propel a spacecraft into space and position it properly. From 1979 through 1988, NASA used both expendable launch vehicles (ELVs)—those that can be used only once—and reusable launch vehicles. This chapter addresses both types of vehicles, as well as other launch system-related elements.

NASA used three families of ELVs (Scout, Delta, and Atlas) and one reusable launch vehicle (Space Shuttle) from 1979 through 1988 (Figure 2–1). Each family of ELVs had several models, which are described in this chapter. For the Space Shuttle, or Space Transportation System (STS), the solid rocket booster, external tank, and main engine elements comprised the launch-related elements and are addressed. The orbital maneuvering vehicle and the various types of upper stages that boosted satellites into their desired orbit are also described.

This chapter includes an overview of the management of NASA's launch vehicle program and summarizes the agency's launch vehicle budget. In addition, this chapter addresses other launch vehicle development, such as certain elements of advanced programs.

Several trends that began earlier in NASA's history continued in this decade (1979–1988). The trend toward acquiring launch vehicles and services from the commercial sector continued, as did the use of NASA-launched vehicles for commercial payloads. President Reagan's policy directive of May 1983 reiterated U.S. government support for commercial ELV activities and the resulting shift toward commercialization of ELV activities. His directive stated that the "U.S. government fully endorses and will facilitate commercialization of U.S. Expendable Launch Vehicles." His directive said that the United States would encourage use of its national ranges for commercial ELV operations and would "make available, on a reimbursable basis, facilities, equipment, tooling, and services that are required to support the production and operation of

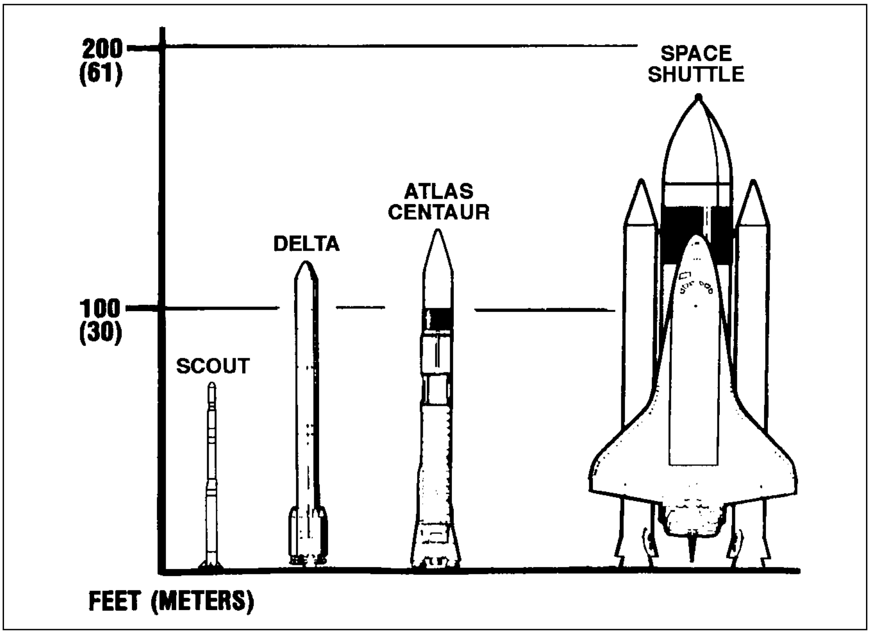


Figure 2–1. NASA Space Transportation System (1988)

U.S. commercial ELVs." Use of these facilities would be priced to encourage "viable commercial ELV launch activities."[1]

The policy also stated the government's intention of replacing ELVs with the STS as the primary launch system for most spaceflights. (Original plans called for a rate flight of up to fifty Space Shuttle flights per year.) However, as early as FY 1984, Congress recognized that relying exclusively on the Shuttle for all types of launches might not be the best policy. Congress stated in the 1984 appropriations bill that "the Space Shuttle system should be used primarily as a launch vehicle for government defense and civil payloads only" and "commercial customers for communications satellites and other purposes should begin to look to the commercialization of existing expendable launch vehicles."[2] The *Challenger* accident, which delayed the Space Shuttle program, also con-

[1]*Announcement of U.S. Government Support for Commercial Operations by the Private Sector, May 16, 1983,* from National Archives and Records Service's *Weekly Compilation of Presidential Documents* for May 16, 1983, pp. 721–23.

[2]House Committee on Appropriations, *Department of Housing and Urban Development-Independent Agencies Appropriation Bill, 1984, Report to Accompany H.R. 3133,* 98th Cong., 1st sess., 1983, H. Rept. 98— (unnumbered).

tributed to the development of a “mixed fleet strategy,” which recommended using both ELVs and the Shuttle.[3]

Management of the Launch Vehicle Program

Two NASA program offices shared management responsibility for the launch vehicle program: Code M (at different times called the Office of Space Transportation, the Office of Space Transportation Acquisition, and the Office of Space Flight) and Code O (the Office of Space Transportation Operations). Launch system management generally resided in two or more divisions within these offices, depending on what launch system elements were involved.

The organizational charts that follow illustrate the top-level structure of Codes M and O during the period 1979–1988. As in other parts of this chapter, there is some overlap between the management-related material presented in this chapter and the material in Chapter 3, “Space Transportation and Human Spaceflight.”

Also during the period 1979 through 1988, two major reorganizations in the launch vehicle area occurred (Figure 2–2): the split of the Office of Space Transportation into Codes M and O in 1979 (Phase I) and the merger of the two program offices into Code M in 1982 (Phase II). In addition, the adoption of the mixed fleet strategy following the loss of the Challenger reconfigured a number of divisions (Phase III). These management reorganizations reflected NASA’s relative emphasis on the Space Shuttle or on ELVs as NASA’s primary launch vehicle, as well as the transition of the Shuttle from developmental to operational status.

Phase I: Split of Code M Into Space Transportation Acquisition (Code M) and Space Transportation Operations (Code O)

John F. Yardley, the original associate administrator for the Office of Space Transportation Systems since its establishment in 1977, continued in that capacity, providing continuous assessment of STS development, acquisition, and operations status. In October 1979, Charles R. Gunn assumed the new position of deputy associate administrator for STS (Operations) within Code M, a position designed to provide transition management in anticipation of the formation of a new program office planned for later that year (Figure 2–3).

[3]NASA Office of Space Flight, *Mixed Fleet Study,* January 12, 1987. The NASA Advisory Council had also established a Task Force on Issues of a Mixed Fleet in March 1987 to study the issues associated with the employment of a mixed fleet of launch vehicles and endorsed the Office of Space Flight study results in its *Study of the Issues of a Mixed Fleet.* Further references to a mixed fleet are found in remarks made by NASA Administrator James C. Fletcher on May 15, 1987.

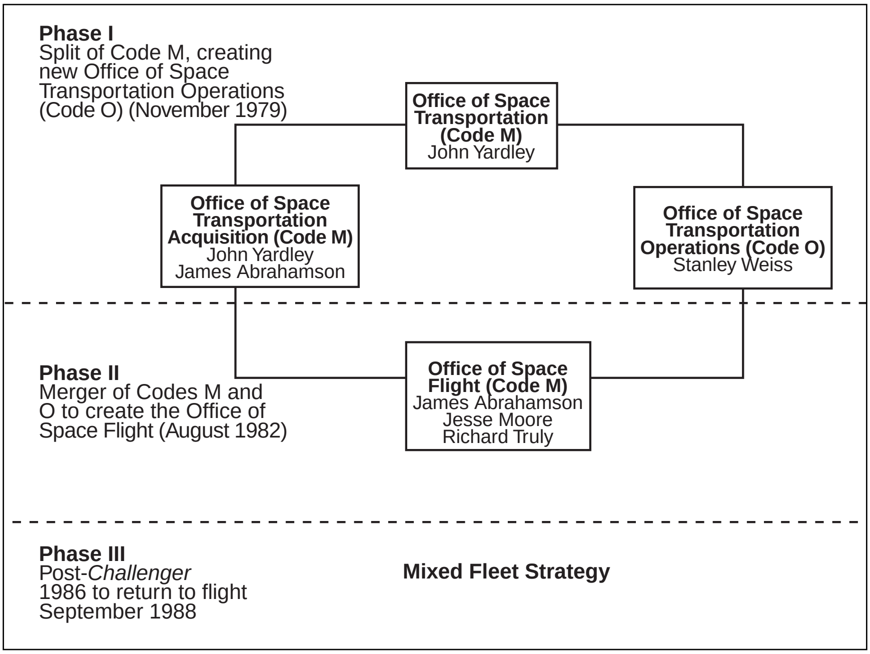


Figure 2–2. Top-Level Launch Vehicle Organizational Structure

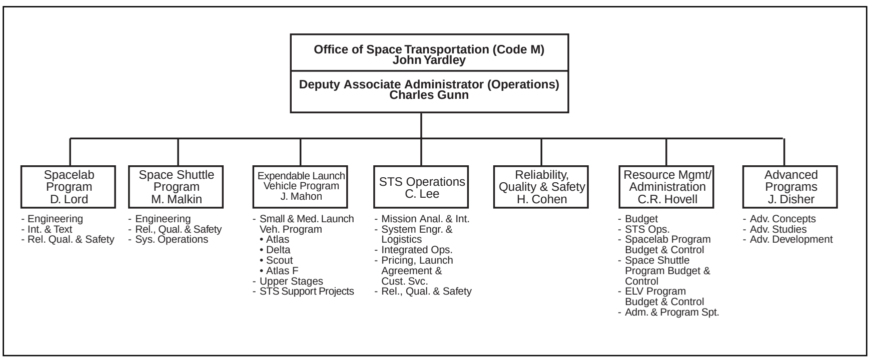
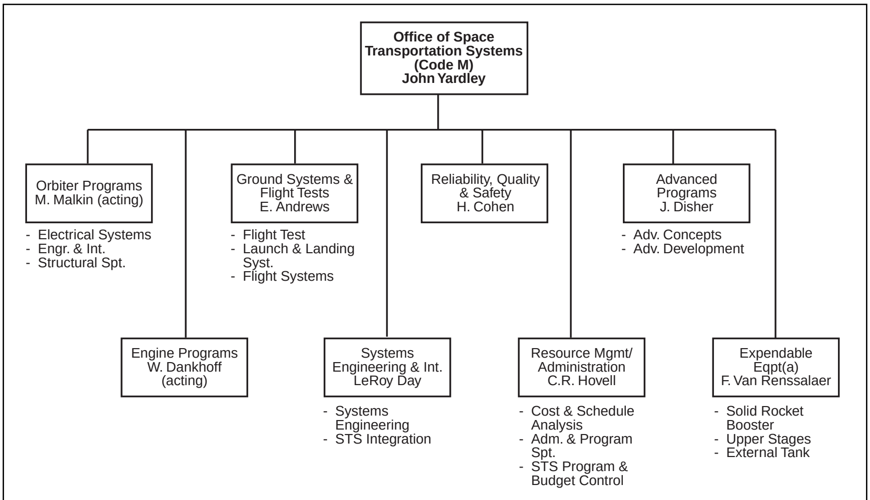


Figure 2–3. Office of Space Transportation (as of October 1979)

The formal establishment of the new Office of Space Operations (Code O) occurred in November 1979, and Dr. Stanley I. Weiss became its first permanent associate administrator in July 1980. Code O was the principal interface with all STS users and assumed responsibilities for Space Shuttle operations and functions, including scheduling, manifesting, pricing, launch service agreements, Spacelab, and ELVs, except for the development of Space Shuttle upper stages. The ELV program—Atlas, Centaur, Delta, Scout, and Atlas F—moved to Code O and was managed by Joseph B. Mahon, who had played a significant role in launch vehicle management during NASA's second decade.

Yardley remained associate administrator for Code M until May 1981, when L. Michael Weeks assumed associate administrator responsibilities.

Two new divisions within Code M were established in May 1981. The Upper Stage Division, with Frank Van Renssalaer as director, assumed responsibility for managing the wide-body Centaur, the Inertial Upper Stage (IUS), the Solid Spinning Upper Stage (SSUS), and the Solar-Electric Propulsion System. The Solid Rocket Booster and External Tank Division, with Jerry Fitts as director, was also created. In November 1981, Major General James A. Abrahamson, on assignment from the Air Force, assumed duties as permanent associate administrator of Code M (Figure 2–4).



(a) May 1981—Expendable Equipment Division disestablished.
New divisions established:
Upper Stages Division—Frank Van Renssalaer, Branches—Centaur, Solar Electric Propulsion Systems, IUS, and SSUS
Solid Rocket Booster and External Tank Division—Jerry Fitts, Branches—Solid Rocket Booster and External Tank

Figure 2–4. Code M/Code O Split (as of February 1980) (1 of 2)

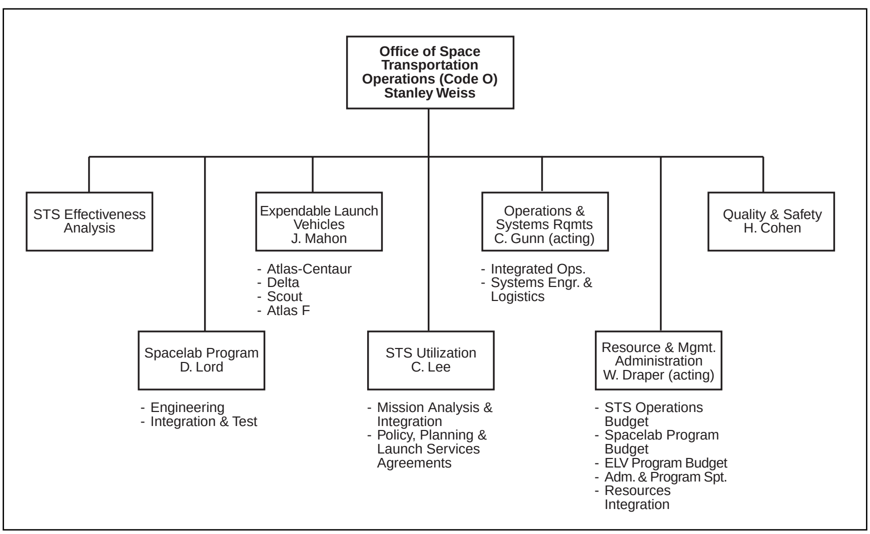
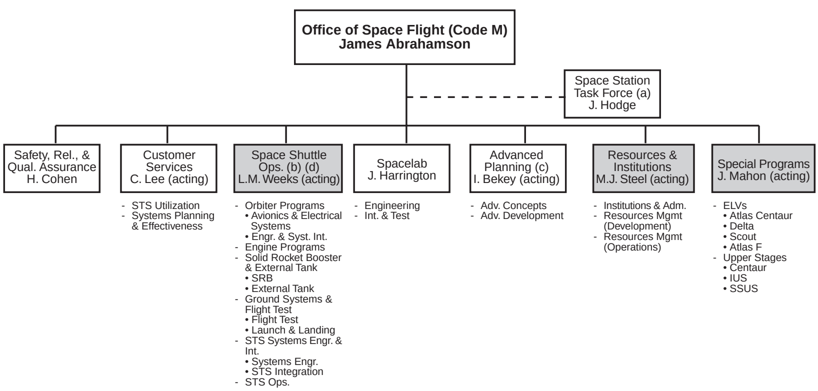


Figure 2–4. Code M/Code O Split (as of February 1980) (2 of 2)

Phase II: Merger of Codes M and O Into the Office of Space Flight

In preparation for Space Shuttle operations, Codes M and O merged in 1982 into the Office of Space Flight, Code M, with Abrahamson serving as associate administrator (Figure 2–5). Weiss became NASA's chief engineer. Code M was responsible for the fourth and final developmental Shuttle flight, the operational flights that would follow, future Shuttle procurements, and ELVs. The new office structure included the Special Programs Division (responsible for managing ELVs and upper stages), with Mahon continuing to lead that division, the Spacelab Division, the Customer Services Division, the Space Shuttle Operations Office, and the Space Station Task Force. This task force, under the direction of John D. Hodge, developed the programmatic aspects of a space station, including mission analysis, requirements definition, and program management. In April 1984, an interim Space Station Program Office superseded the Space Station Task Force and, in August 1984, became the permanent Office of Space Station (Code S), with Philip E. Culbertson serving as associate administrator. In the second quarter of 1983, organizational responsibility for ELVs moved from the Special Programs Division to the newly formed Space Transportation Support Division, still under the leadership of Joseph Mahon.

Jesse W. Moore took over as Code M associate administrator on August 1, 1984, replacing Abrahamson, who accepted a new assignment



- These divisions have an additional subsidiary organizational level also headed by Directors.

(a) The Space Station Task Force became the Office of Space Station (Code S) in August 1984.
(b) In early 1983, the following changes took place in the Space Shuttle Operations Division:
- Propulsion Branch added
- Flight & Turnaround Operations added
- Engine Programs eliminated
- SRB & external tank eliminated
- STS Systems Engineering and Integration eliminated and replaced by Integration Office
- STS Operations eliminated

(c) Advanced Planning Division added Advanced Transportation, Platforms and Services, and Requirements Definition; eliminated Advanced Concepts and Advanced Development.
(d) In the second quarter of 1983, organizational responsibility for ELVs moved from the Special Programs Division to the new Space Transportation Support Division, also under the leadership of Joseph Mahon.
(e) In late 1983, the Shuttle Propulsion Division was added. Within it were the Productivity Operations Support office, the Engine Program office, the Solid Rocket Program office, and the External Tank Program office.
(f) In early 1984, the Tether Satellite System office was added to the Space Transportation Support Division, and a Flight Demonstrations and Satellite Services and Crew Services office were added to the Advanced Programs Division.
(g) In 1986, the Orbital Maneuvering Vehicle office was added to the Space Transportation Support Division.

Figure 2–5. Code M Merger (as of October 1982) in the Department of Defense (DOD). Moore was succeeded by Rear Admiral Richard H. Truly, a former astronaut, on February 20, 1986.

*Phase III: Post-***Challenger** *Launch Vehicle Management*

From the first Space Shuttle orbital test flight in April 1981 through STS 61-C on January 12, 1986, NASA flew twenty-four successful Shuttle missions, and the agency was well on its way to establishing the Shuttle as its only launch vehicle. The loss of the *Challenger* (STS 51-L) on January 26, 1986, grounded the Shuttle fleet for thirty-two months. When flights resumed with STS-26 in September 1988, NASA planned a more conservative launch rate of twelve launches per year. The reduction of the planned flight rate forced many payloads to procure ELV launch services and forced NASA to plan to limit Shuttle use to payloads that required a crewed presence or the unique capabilities of the Shuttle. It also forced NASA to recognize the inadvisability of relying totally on the Shuttle. The resulting adoption of a "mixed fleet strategy" included increased NASA-DOD collaboration for the acquisition of launch vehicles and the purchase of ELV launch services. This acquisition strategy consisted of competitive procurements of the vehicle, software, and engineering and logistical work, except for an initial transitional period through 1991, when procurements would be noncompetitive if it was shown that it was in the government's best interest to match assured launch vehicle availability with payloads and established mission requirements.

The mixed fleet strategy was aimed at a healthy and affordable launch capability, assured access to space, the utilization of a mixed fleet to support NASA mission requirements, a dual-launch capability for critical payloads, an expanded national launch capability, the protection of the Shuttle fleet, and the fostering of ELV commercialization. This last goal was in accordance with the Reagan administration's policy of encouraging the growth of the fledgling commercial launch business whenever possible. The Office of Commercial Programs (established in 1984) was designated to serve as an advocate to ensure that NASA's internal decision-making process encouraged and facilitated the development of a domestic industrial base to provide access to space.

During this regrouping period, the ELV program continued to be managed at Headquarters within the Office of Space Flight, through the Space Transportation Support Division, with Joseph Mahon serving as division director and Peter Eaton as chief of ELVs, until late 1986. During this period, the Tethered Satellite System and the Orbital Maneuvering Vehicle also became responsibilities of this division. In late 1986, Code M reorganized into the basic configuration that it would keep through 1988 (Figure 2–6). This included a new management and operations structure for the National Space Transportation System (NSTS). Arnold J. Aldrich was named director of the NSTS at NASA Headquarters. A new Flight Systems Division, still under the leadership of Mahon, consisted of divisions for ELVs and upper stages, as well as divisions for advanced programs and Space Shuttle

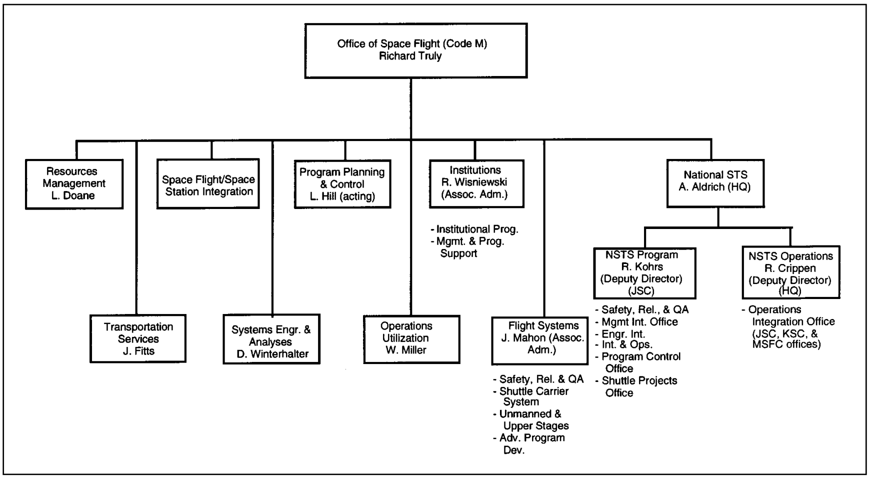


Figure 2–6. Office of Space Flight 1986 Reorganization

carrier systems. The Propulsion Division was eliminated as part of the NSTS's move to clarify the points of authority and responsibility in the Shuttle program and to establish clear lines of communication in the information transfer and decision-making processes.

Money for NASA's Launch Systems

From 1979 through 1983, all funds for NASA's launch systems came from the Research and Development (R&D) appropriation. Beginning in FY 1984, Congress authorized a new appropriation, Space Flight, Control, and Data Communications (SFC&DC), to segregate funds for ongoing Space Shuttle-related activities. This appropriation was in response to an October 1983 recommendation by the NASA Advisory Council, which stated that the operating budgets, facilities, and personnel required to support an operational Space Shuttle be "fenced" from the rest of NASA's programs. The council maintained that such an action would speed the transition to more efficient operations, help reduce costs, and ease the transfer of STS operations to the private sector or some new government operating agency, should such a transfer be desired.[4] SFC&DC was used for Space Shuttle production and capability development, space transportation operations (including ELVs), and space and ground network communications and data systems activities.

Most data in this section came from two sources. Programmed (actual) figures came from the yearly budget estimates prepared by NASA's Budget Operations Division, Office of the Comptroller. Data on NASA's submissions and congressional action came from the chronological history budget submissions issued for each fiscal year.

[4]NASA, *Fiscal Year 1985 Budget Submission, Chronological History,* House Authorization Committee Report, issued April 22, 1986, p. 15.

Table 2–1 shows the total appropriated amounts for launch vehicles and launch-related components. Tables 2–2 through 2–12 show the requested amount that NASA submitted to Congress, the amount authorized for each item or program, the final appropriation, and the programmed (or actual) amounts spent for each item or program. The submission represented the amount agreed to by NASA and OMB, not necessarily the initial request NASA made to the President's budget officer. The authorized amount was the ceiling set by Congress for a particular purpose. The appropriated amount reflected the amount that Congress actually allowed the Treasury to provide for specific purposes.[5]

As is obvious from examining the tables, funds for launch vehicles and other launch-related components were often rolled up into the total R&D or SFC&DC appropriation or other major budget category ("undistributed" funds). This made tracking the funding levels specifically designated for launch systems difficult. However, supporting congressional committee documentation clarified some of Congress's intentions. In the late 1970s and early 1980s, Congress intended that most space launches were to move from ELVs to the Space Shuttle as soon as the Shuttle became operational. This goal was being rethought by 1984, and it was replaced by a mixed fleet strategy after 1986. However, even though the government returned to using ELVs for many missions, it never again took prime responsibility for most launch system costs. From 1985 through 1987, Congress declared that the NASA ELV program would be completely funded on a reimbursable basis. Launch costs would be paid by the customer (for example, commercial entities, other government agencies, or foreign governments). Not until 1988 did Congress provide direct funding for two Delta II launch vehicles that would be used for NASA launches in the early 1990s. Although the federal government funded the Shuttle to a much greater degree, it was also to be used, when possible, for commercial or other government missions in which the customer would pay part of the launch and payload costs.

In some fiscal years, ELVs, upper stages, Shuttle-related launch elements, and advanced programs had their own budget lines in the congressional budget submissions. However, no element always had its own budget line. To follow the changes that took place, readers should consult the notes that follow each table as well as examine the data in each table. Additional data relating to the major Space Shuttle budget categories can be found in the budget tables in Chapter 3.

NASA's budget structure changed from one year to the next depending on the status of various programs and budget priorities. From 1979 through 1983, all launch-related activities fell under the R&D appropriation.

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[5]The term "appropriation" is used in two ways. It names a major budget category (for instance, R&D or SFC&DC). It is also used to designate an amount that Congress allows an agency to spend (for example, NASA's FY 1986 appropriation was $7,546.7 million).

Launch elements were found in the Space Flight Operations program, the Space Shuttle program, and the ELV program. The Space Flight Operations program included the major categories of space transportation systems operations capability development, space transportation system operations, and advanced programs (among others not relevant here). Upper stages were found in two areas: space transportation systems operations capability development included space transportation system upper stages, and space transportation system operations included upper stage operations.

The Space Shuttle program included design, development, test, and evaluation (DDT&E), which encompassed budget items for the orbiter, main engine, external tank, solid rocket booster (SRB), and launch and landing. The DDT&E category was eliminated after FY 1982. The production category also was incorporated into the Space Shuttle program. Production included budget line items for the orbiter, main engine, and launch and landing.

The ELV program included budget items for the Delta, Scout, Centaur, and Atlas F. (FY 1982 was the last year that the Atlas F appeared in the budget.)

FY 1984 was a transition year. Budget submissions (which were submitted to Congress as early as FY 1982) and authorizations were still part of the R&D appropriation. By the time the congressional appropriations committee acted, the SFC&DC appropriation was in place. Two major categories, Shuttle production and operational capability and space transportation operations, were in SFC&DC. Shuttle production and operational capability contained budget items for the orbiter, launch and mission support, propulsion systems (including the main engine, solid rocket booster, external tank, and systems support), and changes and systems upgrading. Space transportation operations included Shuttle operations and ELVs. Shuttle operations included flight operations, flight hardware (encompassing the orbiter, solid rocket booster, and external tank), and launch and landing. ELVs included the Delta and Scout. (FY 1984 was the last year that there was a separate ELV budget category until the FY 1988 budget.) R&D's Space Transportation Capability Development program retained upper stages, advanced programs, and the Tethered Satellite System.

Beginning in FY 1985, most launch-related activities moved to the SFC&DC appropriation. In 1987, NASA initiated the Expendable Launch Vehicles/Mixed Fleet program to provide launch services for selected NASA payloads not requiring the Space Shuttle's capabilities.

Space Shuttle Funding

Funds for the Space Shuttle Main Engine (SSME) were split into a DDT&E line item and a production line item from 1979 through 1983. Funds for the external tank and SRB were all designated as DDT&E. Beginning with FY 1984, SSME, external tank, and SRB funds were located in the capability development/flight hardware category and in the Propulsion System program. Capability development included continuing capability development tasks for the orbiter, main engine, external tank, and SRB and the development of the filament wound case SRB. Congress defined propulsion systems as systems that provided "for the production of the SSME, the implementation of the capability to support operational requirements, and the anomaly resolution for the SSME, SRB, and external tank."

Some Space Shuttle funds were located in the flight hardware budget category. Flight hardware provided for the procurement of the external tank, the manufacturing and refurbishment of SRB hardware and motors, and space components for the main engine; orbiter spares, including external tank disconnects, sustaining engineering, and logistics support for external tank, SRB, and main engine flight hardware elements; and maintenance and operation of flight crew equipment.

Tables 2–1 through 2–9 provide data for the launch-related elements of the Space Shuttle and other associated items. Budget data for additional Shuttle components and the major Shuttle budget categories are found in the Chapter 3 budget tables.

Characteristics

The following sections describe the launch vehicles and launch-related components used by NASA during the period 1979 through 1988. A chronology of each vehicle's use and its development is also presented, as well as the characteristics of each launch vehicle and launch-related component.

In some cases, finding the "correct" figures for some characteristics was difficult. The specified height, weight, or thrust of a launch vehicle occasionally differed among NASA, contractor, and media sources. Measurements, therefore, are approximate. Height or length was measured in several different ways, and sources varied on where a stage began and ended for measuring purposes. The heights of individual stages were generally without any payload. However, the overall height of the assembled launch vehicle may include the payload. Source material did not always indicate whether the overall length included the payload, and sometimes one mission operations report published two figures for the height of a launch vehicle within the same report.

Thrust was also expressed in more than one way. Source material referred to thrust "in a vacuum," "at sea level," "average," "nominal," and "maximum." Thrust levels vary during a launch and were sometimes presented as a range of values or as a percentage of "rated thrust." Frequently, there was no indication of which definition of thrust was being used.

This chapter uses the following abbreviations for propellants: LH_2 = liquid hydrogen, LOX = liquid oxygen, N_2H_2 = hydrazine, N_2O_4 = nitrogen tetroxide, RJ-1 = liquid hydrocarbon, and RP-1 = kerosene.

Expendable Launch Vehicles

From 1979 through 1988, NASA attempted seventy-four launches with a 94.6-percent success rate using the expendable Atlas E/F, Atlas-Centaur, Delta, or all-solid-fueled Scout vehicle—all vehicles that had been used during NASA's second decade. During this time, the agency continued to built Deltas and maintained its capability to build Scouts and Atlases on demand. It did not emphasize ELV development but rather focused on Space Shuttle development and the start of STS operational status. However, the adoption of the mixed fleet strategy returned some attention to ELV development

The following section summarizes ELV activities during the decade from 1979 through 1988. Figure 2–7 and Table 2–13 present the success rate of each launch vehicle.

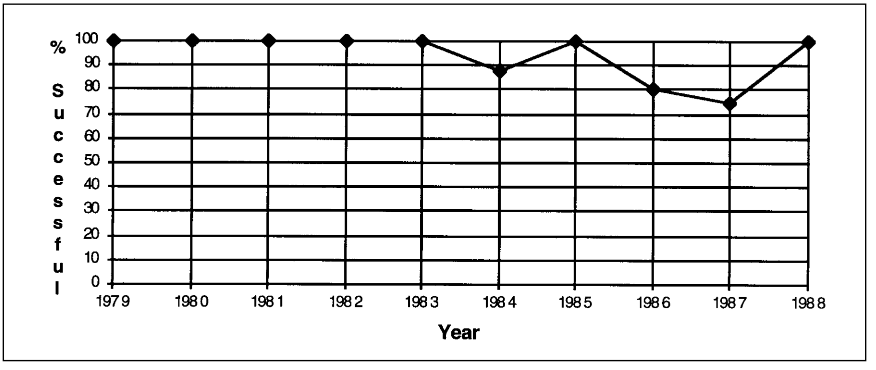

Figure 2–7. Expendable Launch Vehicle Success Rate

1979

NASA conducted nine launches during 1979, all successful. These used the Scout, the Atlas E/F, the Atlas-Centaur, and the Delta. Of the nine launches, three launched NASA scientific and application payloads, and six supported other U.S. government and nongovernment reimbursing customers.[6]

A Scout vehicle launched the NASA Stratospheric Aerosol and Gas Experiment (SAGE), a NASA magnetic satellite (Magsat), and a reimbursable United Kingdom scientific satellite (UK-6/Ariel). An Atlas-Centaur launched a FltSatCom DOD communications satellite and a NASA scientific satellite (HEAO-3). Three launches used the Delta: one domestic communications satellite for Western Union, another for RCA, and an experimental satellite, called SCATHA, for DOD. A weather satellite was launched on an Atlas F by the Air Force for NASA and the National Oceanic and Atmospheric Administration (NOAA).

[6]*Aeronautics and Space Report of the President, 1979* (Washington, DC: U.S. Government Printing Office (GPO), 1980), p. 39.

1980

Seven ELV launches took place in 1980: three on Deltas, three on Atlas-Centaurs, and one on an Atlas F. Of the seven, one was for NASA; the other six were reimbursable launches for other U.S. government, international, and domestic commercial customers that paid NASA for the launch and launch support costs.[7]

A Delta launched the Solar Maximum Mission, the single NASA mission, with the goal of observing solar flares and other active Sun phenomena and measuring total radiative output of the Sun over a six-month period. A Delta also launched GOES 4 (Geostationary Operational Environmental Satellite) for NOAA. The third Delta launch, for Satellite Business Systems (SBS), provided integrated, all-digital, interference-free transmission of telephone, computer, electronic mail, and videoconferencing to clients.

An Atlas-Centaur launched FltSatCom 3 and 4 for the Navy and DOD. An Atlas-Centaur also launched Intelsat V F-2. This was the first in a series of nine satellites launched by NASA for Intelsat and was the first three-axis stabilized Intelsat satellite. An Atlas F launched NOAA-B, the third in a series of Sun-synchronous operational environmental monitoring satellites launched by NASA for NOAA. A booster failed to place this satellite in proper orbit, causing mission failure.

1981

During 1981, NASA launched missions on eleven ELVs: one on a Scout, five using Deltas (two with dual payloads), four on Atlas-Centaurs, and one using an Atlas F. All but two were reimbursable launches for other agencies or commercial customers, and all were successful.[8]

A Scout vehicle launched the DOD navigation satellite, NOVA 1. In five launches, the Delta, NASA's most-used launch vehicle, deployed seven satellites. Two of these launches placed NASA's scientific Explorer satellites into orbit: Dynamics Explorer 1 and 2 on one Delta and the Solar Mesosphere Explorer (along with Uosat for the University of Surrey, England) on the other. The other three Delta launches had paying customers, including the GOES 5 weather satellite for NOAA and two communications satellites, one for SBS and one for RCA.

An Atlas-Centaur, which was the largest ELV being used by NASA, launched four missions: Comstar D-4, a domestic communications satellite for Comsat; two Intelsat V communications satellites for Intelsat; and the last in the current series of FltSatCom communications satellites for DOD. An Atlas F launched the NOAA 7 weather satellite for NOAA.

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[7] *Aeronautics and Space Report of the President, 1980* (Washington, DC: GPO, 1981).

[8] *Aeronautics and Space Report of the President, 1981* (Washington, DC: GPO, 1982).

In addition, ELVs continued to provide backup support to STS customers during the early development and transition phase of the STS system.

1982

NASA launched nine missions on nine ELVs in 1982, using seven Deltas and two Atlas-Centaurs. Of the nine, eight were reimbursable launches for other agencies or commercial customers, and one was a NASA applications mission.[9]

The Delta supported six commercial and international communications missions for which NASA was fully reimbursed: RCA's Satcom 4 and 5, Western Union's Westar 4 and 5, India's Insat 1A, and Canada's Telesat G (Anik D-1). In addition, a Delta launched Landsat 4 for NASA. The Landsat and Telesat launches used improved, more powerful Deltas. An Aerojet engine and a tank with a larger diameter increased the Delta weight-carrying capability into geostationary-transfer orbit by 140 kilograms. An Atlas-Centaur launched two communications satellites for the Intelsat.

1983

During 1983, NASA launched eleven satellites on eleven ELVs, using eight Deltas, one Atlas E, one Atlas-Centaur, and one Scout. A Delta launch vehicle carried the European Space Agency's EXOSAT x-ray observatory to a highly elliptical polar orbit. Other 1983 payloads launched into orbit on NASA ELVs were the NASA-Netherlands Infrared Astronomy Satellite (IRAS), NOAA 8 and GOES 6 for NOAA, Hilat for the Air Force, Intelsat VF-6 for Intelsat, Galaxy 1 and 2 for Hughes Communications, Telstar 3A for AT&T, and Satcom 1R and 2R for RCA; all except IRAS were reimbursable.[10]

The increased commercial use of NASA's launch fleet and launch services conformed to President Reagan's policy statement on May 16, 1983, in which he announced that the U.S. government would facilitate the commercial operation of the ELV program.

1984

During 1984, NASA's ELVs provided launch support to seven satellite missions using four Deltas, one Scout, one Atlas-Centaur, and one Atlas E. During this period, the Delta vehicle completed its forty-third consecutive successful launch with the launching of the NATO-IIID satellite in November 1984. In addition, a Delta successfully launched Landsat 5 for NOAA in March (Landsat program management had transferred to

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[9] *Aeronautics and Space Report of the President, 1982* (Washington, DC: GPO, 1983), p. 19.

[10] *Aeronautics and Space Report of the President, 1983* (Washington, DC: GPO, 1984), p. 17.

NOAA in 1983); AMPTE, a joint American, British, and German space physics mission involving three satellites, in August; and Galaxy-C in September. Other payloads launched during 1984 by NASA ELVs included a Navy navigation satellite by a Scout, an Intelsat communications satellite by an Atlas-Centaur, and a NOAA weather satellite by an Atlas F vehicle. The launch of the Intelsat satellite experienced an anomaly in the launch vehicle that resulted in mission failure. All missions, except the NASA scientific satellite AMPTE, were reimbursable launches for other U.S. government, international, and domestic commercial missions that paid NASA for launch and launch support.[11]

In accordance with President Reagan's policy directive to encourage commercialization of the launch vehicle program, Delta, Atlas-Centaur, and Scout ELVs were under active consideration during this time by commercial operators for use by private industry. NASA and Transpace Carriers, Inc. (TCI), signed an interim agreement for exclusive rights to market the Delta vehicle, and negotiations took place with General Dynamics on the Atlas-Centaur. A *Commerce Business Daily* announcement, published August 8, 1984, solicited interest for the private use of the Scout launch vehicle. Ten companies expressed interest in assuming a total or partial takeover of this vehicle system.

Also in August 1984, President Reagan approved a National Space Strategy intended to implement the 1983 National Space Policy. This strategy called for the United States to encourage and facilitate commercial ELV operations and minimize government regulation of these operations. It also mandated that the U.S. national security sector pursue an improved assured launch capability to satisfy the need for a launch system that complemented the STS as a hedge against "unforeseen technical and operational problems" and to use in case of crisis situations. To accomplish this, the national security sector should "pursue the use of a limited number of ELVs."[12]

1985

In 1985, NASA's ELVs continued to provide launch support during the transition of payloads to the Space Shuttle. Five launches took place using ELVs. Two of these were DOD satellites launched on Scouts—one from the Western Space and Missile Center and the other from the Wallops Flight Facility. Atlas-Centaurs launched the remaining three missions for Intelsat on a reimbursable basis.[13]

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[11] *Aeronautics and Space Report of the President, 1984* (Washington, DC: GPO, 1985), p. 23

[12] White House Fact Sheet, "National Space Strategy," August 15, 1984.

[13] *Aeronautics and Space Report of the President, 1985* (Washington, DC: GPO, 1986).

1986

In 1986, NASA's ELVs launched five space application missions for NOAA and DOD. A Scout launched the Polar Beacon Experiments and Auroral Research satellite (Polar Bear) from Vandenberg Air Force Base; an Atlas-Centaur launched a FltSatCom satellite in December; an Atlas E launched a NOAA satellite; and two Delta vehicles were used—one to launch a NOAA GOES satellite and the other to launch a DOD mission. One of the Delta vehicles failed during launch and was destroyed before boosting the GOES satellite into transfer orbit. An investigation concluded that the failure was caused by an electrical short in the vehicle wiring. Wiring modifications were incorporated into all remaining Delta vehicles. In September, the second Delta vehicle successfully launched a DOD mission.[14]

Partly as a result of the *Challenger* accident, NASA initiated studies in 1986 on the need to establish a Mixed Fleet Transportation System, consisting of the Space Shuttle and existing or new ELVs. This policy replaced the earlier stated intention to make the Shuttle NASA's sole launch vehicle.

1987

In 1987, NASA launched four spacecraft missions using ELVs. Three of these missions were successful: a Delta launch of GOES 7 for NOAA into geostationary orbit in February; a Delta launch of Palapa B-2, a communications satellite for the Indonesian government, in March; and a Scout launch of a Navy Transit satellite in September. In March, an Atlas-Centaur launch attempt of FltSatCom 6, a Navy communications satellite, failed when lightning in the vicinity of the vehicle caused the engines to malfunction. The range safety officer destroyed the vehicle approximately fifty-one seconds after launch.[15]

1988

The ELV program had a perfect launch record in 1988 with six successful launches. In February, a Delta ELV lifted a classified DOD payload into orbit. This launch marked the final east coast Delta launch by a NASA launch team. A NASA-Air Force agreement, effective July 1, officially transferred custody of Delta Launch Complex 17 at Cape Canaveral Air Force Station to the Air Force. Over a twenty-eight-year period, NASA had launched 143 Deltas from the two Complex 17 pads. A similar transaction transferred accountability for Atlas/Centaur Launch Complex 36 to the Air Force.[16]

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[14] *Aeronautics and Space Report of the President, 1986* (Washington, DC: GPO, 1987).

[15] *Aeronautics and Space Report of the President, 1987* (Washington, DC: GPO, 1988).

[16] *Aeronautics and Space Report of the President, 1988* (Washington, DC: GPO, 1989).

Also in 1988, a Scout launched San Marcos DL from the San Marco launch facility in the Indian Ocean, a NASA-Italian scientific mission, during March. Its goal was to explore the relationship between solar activity and meteorological phenomena by studying the dynamic processes that occur in the troposphere, stratosphere, and thermosphere. In April, another Scout deployed the SOOS-3, a Navy navigation satellite. In June, a third Scout carried the NOVA-II, the third in a series of improved Navy Transit navigation satellites, into space. The final Scout launch of the year deployed a fourth SOOS mission in August. In September, an Atlas E launched NOAA H, a National Weather Service meteorological satellite funded by NOAA, into Sun-synchronous orbit. This satellite payload included on-board search-and-rescue instruments.

In addition to arranging for the purchase of launch services from the commercial sector, NASA took steps to divest itself of an adjunct ELV capability and by making NASA-owned ELV property and services available to the private sector. During 1988, NASA finalized a barter agreement with General Dynamics that gave the company ownership of NASA's Atlas-Centaur flight and nonflight assets. In exchange, General Dynamics agreed to provide the agency with two Atlas-Centaur launches at no charge. An agreement was signed for the first launch service—supporting the FltSatCom F-8 Navy mission. NASA and General Dynamics also completed a letter contract for a second launch service to support the NASA-DOD Combined Release and Radiation Effects Satellite (CRRES) mission. In addition, NASA transferred its Delta vehicle program to the U.S. Air Force. Finally, enabling agreements were completed to allow ELV companies to negotiate directly with the appropriate NASA installation. During 1988, NASA Headquarters signed enabling agreements with McDonnell Douglas, Martin Marietta, and LTV Corporation. The Kennedy Space Center and General Dynamics signed a subagreement in March to allow General Dynamics to take over maintenance and operations for Launch Complex 36.

ELV Characteristics

The Atlas Family

The basic Atlas launch vehicle was a one-and-a-half stage stainless steel design built by the Space Systems Division of General Dynamics. It was designed as an intercontinental ballistic missile (ICBM) and was considered an Air Force vehicle. However, the Atlas launch vehicle was also used successfully in civilian space missions dating from NASA's early days. The Atlas launched all three of the unmanned lunar exploration programs (Ranger, Lunar Orbiter, and Surveyor). Atlas vehicles also launched the Mariner probes to Mars, Venus, and Mercury and the Pioneer probes to Jupiter, Saturn, and Venus.

NASA used two families of Atlas vehicles during the 1979–1988 period: the Atlas E/F series and the Atlas-Centaur series. The Atlas E/F launched seven satellites during this time, six of them successful (Table 2–14). The Atlas E/F space booster was a refurbished ICBM. It burned kerosene (RP-1) and liquid oxygen in its three main engines, two Rocketdyne MA-3 booster engines, and one sustainer engine. The Atlas E/F also used two small vernier engines located at the base of the RP-1 tank for added stability during flight (Table 2–15). The Atlas E/F was designed to deliver payloads directly into low-Earth orbit without the use of an upper stage.

The Atlas-Centaur (Figure 2–8) was the nation's first high-energy launch vehicle propelled by liquid hydrogen and liquid oxygen. Developed and launched under the direction of the Lewis Research Center, it became operational in 1966 with the launch of Surveyor 1, the first U.S. spacecraft to soft-land on the Moon's surface. Beginning in 1979, the Centaur stage was used only in combination with the Atlas booster, but it had been successfully used earlier in combination with the Titan III booster to launch payloads into interplanetary trajectories, sending two Helios spacecraft toward the Sun and two Viking spacecraft toward Mars.[17] From 1979 through 1988, the Atlas-Centaur launched 18 satellites with only two failures (Table 2–16).

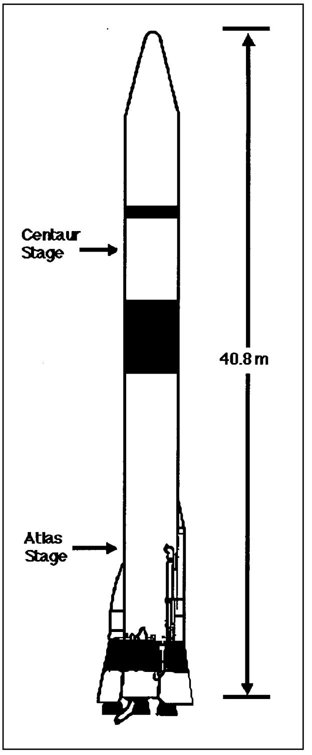

Figure 2–8. Atlas-Centaur Launch Vehicle

The Centaur stage for the Atlas booster was upgraded in 1973 and incorporated an integrated electronic system controlled by a digital computer. This flight-proven "astrionics" system checked itself and all other systems prior to and during the launch phase; during flight, it controlled all events after the liftoff. This system was located on the equipment module on the forward end of the Centaur stage. The 16,000-word capacity computer replaced the original 4,800-word capacity computer and enabled it to take over many of the functions previously handled by separate mechanical and electrical systems. The new Centaur system handled navigation, guidance tasks, control pressurization, propellant management, telemetry formats and transmission, and initiation of vehicle events (Table 2–17).

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

The Delta Family

NASA has used the Delta launch vehicle since the agency's inception. In 1959, NASA's Goddard Space Flight Center awarded a contract to Douglas Aircraft Company (later McDonnell Douglas) to produce and integrate twelve launch vehicles. The Delta, using components from the Air Force's Thor intermediate range ballistic missile (IRBM) program and the Navy's Vanguard launch program, was available eighteen months later. The Delta has evolved since that time to meet the increasing demands of its payloads and has been the most widely used launch vehicle in the U.S. space program, with thirty-five launches from 1979 through 1988 and thirty-four of them successful (Table 2–18).

The Delta configurations of the late 1970s and early 1980s were designated the 3900 series. Figure 2–9 illustrates the 3914, and Figure 2–10 shows the 3920 with the Payload Assist Module (PAM) upper stage. The 3900 series resembled the earlier 2900 series (Table 2–19), except for the replacement of the Castor II solid strap-on motors with nine larger and more powerful Castor IV solid motors (Tables 2–20 and 2–21).

The RS-27 engine, manufactured by the Rocketdyne Division of Rockwell International, powered the first stage of the Delta. It was a single-start power plant, gimbal-mounted and operated on a combination of liquid oxygen and kerosene (RP-1). The thrust chamber was regeneratively

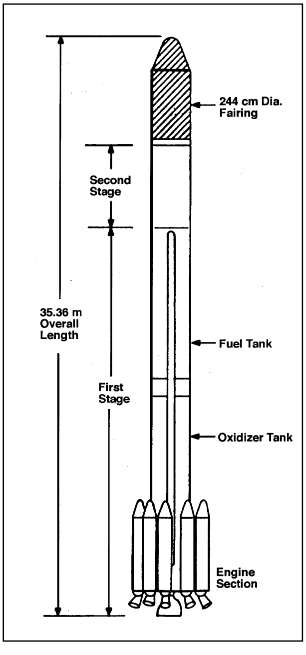

Figure 2–9.
Delta 3914

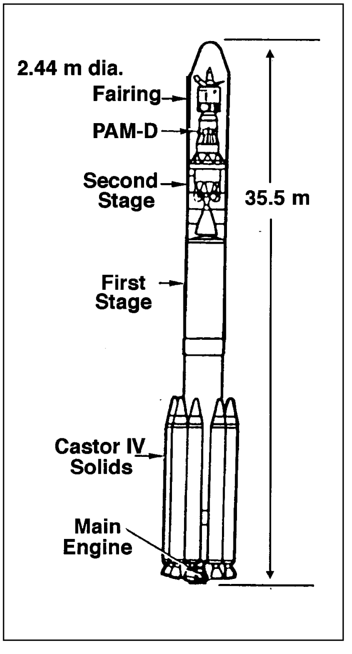

Figure 2–10.
Delta 3920/PAM-D

cooled, with the fuel circulating through 292 tubes that comprised the inner wall of the chamber.

The following four-digit code designated the type of Delta launch vehicle:

- 1st digit designated the type of strap-on engines:
  - 2 = Castor II, extended long tank Thor with RS-27 main engine
  - 3 = Castor IV, extended long tank Thor with RS-27 main engine
- 2nd digit designated the number of strap-on engines
- 3rd digit designated the type of second stage and manufacturer:
  - 1 = ninety-six-inch manufactured by TRW (TR-201)
  - 2 = ninety-six-inch stretched tank manufactured by Aerojet (AJ10-118K)
- 4th digit designated the type of third stage:
  - 0 = no third stage
  - 3 = TE-364-3
  - 4 = TE-364-4

For example, a model designation of 3914 indicated the use of Castor IV strap-on engines, extended long tank with an RS-27 main engine; nine strap-ons; a ninety-six-inch second stage manufactured by TRW; and a TE-364-4 third stage engine. A PAM designation appended to the last digit indicated the use of a McDonnell-Douglas PAM.

Scout Launch Vehicle

The standard Scout launch vehicle (Scout is an acronym for Solid Controlled Orbital Utility Test) was a solid propellant four-stage booster system. It was the world's first all-solid propellant launch vehicle and was one of NASA's most reliable launch vehicles. The Scout was the smallest of the basic launch vehicles used by NASA and was used for orbit, probe, and reentry Earth missions (Figure 2–11).

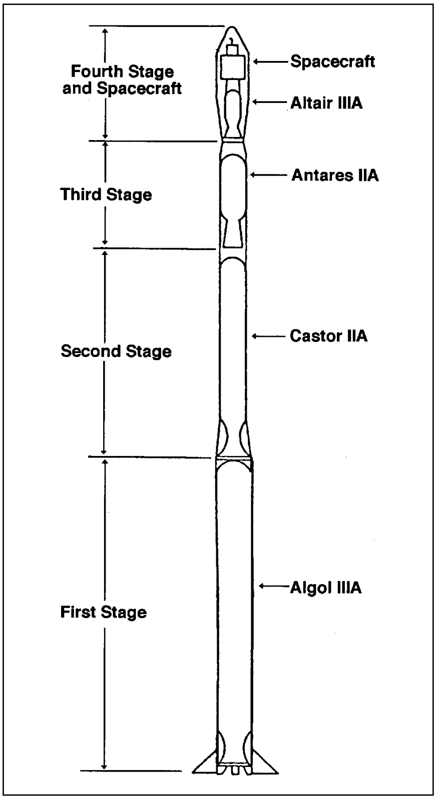

Figure 2–11. Scout-D Launch Vehicle (Used in 1979)

The first Scout launch took place in 1960. Since that time, forty-six NASA Scout launches have taken place, including fourteen between 1979 and 1988, when every launch was successful (Table 2–22). In addition to NASA payloads, Scout clients included DOD, the European Space Research Organization, and several European governments. The Scout was used for both orbital and suborbital missions and has participated in research in navigation, astronomy, communications, meteorology, geodesy, meteoroids, reentry materials, biology, and Earth and atmospheric sensing. It was the only U.S. ELV launched from three launch sites: Wallops on the Atlantic Ocean, Vandenberg on the Pacific Ocean, and the San Marco platform in the Indian Ocean. It could also inject satellites into a wider range of orbital inclinations than any other launch vehicle.

Unlike NASA's larger ELVs, the Scout was assembled and the payload integrated and checked out in the horizontal position. The vehicle was raised to the vertical orientation prior to launch. The propulsion motors were arranged in tandem with transition sections between the stages to tie the structure together and to provide space for instrumentation. A standard fifth stage was available for highly elliptical and solar orbit missions.

Scout's first-stage motor was based on an earlier version of the Navy's Polaris missile motor; the second-stage motor was developed from the Army's Sergeant surface-to-surface missile; and the third- and fourth-stage motors were adapted by NASA's Langley Research Center from the Navy's Vanguard missile. The fourth-stage motor used on the G model could carry almost four times as much payload to low-Earth orbit as the original model in 1960—that is, 225 kilograms versus fifty-nine kilograms (Table 2–23).

Vought Corporation, a subsidiary of LTV Corporation, was the prime contractor for the Scout launch vehicle. The Langley Research Center managed the Scout program.

Space Shuttle

The reusable, multipurpose Space Shuttle was designed to replace the ELVs that NASA used to deliver commercial, scientific, and applications spacecraft into Earth's orbit. Because of its unique design, the Space Shuttle served as a launch vehicle, a platform for scientific laboratories, an orbiting service center for other satellites, and a return carrier for previously orbited spacecraft. Beginning with its inaugural flight in 1981 and through 1988, NASA flew twenty-seven Shuttle missions (Table 2–24). This section focuses on the Shuttle's use as a launch vehicle. Chapter 3 discusses its use as a platform for scientific laboratories and servicing functions.

The Space Shuttle system consisted of four primary elements: an orbiter spacecraft, two solid rocket boosters (SRBs), an external tank to house fuel and an oxidizer, and three main engines. Rockwell International built the orbiter and the main engines; Thiokol Corporation produced the SRB motors; and the external tank was built by Martin Marietta Corporation. The Johnson Space Center directed the orbiter and integration contracts, while the Marshall Space Flight Center managed the SRB, external tank, and main engine contracts.

The Shuttle could transport up to 29,500 kilograms of cargo into near-Earth orbit (185.2 to 1,111.2 kilometers). This payload was carried in a bay about four and a half meters in diameter and eighteen meters long. Major system requirements were that the orbiter and the two SRBs be reusable and that the orbiter have a maximum 160-hour turnaround time after landing from the previous mission. The orbiter vehicle carried personnel and payloads to orbit, provided a space base for performing their assigned tasks, and returned personnel and payloads to Earth. The orbiter provided a habitable environment for the crew and passengers, including scientists and engineers. Additional orbiter characteristics are addressed in Chapter 3.

The Shuttle was launched in an upright position, with thrust provided by the three main engines and the two SRBs. After about two minutes, at an altitude of about forty-four kilometers, the two boosters were spent and were separated from the orbiter. They fell into the ocean at predetermined points and were recovered for reuse.

The main engines continued firing for about eight minutes, cutting off at about 109 kilometers altitude just before the spacecraft was inserted into orbit. The external tank was separated, and it followed a ballistic trajectory back into a remote area of the ocean but was not recovered.

Two smaller liquid rocket engines made up the orbital maneuvering system (OMS). The OMS injected the orbiter into orbit, performed maneuvers while in orbit, and slowed the vehicle for reentry. After reentry, the unpowered orbiter glided to Earth and landed on a runway.

The Shuttle used two launch sites: the Kennedy Space Center in Florida and Vandenberg Air Force Base in California. Under optimum conditions, the orbiter landed at the site from which it was launched. However, as shown in the tables in Chapter 3 that describe the individual Shuttle missions, weather conditions frequently forced the Shuttle to land at Edwards Air Force Base in California, even though it had been launched from Kennedy.

Main Propulsion System

The main propulsion system (MPS) consisted of three Space Shuttle main engines (SSMEs), three SSME controllers, the external tank, the orbiter MPS propellant management subsystem and helium subsystem, four ascent thrust vector control units, and six SSME hydraulic servo-actuators. The MPS, assisted by the two SRBs during the initial phases of the ascent trajectory, provided the velocity increment from liftoff to a predetermined velocity increment before orbit insertion. The Shuttle jettisoned the two SRBs after their fuel had been expended, but the MPS continued to thrust until the predetermined velocity was achieved. At that time, main engine cutoff (MECO) was initiated, the external tank was jettisoned, and the OMS was ignited to provide the final velocity increment for orbital insertion. The magnitude of the velocity increment supplied by the OMS depended on payload weight, mission trajectory, and system limitations.

Along with the start of the OMS thrusting maneuver (which settled the MPS propellants), the remaining liquid oxygen propellant in the orbiter feed system and SSMEs was dumped through the nozzles of the engines. At the same time, the remaining liquid hydrogen propellant in the orbiter feed system and SSMEs was dumped overboard through the hydrogen fill and drain valves for six seconds. Then the hydrogen inboard fill and drain valve closed, and the hydrogen recirculation valve opened, continuing the dump. The hydrogen flowed through the engine hydrogen bleed valves to the orbiter hydrogen MPS line between the inboard and outboard hydrogen fill and drain valves, and the remaining hydrogen was dumped through the outboard fill and drain valve for approximately 120 seconds.

During on-orbit operations, the flight crew vacuum made the MPS inert by opening the liquid oxygen and liquid hydrogen fill and drain valves, which allowed the remaining propellants to be vented to space. Before entry into the Earth's atmosphere, the flight crew repressurized the MPS propellant lines with helium to prevent contaminants from being drawn into the lines during entry and to maintain internal positive pressure. MPS helium also purged the spacecraft's aft fuselage. The last activity involving the MPS occurred at the end of the landing rollout. At that time, the helium remaining in on-board helium storage tanks was released into the MPS to provide an inert atmosphere for safety.

Main Engine

The SSME represented a major advance in propulsion technology. Each engine had an operating life of seven and a half hours and fifty-five starts and the ability to throttle a thrust level that extended over a wide range (65 percent to 109 percent of rated power level). The SSME was the first large, liquid-fuel rocket engine designed to be reusable.

A cluster of three SSMEs housed in the orbiter's aft fuselage provided the main propulsion for the orbiter. Ignited on the ground prior to launch, the cluster of liquid hydrogen–liquid oxygen engines operated in parallel with the SRBs during the initial ascent. After the boosters separated, the main engines continued to operate. The nominal operating time was 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 cycle ensured maximum performance because it eliminated parasitic losses. The various thrust levels provided for high thrust 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 engines were gimbaled to provide pitch, yaw, and roll control during the orbiter boost phase.

Key components of each engine included four turbopumps (two low- and two high-pressure), two preburners, the main injector, the main combustion chamber, the nozzle, and the hot-gas manifold. The manifold was the structural backbone of the engine. It supported the two preburners, the high-pressure pumps, the main injector, the pneumatic control assembly, and the main combustion chamber with the nozzle. Table 2–25 summarizes SSME characteristics.

The SSME was the first rocket engine to use a built-in electronic digital controller. The controller accepted commands from the orbiter for engine start, shutdown, and change in throttle setting and also monitored engine operation. In the event of a failure, the controller automatically corrected the problem or shut down the engine safely.

Main Engine Margin Improvement Program. Improvements to the SSMEs for increased margin and durability began with a formal Phase II program in 1983. Phase II focused on turbomachinery to extend the time between high-pressure fuel turbopump (HPFT) overhauls by reducing the operating temperature in the HPFT and by incorporating margin improvements to the HPFT rotor dynamics (whirl), turbine blade, and HPFT bearings. Phase II certification was completed in 1985, and all the changes were incorporated into the SSMEs for the STS-26 mission.

In addition to the Phase II improvements, NASA made additional changes to the SSME to further extend the engine's margin and durability. The main changes were to the high-pressure turbomachinery, main combustion chamber, hydraulic actuators, and high-pressure turbine discharge temperature sensors. Changes were also made in the controller software to improve engine control. Minor high-pressure turbomachinery design changes resulted in margin improvements to the turbine blades, thereby extending the operating life of the turbopumps. These changes included applying surface texture to important parts of the fuel turbine blades to improve the material properties in the pressure of hydrogen and incorporating a damper into the high-pressure oxidizer turbine blades to reduce vibration.

Plating a welded outlet manifold with nickel increased the main combustion chamber's life. Margin improvements were also made to five hydraulic actuators to preclude a loss in redundancy on the launch pad. Improvements in quality were incorporated into the servo-component coil design, along with modifications to increase margin. To address a temperature sensor in-flight anomaly, the sensor was redesigned and extensively tested without problems.

To certify the improvements to the SSMEs and demonstrate their reliability through margin (or limit) testing, NASA initiated a ground test program in December 1986. Its primary purposes were to certify the improvements and demonstrate the engine's reliability and operating margin. From December 1986 to December 1987, 151 tests and 52,363 seconds of operation (equivalent to 100 Shuttle missions) were performed. These hot-fire ground tests were performed at the single-engine test stands at the Stennis Space Center in Mississippi and at the Rockwell International Rocketdyne Division's Santa Susana Field Laboratory in California.

NASA also conducted checkout and acceptance tests of the three main engines for the STS-26 mission. Those tests, also at Stennis, began in August 1987, and all three STS-26 engines were delivered to the Kennedy Space Center by January 1988.

Along with hardware improvements, NASA conducted several major reviews of requirements and procedures. These reviews addressed such topics as possible failure modes and effects, as well as the associated critical items list. Another review involved having a launch/abort reassessment team examine all launch-commit criteria, engine redlines, and software logic. NASA also performed a design certification review. Table 2–26 lists these improvements, as well as events that occurred earlier in the development of the SSME.

A related effort involved Marshall Space Flight Center engineers who, working with their counterparts at Kennedy, accomplished a comprehensive launch operations and maintenance review. This ensured that engine processing activities at the launch site were consistent with the latest operational requirements.

External Tank

The external tank contained the propellants (liquid hydrogen and liquid oxygen) for the SSMEs and supplied them under pressure to the three main engines in the orbiter during liftoff and ascent. Just prior to orbital insertion, the main engines cut off, and the external tank separated from the orbiter, descended through a ballistic trajectory over a predesignated area, broke up, and impacted in a remote ocean area. The tank was not recovered.

The largest and heaviest (when loaded) element of the Space Shuttle, the external tank had three major components: a forward liquid oxygen tank; an unpressurized intertank, which contained most of the electrical components; and an aft liquid hydrogen tank. Beginning with the STS-6 mission, NASA used a lightweight external tank (LWT). For each kilogram of weight reduced from the original external tank, the cargo-carrying capability of the Space Shuttle spacecraft increased one kilogram. The weight reduction was accomplished by eliminating portions of stringers (structural stiffeners running the length of the hydrogen tank), using fewer stiffener rings, and by modifying major frames in the hydrogen tank. Also, significant portions of the tank were milled differently to reduce thickness, and the weight of the external tank's aft SRB attachments was reduced by using a stronger, yet lighter and less expensive, titanium alloy. Earlier, the use of the LWT reduced the total weight by deleting the antigeyser line. The line paralleled the oxygen feed line and provided a circulation path for liquid oxygen to reduce the accumulation of gaseous oxygen in the feed line while the oxygen tank was being filled before launch. After NASA assessed propellant loading data from ground tests and the first four Space Shuttle missions, engineers removed the antigeyser line for STS-5 and subsequent missions. The total length and

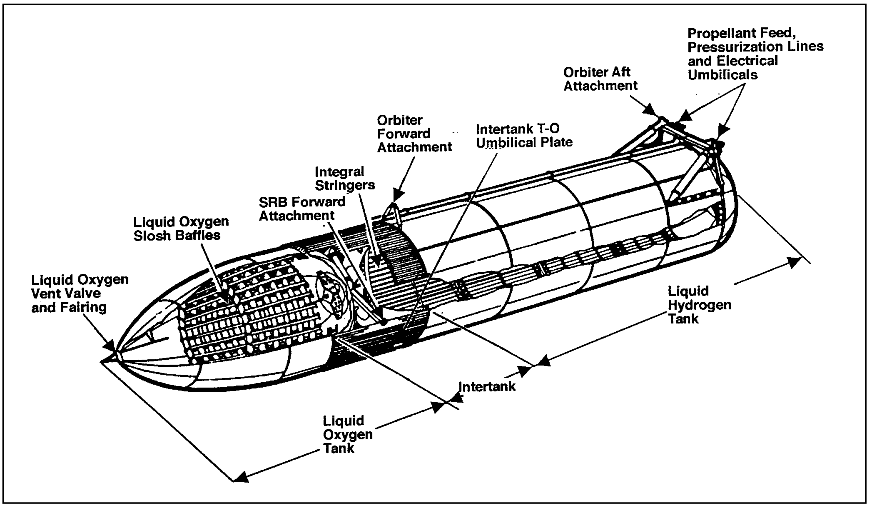

Figure 2–12. External Tank

diameter of the external tank remained unchanged (Figure 2–12). Table 2–27 summarizes the external tank characteristics, and Table 2–28 presents a chronology of external development.

As well as containing and delivering the propellant, the external tank served as the structural backbone of the Space Shuttle during launch operations. The external tank consisted of two primary tanks: a large hydrogen tank and a smaller oxygen tank, joined by an intertank to form one large propellant-storage container. Superlight ablator (SLA-561) and foam insulation sprayed on the forward part of the oxygen tank, the intertank, and the sides of the hydrogen tank protected the outer surfaces. The insulation reduced ice or frost formation during launch preparation, protecting the orbiter from free-falling ice during flight. This insulation also minimized heat leaks into the tank, avoided excessive boiling of the liquid propellants, and prevented liquification and solidification of the air next to the tank.

The external tank attached to the orbiter at one forward attachment point and two aft points. In the aft attachment area, umbilicals carried fluids, gases, electrical signals, and electrical power between the tank and the orbiter. Electrical signals and controls between the orbiter and the two SRBs also were routed through those umbilicals.

Liquid Oxygen Tank. The liquid oxygen tank was an aluminum monocoque structure composed of a fusion-welded assembly of preformed, chem-milled gores, panels, machined fittings, and ring chords. It operated in a pressure range of 1,035 to 1,138 mmHg. The tank contained antislosh and antivortex provisions to minimize liquid residuals and damp fluid motion. The tank fed into a 0.43-meter-diameter feedline that sent the liquid oxygen through the intertank, then outside the external tank to the aft righthand external tank/orbiter disconnect umbilical. The feedline permitted liquid oxygen to flow at approximately 1,268 kilograms per second, with the SSMEs operating at 104 percent of rated thrust, or permitted a maximum flow of 71,979 liters per minute. The liquid oxygen tank's double-wedge nose cone reduced drag and heating, contained the vehicle's ascent air data system, and served as a lightning rod.

Intertank. The intertank was not a tank in itself but provided a mechanical connection between the liquid oxygen and liquid hydrogen tanks. The primary functions of the intertank were to provide structural continuity to the propellant tanks, to serve as a protective compartment to house instruments, and to receive and distribute thrust loads from the SRBs. The intertank was a steel/aluminum semimonocoque cylindrical structure with flanges on each end for joining the liquid oxygen and liquid hydrogen tanks. It housed external tank instrumentation components and provided an umbilical plate that interfaced with the ground facility arm for purging the gas supply, hazardous gas detection, and hydrogen gas boiloff during ground operations. It consisted of mechanically joined skin, stringers, and machined panels of aluminum alloy. The intertank was vented during flight. It contained the forward SRB-external tank attach thrust beam and fittings that distributed the SRB loads to the liquid oxygen and liquid hydrogen tanks.

Liquid Hydrogen Tank. The liquid hydrogen tank was an aluminum semimonocoque structure of fusion-welded barrel sections, five major ring frames, and forward and aft ellipsoidal domes. Its operating pressure was 1,759 mmHg. The tank contained an antivortex baffle and siphon outlet to transmit the liquid hydrogen from the tank through a 0.43-meter line to the left aft umbilical. The liquid hydrogen feedline flow rate was 211.4 kilograms per second, with the SSMEs at 104 percent of rated thrust, or a maximum flow of 184,420 liters per minute. At the forward end of the liquid hydrogen tank was the external tank/orbiter forward attachment pod strut, and at its aft end were the two external tank/orbiter aft attachment ball fittings as well as the aft SRB-external tank stabilizing strut attachments.

External Tank Thermal Protection System. The external tank thermal protection system consisted of sprayed-on foam insulation and premolded ablator materials. The system also included the use of phenolic thermal insulators to preclude air liquefaction. Thermal isolators were required for liquid hydrogen tank attachments to preclude the liquefaction of air-exposed metallic attachments and to reduce heat flow into the liquid hydrogen. The thermal protection system weighed 2,192 kilograms.

External Tank Hardware. The external hardware, external tank/orbiter attachment fittings, umbilical fittings, and electrical and range safety system weighed 4,136.4 kilograms.

Each propellant tank had a vent and relief valve at its forward end. This dual-function valve could be opened by ground support equipment for the vent function during prelaunch and could open during flight when the ullage (empty space) pressure of the liquid hydrogen tank reached 1,966 mmHg or the ullage pressure of the liquid oxygen tank reached 1,293 mmHg.

The liquid oxygen tank contained a separate, pyrotechnically operated, propulsive tumble vent valve at its forward end. At separation, the liquid oxygen tumble vent valve was opened, providing impulse to assist in the separation maneuver and more positive control of the entry aerodynamics of the external tank.

There were eight propellant-depletion sensors, four each for fuel and oxidizer. The fuel-depletion sensors were located in the bottom of the fuel tank. The oxidizer sensors were mounted in the orbiter liquid oxygen feedline manifold downstream of the feedline disconnect. During SSME thrusting, the orbiter general purpose computers constantly computed the instantaneous mass of the vehicle because of the usage of the propellants. Normally, MECO was based on a predetermined velocity; however, if any two of the fuel or oxidizer sensors sensed a dry condition, the engines would be shut down.

The locations of the liquid oxygen sensors allowed the maximum amount of oxidizer to be consumed in the engines, while allowing sufficient time to shut down the engines before the oxidizer pumps ran dry. In addition, 500 kilograms of liquid hydrogen were loaded over and above that required by the six-to-one oxidizer/fuel engine mixture ratio. This assured that MECO from the depletion sensors was fuel rich; oxidizer-rich engine shutdowns could cause burning and severe erosion of engine components.

Four pressure transducers located at the top of the liquid oxygen and liquid hydrogen tanks monitored the ullage pressures. Each of the two aft external tank umbilical plates mated with a corresponding plate on the orbiter. The plates helped maintain alignment among the umbilicals. Physical strength at the umbilical plates was provided by bolting corresponding umbilical plates together. When the orbiter general purpose computers commanded external tank separation, the bolts were severed by pyrotechnic devices.

The external tank had five propellant umbilical valves that interfaced with orbiter umbilicals—two for the liquid oxygen tank and three for the liquid hydrogen tank. One of the liquid oxygen tank umbilical valves was for liquid oxygen, the other for gaseous oxygen. The liquid hydrogen tank umbilical had two valves for liquid and one for gas. The intermediate-diameter liquid hydrogen umbilical was a recirculation umbilical used only during the liquid hydrogen chill-down sequence during prelaunch.

The external tank also had two electrical umbilicals that carried electrical power from the orbiter to the tank and the two SRBs and provided information from the SRBs and external tank to the orbiter. A swing-arm-mounted cap to the fixed service structure covered the oxygen tank vent on top of the external tank during countdown and was retracted about two minutes before liftoff. The cap siphoned off oxygen vapor that threatened to form large ice on the external tank, thus protecting the orbiter's thermal protection system during launch.

External Tank Range Safety System. A range safety system, monitored by the flight crew, provided for dispersing tank propellants if necessary. It included a battery power source, a receiver/decoder, antennas, and ordnance.

Post-*Challenger *Modification. Prior to the launch of STS-26, NASA modified the external tank by strengthening the hydrogen pressurization line. In addition, freezer wrap was added to the hydrogen line. This permitted the visual detection of a hydrogen fire (Table 2–28).

Solid Rocket Boosters

The two SRBs provided the main thrust to lift the Space Shuttle off the pad and up to an altitude of about forty-four and a half kilometers. In addition, the two SRBs carried the entire weight of the external tank and orbiter and transmitted the weight load through their structure to the mobile launcher platform. The SRBs were ignited after the three SSMEs' thrust level was verified. The two SRBs provided 71.4 percent of the thrust at liftoff and during first-stage ascent. Seventy-five seconds after SRB separation, SRB apogee occurred at an altitude of approximately sixty-five kilometers. SRB impact occurred in the ocean approximately 226 kilometers downrange, to be recovered and returned for refurbishment and reuse.

The primary elements of each booster were the motor (including case, propellant, igniter, and nozzle), structure, separation systems, operational flight instrumentation, recovery avionics, pyrotechnics, deceleration system, thrust vector control system, and range safety destruct system (Figure 2–13). Each booster attached to the external tank at the SRB's aft frame with two lateral sway braces and a diagonal attachment. The forward end of each SRB joined the external tank at the forward end

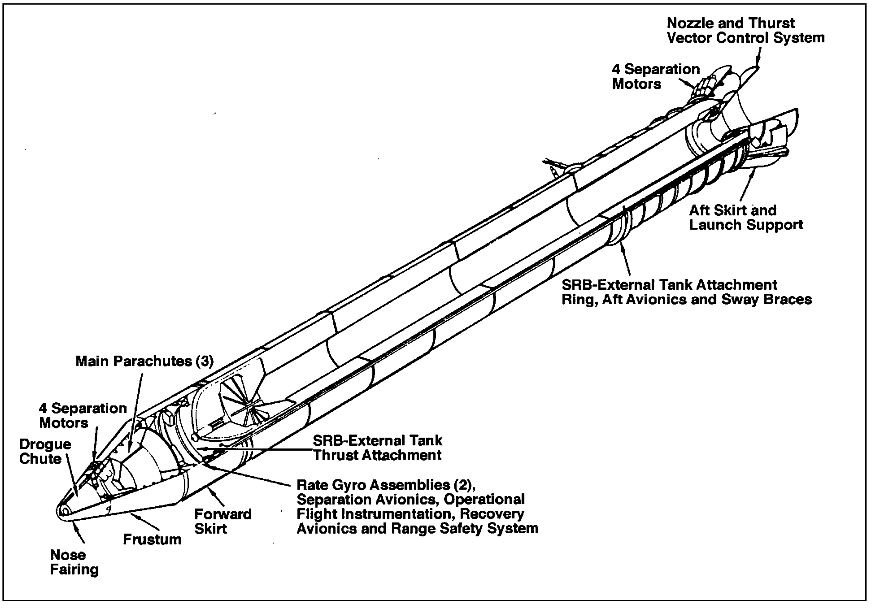

Figure 2–13. Solid Rocket Booster

of the SRB's forward skirt. On the launch pad, each booster also connected to the mobile launcher platform at the aft skirt with four bolts and nuts that were severed by small explosives at liftoff.

The SRBs were used as matched pairs. Each consisted of four solid rocket motor (SRM) segments. The pairs were matched by loading each of the four motor segments in pairs from the same batches of propellant ingredients to minimize any thrust imbalance. The exhaust nozzle in the aft segment of each motor, in conjunction with the orbiter engines, steered the Space Shuttle during the powered phase of launch. The segmented-casing design assured maximum flexibility in fabrication and ease of transportation and handling. Each segment was shipped to the launch site on a heavy-duty rail car with a specially built cover.

The propellant mixture in each SRB motor consisted of an ammonium perchlorate (oxidizer, 69.6 percent by weight), aluminum (fuel, 16 percent), iron oxide (a catalyst, 0.4 percent), a polymer (a binder that held the mixture together, 12.04 percent), and an epoxy curing agent (1.96 percent). The propellant was an eleven-point star-shaped perforation in the forward motor segment and a double-truncated-cone perforation in each of the aft segments and aft closure. This configuration provided high thrust at ignition and then reduced the thrust by approximately one-third fifty seconds after liftoff to prevent overstressing the vehicle during maximum dynamic pressure.

The cone-shaped aft skirt supported the four aft separation motors. The aft section contained avionics, a thrust vector control system that consisted of two auxiliary power units and hydraulic pumps, hydraulic systems, and a nozzle extension jettison system. The forward section of each booster contained avionics, a sequencer, forward separation motors, a nose cone separation system, drogue and main parachutes, a recovery beacon, a recovery light, a parachute camera on selected flights, and a range safety system. Each SRB incorporated a range safety system that included a battery power source, a receiver-decoder, antennas, and ordnance.

Each SRB had two integrated electronic assemblies, one forward and one aft. After burnout, the forward assembly initiated the release of the nose cap and frustum and turned on the recovery aids. The aft assembly, mounted in the external tank-SRB attach ring, connected with the forward assembly and the orbiter avionics systems for SRB ignition commands and nozzle thrust vector control. Each integrated electronic assembly had a multiplexer-demultiplexer, which sent or received more than one message, signal, or unit of information on a single communications channel.

Eight booster separation motors (four in the nose frustum and four in the aft skirt) of each SRB thrust for 1.02 seconds at SRB separation from the external tank. SRB separation from the external tank was electrically initiated. Each solid rocket separation motor was 0.8 meter long and 32.5 centimeters in diameter (Table 2–29).

Location aids were provided for each SRB, frustum-drogue chutes, and main parachutes. These included a transmitter, antenna, strobe/converter, battery, and saltwater switch electronics. The recovery crew retrieved the SRBs, frustum/drogue chutes, and main parachutes. The nozzles were plugged, the solid rocket motors were dewatered, and the crew towed the SRBs back to the launch site. Each booster was removed from the water, and its components disassembled and washed with fresh and de-ionized water to limit saltwater corrosion. The motor segments, igniter, and nozzle were shipped back to Thiokol for refurbishment. The SRB nose caps and nozzle extensions were not recovered.

Testing and production of the SRB were well under way in 1979. The booster performed well until the *Challenger* accident revealed flaws that had very likely existed for several missions but had resulted in little remedial action. The 1986 *Challenger* accident forced major modifications to the SRB and SRM.

Post-*Challenger *Modifications. On June 13, 1986, President Reagan directed NASA to implement, as soon as possible, the recommendations of the Presidential Commission on the Space Shuttle *Challenger* Accident. During the downtime following the *Challenger* accident, NASA analyzed critical structural elements of the SRB, primarily focused in areas where anomalies had been noted during postflight inspection of recovered hardware.

Anomalies had been noted in the attach ring where the SRBs joined the external tank. Some of the fasteners showed distress where the ring attached to the SRB motor case. Tests attributed this to the high loads encountered during water impact. To correct the situation and ensure higher strength margins during ascent, the attach ring was redesigned to encircle the motor case completely (360 degrees). Previously, the attach ring formed a "C" and encircled the motor case 270 degrees.

In addition, NASA performed special structural tests on the aft skirt. During this test program, an anomaly occurred in a critical weld between the hold-down post and skin of the skirt. A redesign added reinforcement brackets and fittings in the aft ring of the skirt. These modifications added approximately 200 kilograms to the weight of each SRB.

Solid Rocket Motor Redesign. The Presidential Commission determined that the cause of the loss of the *Challenger* was "a failure in the joint between the two lower segments of the right solid rocket motor. The specific failure was the destruction of the seals that are intended to prevent hot gases from leaking through the joint during the propellant burn of the rocket motor."[18]

Consequently, NASA developed a plan for a redesigned solid rocket motor (RSRM). Safety in flight was the primary objective of the SRM redesign. Minimizing schedule impact by using existing hardware, to the extent practical, without compromising safety was another objective.

[18]*Report at a Glance*, report to the President by the Presidential Commission on the Space Shuttle *Challenger* Accident, Chapter IV, "The Cause of the Accident," Finding (no pg. number).

NASA established a joint redesign team with participants from the Marshall Space Flight Center, other NASA centers, Morton Thiokol, and outside NASA. The team developed an "SRM Redesign Project Plan" to formalize the methodology for SRM redesign and requalification. The plan provided an overview of the organizational responsibilities and relationships; the design objectives, criteria, and process; the verification approach and process; and a master schedule. Figure 2–14 shows the SRM Project Schedule as of August 1986. The companion "Development and Verification Plan" defined the test program and analyses required to verify the redesign and unchanged components of the SRM. The SRM was carefully and extensively redesigned. The RSRM received intense scrutiny and was subjected to a thorough certification process to verify that it worked properly and to qualify the motor for human spaceflight.

NASA assessed all aspects of the existing SRM and required design changes in the field joint, case-to-nozzle joint, nozzle, factory joint, propellant grain shape, ignition system, and ground support equipment. The propellant, liner, and castable inhibitor formulations did not require changes. Design criteria were established for each component to ensure a safe design with an adequate margin of safety. These criteria focused on loads, environments, performance, redundancy, margins of safety, and verification philosophy.

The team converted the criteria into specific design requirements during the Preliminary Requirements Reviews held in July and August 1986. NASA assessed the design developed from these requirements at the Preliminary Design Review held in September 1986 and baselined in October 1986. NASA approved the final design at the Critical Design

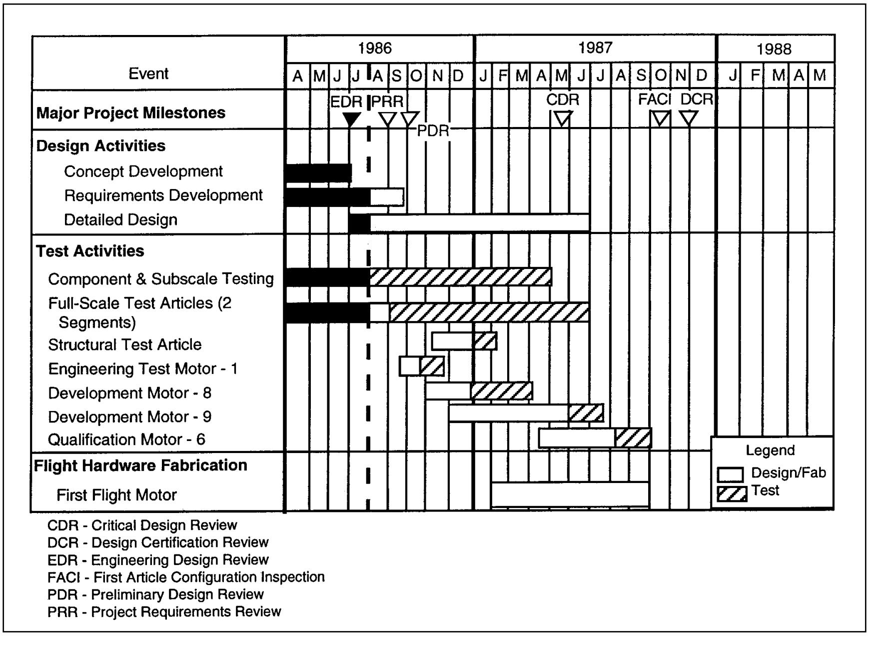

Figure 2–14. Solid Rocket Motor Redesign Schedule

Review held in October 1987. Manufacture of the RSRM test hardware and the first flight hardware began prior to the Preliminary Design Review and continued in parallel with the hardware certification program. The Design Certification Review considered the analyses and test results versus the program and design requirements to certify that the RSRM was ready to fly.

Specific Modifications. The SRM field-joint metal parts, internal case insulation, and seals were redesigned, and a weather protection system was added. The major change in the motor case was the new tang capture feature to provide a positive metal-to-metal interference fit around the circumference of the tang and clevis ends of the mating segments. The interference fit limited the deflection between the tang and clevis O-ring sealing surfaces caused by motor pressure and structural loads. The joints were designed so that the seals would not leak under twice the expected structural deflection and rate.

The new design, with the tang capture feature, the interference fit, and the use of custom shims between the outer surface of the tang and inner surface of the outer clevis leg, controlled the O-ring sealing gap dimension. The sealing gap and the O-ring seals were designed so that a positive compression (squeeze) was always on the O-rings. The minimum and maximum squeeze requirements included the effects of temperature, O-ring resiliency and compression set, and pressure. The redesign increased the clevis O-ring groove dimension so that the O-ring never filled more than 90 percent of the O-ring groove, and pressure actuation was enhanced.

The new field-joint design also included a new O-ring in the capture feature and an additional leak check port to ensure that the primary O-ring was positioned in the proper sealing direction at ignition. This new or third O-ring also served as a thermal barrier in case the sealed insulation was breached. The field-joint internal case insulation was modified to be sealed with a pressure-actuated flap called a j-seal, rather than with putty as in the STS 51-L (*Challenger*) configuration.

The redesign added longer field-joint-case mating pins, with a reconfigured retainer band, to improve the shear strength of the pins and increase the metal parts' joint margin of safety. The joint safety margins, both thermal and structural, were demonstrated over the full ranges of ambient temperature, storage compression, grease effect, assembly stresses, and other environments. The redesign incorporated external heaters with integral weather seals to maintain the joint and O-ring temperature at a minimum of 23.9 degrees Celsius. The weather seal also prevented water intrusion into the joint.

Original Versus Redesigned SRM Case-to-Nozzle Joint. The SRM case-to-nozzle joint, which experienced several instances of O-ring erosion in flight, was redesigned to satisfy the same requirements imposed on the case field joint. Similar to the field joint, case-to-nozzle joint modifications were made in the metal parts, internal insulation, and O-rings. The redesign added radial bolts with Stato-O-Seals to minimize the joint sealing gap opening. The internal insulation was modified to be sealed adhesively, and a third O-ring was included. The third O-ring served as a dam or wiper in front of the primary O-ring to prevent the polysulfide adhesive from being extruded in the primary O-ring groove. It also served as a thermal barrier in case the polysulfide adhesive was breached. The polysulfide adhesive replaced the putty used in the STS 51-L joint. Also, the redesign added an another leak check port to reduce the amount of trapped air in the joint during the nozzle installation process and to aid in the leak check procedure.

Nozzle. Redesigned internal joints of the nozzle metal parts incorporated redundant and verifiable O-rings at each joint. The modified nozzle steel fixed housing part permitted the incorporation of the 100 radial bolts that attached the fixed housing to the case's aft dome. The new nozzle nose inlet, cowl/boot, and aft exit cone assemblies used improved bonding techniques. Increasing the thickness of the aluminum nose inlet housing and improving the bonding process eliminated the distortion of the nose inlet assembly's metal-part-to-ablative-parts bond line. The changed tape-wrap angle of the carbon cloth fabric in the areas of the nose inlet and throat assembly parts improved the ablative insulation erosion tolerance. Some of these ply-angle changes had been in progress prior to STS 51-L. Additional structural support with increased thickness and contour changes to the cowl and outer boot ring increased their margins of safety. In addition, the outer boot ring ply configuration was altered.

Factory Joint. The redesign incorporated minor modifications in the case factory joints by increasing the insulation thickness and layup to increase the margin of safety on the internal insulation. Longer pins were also added, along with a reconfigured retainer band and new weather seal to improve factory joint performance and increase the margin of safety. In addition, the redesign changed the O-ring and O-ring groove size to be consistent with the field joint.

Propellant. The motor propellant forward transition region was recontoured to reduce the stress fields between the star and cylindrical portions of the propellant grain.

Ignition System. The redesign incorporated several minor modifications into the ignition system. The aft end of the igniter steel case, which contained the igniter nozzle insert, was thickened to eliminate a localized weakness. The igniter internal case insulation was tapered to improve the manufacturing process. Finally, although vacuum putty was still used at the joint of the igniter and case forward dome, it eliminated asbestos as one of its constituents.

Ground Support Equipment. Redesigned ground support equipment (1) minimized the case distortion during handling at the launch site, (2) improved the segment tang and clevis joint measurement system for more accurate reading of case diameters to facilitate stacking, (3) minimized the risk of O-ring damage during joint mating, and (4) improved leak testing of the igniter, case, and nozzle field joints. A ground support equipment assembly aid guided the segment tang into the clevis and rounded the two parts with each other. Other ground support equipment modifications included transportation monitoring equipment and the lifting beam.

Testing. Tests of the redesigned motor were carried out in a horizontal attitude, providing a more accurate simulation of actual conditions of the field joint that failed during the STS 51-L mission. In conjunction with the horizontal attitude for the RSRM full-scale testing, NASA incorporated externally applied loads. Morton Thiokol constructed a second horizontal test stand for certification of the redesigned SRM. The contractor used this new stand to simulate environmental stresses, loads, and temperatures experienced during an actual Space Shuttle launch and ascent. The new test stand also provided redundancy for the original stand.

The testing program included five full-scale firings of the RSRM prior to STS-26 to verify the RSRM performance. These included two development motor tests, two qualification motor tests, and a production verification motor test. The production verification motor test in August 1988 intentionally introduced severe artificial flaws into the test motor to make sure that the redundant safety features implemented during the redesign effort worked as planned. Laboratory and component tests were used to determine component properties and characteristics. Subscale motor tests simulated gas dynamics and thermal conditions for components and subsystem design. Simulator tests, consisting of motors using full-size flight-type segments, verified joint design under full flight loads, pressure, and temperature.

Full-scale tests verified analytical models and determined hardware assembly characteristics; joint deflection characteristics; joint performance under short duration, hot-gas tests, including joint flaws and flight loads; and redesigned hardware structural characteristics. Table 2–30 lists the events involved in the redesign of the SRB and SRM as well as earlier events in their development.[19]

Upper Stages

The upper stages boost payloads from the Space Shuttle's parking orbit or low-Earth orbit to geostationary-transfer orbit or geosynchronous orbit. They are also used on ELV missions to boost payloads from an early stage of the orbit maneuver into geostationary-transfer orbit or geosynchronous orbit. The development of the upper stages used by NASA began prior to 1979 and continued throughout the 1980s (Table 2–31).

The upper stages could be grouped into three categories, according to their weight delivery capacity:

- Low capacity: 453- to 1,360-kilogram capacity to geosynchronous orbit

[19]See Ezell, *NASA Historical Data Book, Volume III,* for earlier events in SRB development.

- Medium capacity: 1,360- to 3,175-kilogram capacity to geosynchronous orbit
- High capacity: 3,175- to 5,443-kilogram capacity to geosynchronous orbit

Inertial Upper Stages

DOD designed and developed the Inertial Upper Stage (IUS) medium-capacity system for integration with both the Space Shuttle and Titan launch vehicle. It was used to deliver spacecraft into a wide range of Earth orbits beyond the Space Shuttle's capability. When used with the Shuttle, the solid-propellant IUS and its payload were deployed from the orbiter in low-Earth orbit. The IUS was then ignited to boost its payload to a higher energy orbit. NASA used a two-stage configuration of the IUS primarily to achieve geosynchronous orbit and a three-stage version for planetary orbits.

The IUS was 5.18 meters long and 2.8 meters in diameter and weighed approximately 14,772 kilograms. It consisted of an aft skirt, an aft stage SRM with 9,707 kilograms of solid propellant generating 202,828.8 newtons of thrust, an interstage, a forward stage SRM with 2,727.3 kilograms of propellant generating 82,288 newtons of thrust and using an extendible exit cone, and an equipment support section. The equipment support section contained the avionics that provided guidance, navigation, telemetry, command and data management, reaction control, and electrical power. All mission-critical components of the avionics system and thrust vector actuators, reaction control thrusters, motor igniter, and pyrotechnic stage separation equipment were redundant to ensure better than 98-percent reliability (Figure 2–15).

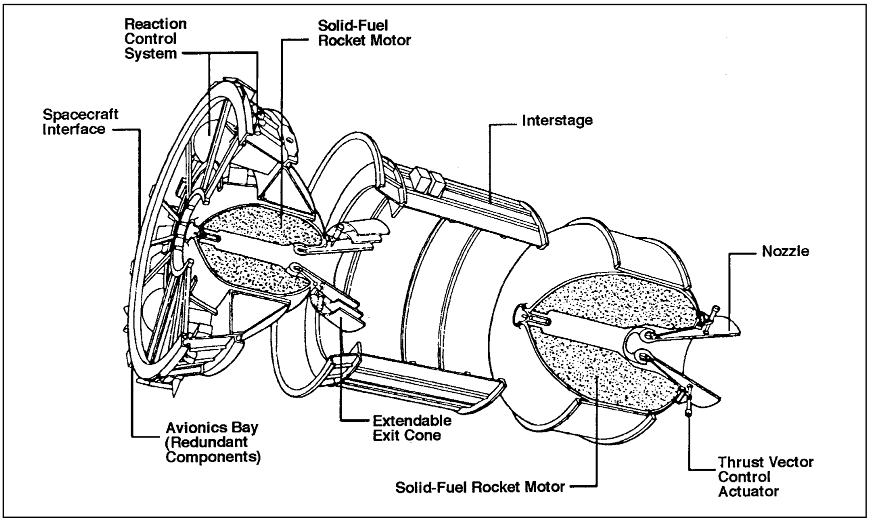

Figure 2–15. Inertial Upper Stage

The spacecraft was attached to the IUS at a maximum of eight attachment points. These points provided substantial load-carrying capability while minimizing thermal transfer. Several IUS interface connectors provided power and data transmission to the spacecraft. Access to these connectors could be provided on the spacecraft side of the interface plane or through the access door on the IUS equipment bay.

The IUS provided a multilayer insulation blanket of aluminized Kapton with polyester net spacers and an aluminized beta cloth outer layer across the IUS and spacecraft interface. All IUS thermal blankets vented toward and into the IUS cavity. All gases within the IUS cavity vented to the orbiter payload bay. There was no gas flow between the spacecraft and the IUS. The thermal blankets were grounded to the IUS structure to prevent electrostatic charge buildup.

Beginning with STS-26, the IUS incorporated a number of advanced features. It had the first completely redundant avionics system developed for an uncrewed space vehicle. This system could correct in-flight features within milliseconds. Other advanced features included a carbon composite nozzle throat that made possible the high-temperature, long-duration firing of the IUS motor and a redundant computer system in which the second computer could take over functions from the primary computer, if necessary.

Payload Assist Module

The Payload Assist Module (PAM), which was originally called the Spinning Stage Upper Stage, was developed by McDonnell Douglas at its own expense for launching smaller spacecraft to geostationary-transfer orbit. It was designed as a higher altitude booster of satellites deployed in near-Earth orbit but operationally destined for higher altitudes. The PAM-D could launch satellites weighing up to 1,247 kilograms. It was originally configured for satellites that used the Delta ELV but was used on both ELVs and the Space Shuttle. The PAM-DII (used on STS 61-B and STS 61-C) could launch satellites weighing up to 1,882 kilograms. A third PAM, the PAM-A, had been intended for satellites weighing up to 1,995 kilograms and was configured for missions using the Atlas-Centaur. NASA halted its development in 1982, pending definition of spacecraft needs. Commercial users acquired the PAM-D and PAM-DII directly from the manufacturer.

The PAM consisted of a deployable (expendable) stage and reusable airborne support equipment. The deployable stage consisted of a spin-stabilized SRM, a payload attach fitting to mate with the unmanned spacecraft, and the necessary timing, sequencing, power, and control assemblies.

The PAM's airborne support equipment consisted of the reusable hardware elements required to mount, support, control, monitor, protect, and operate the PAM's expendable hardware and untended spacecraft from liftoff to deployment from the Space Shuttle or ELV. It also provided these functions for the safing and return of the stage and spacecraft in case of an aborted mission. The airborne support equipment was designed to be as self-contained as possible. The major airborne support equipment elements included the cradle for structural mounting and support, the spin table and drive system, the avionics system to control and monitor the airborne support equipment and the PAM vehicle, and the thermal control system.

The PAM stages were supported through the spin table at the base of the motor and through restraints at the PAF. The forward restraints were retracted before deployment. The sunshield of the PAM-D and DII provided thermal protection of the PAM/untended spacecraft when the Space Shuttle orbiter payload bay doors were open on orbit.

Transfer Orbit Stage

The development of the Transfer Orbit Stage (TOS) began in April 1983 when NASA signed a Space System Development Agreement with Orbital Sciences Corporation (OSC) to develop a new upper stage. Under the agreement, OSC provided technical direction, systems engineering, mission integration, and program management of the design, production, and testing of the TOS. NASA, with participation by the Johnson and Kennedy Space Centers, provided technical assistance during TOS development and agreed to provide technical monitoring and advice during TOS development and operations to assure its acceptability for use with major national launch systems, including the STS and Titan vehicles. NASA also established a TOS Program Office at the Marshall Space Flight Center. OSC provided all funding for the development and manufacturing of TOS (Figure 2–16).

In June 1985, Marshall awarded a 16-month contract to OSC for a laser initial navigation system (LINS) developed for the TOS. Marshall would use the LINS for guidance system research, testing, and other purposes related to the TOS program.

Production of the TOS began in mid-1986. It was scheduled to be used on the Advanced Communications Technology Satellite (ACTS) and the Planetary Observer series of scientific exploration spacecraft, beginning with the Mars Observer mission in the early 1990s.

The TOS could place 2,490 to 6,080 kilograms payloads into geostationary-transfer orbit from the STS and up to 5,227 kilograms from the Titan III and IV and could also deliver spacecraft to planetary and other high-energy trajectories. The TOS allowed smaller satellites to be placed into geostationary-transfer orbit in groups of

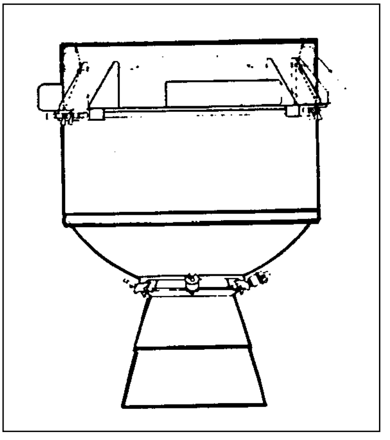

Figure 2–16.
Transfer Orbit Stage

two or three. Two payloads of the Atlas class (1,136 kilograms) or three payloads of the Delta class (636 kilograms) could be launched on a single TOS mission. Besides delivery of commercial communications satellites, its primary market, the TOS would be used for NASA and DOD missions.

The TOS system consisted of flight vehicle hardware and software and associated airborne and ground support equipment required for buildup. Table 3–32 lists its characteristics. Performance capabilities of the TOS included:

- Earth escape transfer capability
- Geosynchronous transfer orbit capability
- Orbit inclination change capability
- Low-altitude transfer capability
- Intermediate transfer orbit capability
- De-orbit maneuver
- Satellite repair and retrieval

Apogee and Maneuvering System

The liquid bipropellant Apogee and Maneuvering System (AMS) was designed to be used both with and independently of the TOS. The AMS would boost the spacecraft into a circular orbit and allow on-orbit maneuvering. Martin Marietta Denver Aerospace worked to develop the AMS with Rockwell International's Rocketdyne Division, providing the AMS RS-51 bipropellant rocket engine, and Honeywell, Inc., supplied the TOS/AMS LINS avionics system.

When it became operational, the TOS/AMS combination would deliver up to approximately 2,950 kilograms into geosynchronous orbit from the orbiter's parking orbit into final geosynchronous orbit. The TOS/AMS would have a delivery capability 30 percent greater than the IUS and would reduce stage and STS user costs. The main propulsion, reaction control, avionics, and airborne support equipment systems would be essentially the same as those used on the TOS. In particular, the avionics would be based on a redundant, fault-tolerant LINS.

Operating alone, the AMS would be able to place communications satellites weighing up to approximately 2,500 kilograms into geostationary-transfer orbit after deployment in the standard Space Shuttle parking orbit. Other missions would include low-orbit maneuvering between the Shuttle and the planned space station, delivery of payloads to Sun-synchronous and polar orbits, and military on-demand maneuvering capability. The AMS was planned to be available for launch in early 1989 and would provide an alternative to the PAM-DII.

The avionics, reaction control system, and airborne support equipment designs of the AMS would use most of the standard TOS components. Main propulsion would be provided by the 2,650-pound thrust Rocketdyne RS-51 engine. This engine was restartable and operable over extended periods. A low-thrust engine option that provided 400 pounds of thrust would also be available for the AMS.

Centaur Upper Stage

NASA studied and began production in the early 1980s of a modified Centaur upper stage for use with the STS for planetary and heavier geosynchronous mission applications. The proposed modifications would increase the size of the propellant tanks to add about 50 percent more propellant capacity and make the stage compatible with the Space Shuttle. This wide-body version would use the same propulsion system and about 85 percent of the existing Centaur's avionics systems. Contracts were negotiated with General Dynamics, Honeywell, Pratt & Whitney, and Teledyne for the design, development, and procurement of Centaur upper stages for the Galileo and International Solar Polar missions that were scheduled for 1986.

However, following the *Challenger* accident, NASA determined that even with modifications, the Centaur could not comply with necessary safety requirements for use on the Shuttle. The Centaur upper stage initiative was then dropped.

Advanced Programs

Advanced programs focused on future space transportation activities, including improving space transportation operations through the introduction of more advanced technologies and processes, and on servicing and protecting U.S. space assets. The following sections describe NASA's major advanced program initiatives. Several of the efforts progressed from advanced program status to operational status during this decade.

Orbital Transfer Vehicle

NASA's Advanced Planning/Programs Division of the Office of Space Transportation identified the need for an Orbital Transfer Vehicle (OTV) in the early 1980s, when it became obvious that a way was needed to transport payloads from the Space Shuttle's low-Earth orbit to a higher orbit and to retrieve and return payloads to the Shuttle or future space station. The Marshall Space Flight Center was designated as the lead center for the development effort, and the Lewis Research Center led the propulsion system studies. An untended OTV was proposed for a first flight in the early 1990s.

NASA believed that the use of aerobraking was necessary to make the OTV affordable. Studies beginning in 1981 conducted at Marshall by definition phase contractors Boeing Aerospace Company and General Electric Reentry Systems determined that aerodynamic braking was an efficient fuel-saving technique for the OTV, perhaps doubling payload capacity. This technique would use the Earth's atmosphere as a braking mechanism for return trips, possibly supplemented by the use of a ballute, an inflatable drag device. When the transfer vehicle passed through the atmosphere, the friction of the air against the vehicle would provide enough drag to slow the vehicle. Otherwise, a rocket engine firing would be required to brake the vehicle. Aeroassist braking would save one burn, and the extra fuel could be used to transport a larger payload to a high orbit. The aeroassisted braking could result in about a twofold increase in the amount of payload that could be ferried to high altitudes.

Boeing's studies emphasized low lifting-body designs—"low lift-to-drag ratio"—designs with a relatively low capability of lift to enable them to fly, but ones that weigh less. General Electric Reentry Systems focused on moderate lift-to-drag ratio designs—relatively moderate lift capability and somewhat heavier weight.

In 1981, NASA designated the Lewis Research Center the lead center for OTV propulsion technology. This program supported technology for three advanced engine concepts that were developed by Aerojet TechSystems, Pratt & Whitney, and Rocketdyne to satisfy a NASA-supplied set of goals. The proposed engines would be used to transfer loads—both personnel and cargo—between low-Earth orbit and geosynchronous orbit, and beyond. In addition, because OTVs would face requirements ranging from high-acceleration round-trip transfers for resupply to very low-acceleration one-way transfers of large, flexible structures, NASA investigated variable thrust propulsion systems, which would provide high performance over a broad throttling range.

In 1983, NASA chose the same three contractors to begin a program leading to the design, development, test, and engineering of the OTV. These contracts expired in 1986. NASA sponsored another competitive procurement to continue the OTV propulsion program. Funding was reduced, and only Rocketdyne and Aerojet continued the advanced engine technology development. Component testing began in 1988, and further investigations into aerobraking continued into the 1990s.

The OTV would be used primarily to place NASA, DOD, and commercial satellites and space platforms into geosynchronous orbit. The OTV could also deliver large payloads into other orbits and boost planetary exploration spacecraft into high-velocity orbits approaching their mission trajectory. The vehicle was expected to use liquid oxygen–liquid hydrogen propellants.

The OTV's reusable design provided for twenty flights before it had to be refurbished or replaced. Because of its reusability, the OTV would significantly reduce payload transportation costs.

At the same time, that Lewis was leading propulsion studies, Marshall initiated studies in 1984 to define OTV concepts and chose Boeing Aerospace and Martin Marietta to conduct the conceptual studies. The studies examined the possibilities of both a space-based and an Earth-based OTV. Both would initially be uncrewed upper stages. The ultimate goal, however, was to develop a crewed vehicle capable of ferrying a crew capsule to geosynchronous orbit. The vehicle would then return the crew and capsule for other missions. The development of a crew capsule for the OTV was planned for the 1990s.

The Space Shuttle would carry the Earth-based OTV into space. It would be launched from the Shuttle's payload bay or from an aft cargo carrier attached to the aft end of the Shuttle's external tank. The OTV would transfer payloads from a low orbit to a higher one. It would also retrieve payloads in high orbits and return them to the Shuttle. The OTV would then return to Earth in the Shuttle's payload bay. The OTV would separate from the Shuttle's external tank at about the same time that the payload was deployed from the orbiter's cargo bay. The two components would then join together and begin to travel to a higher orbit. This Earth-based OTV offered the advantage of performing vehicle maintenance and refueling on the ground with the help of gravity, ground facilities, and workers who do not have to wear spacesuits.

A space-based OTV would be based at the future space station. It would move payloads into higher orbit from the space station and then return to its home there. It would be refueled and maintained at the space station. Studies showed cost savings for space-based OTVs. This type of OTV could be assembled in orbit rather than on the ground so it could be larger than a ground-based unit and capable of carrying more payload. Initial studies of an OTV that would be based at the space station were completed in 1985.

A single-stage OTV could boost payloads of up to 7,272 kilograms to high-Earth or geosynchronous orbit. A multistage OTV could provide up to 36,363 kilograms to lunar orbit with 6,818.2 kilograms returned to low-Earth orbit. After completing its delivery or servicing mission, the OTV would use its rocket engines to start a descent. Skimming through the thin upper atmosphere (above sixty kilometers), the OTV's aerobrake would slow the OTV without consuming extra propellant. Then, because of orbital dynamics, the OTV would navigate back to a low-Earth orbit. When the OTV reached the desired orbital altitude, its rocket engines would again fire, circularizing its orbit until it was retrieved by the Space Shuttle or an orbital maneuvering vehicle (OMV) dispatched from the space station.

NASA Administrator James M. Beggs stated in June 1985 that the OTV would complement the proposed OMV. The OTV would transport payloads from low-Earth orbit to destinations much higher than the OMV could reach. The majority of the payloads transported by the OTV would be delivered to geostationary orbit. Beggs envisioned that most OTVs would be based at the space station, where they would be maintained, fueled, and joined to payloads. In time, the OTV would also be used to transport people to geostationary orbit.

Orbital Maneuvering Vehicle

The OMV (Figure 2–17) was designed to aid satellite servicing and retrieval. This uncrewed vehicle could be characterized as a "space tug," which would move satellites and other orbiting objects from place to

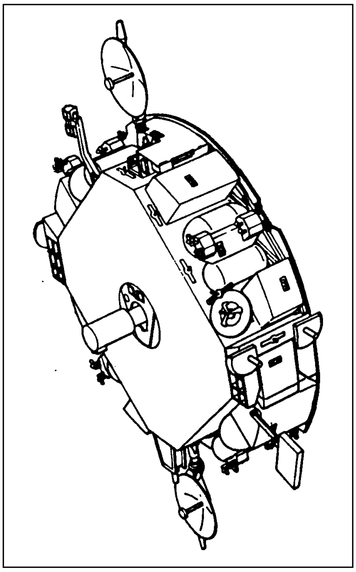

Figure 2–17.
Orbital Maneuvering Vehicle

place above the Earth. A reusable, remotely operated unmanned propulsive vehicle to increase the range of the STS, the OMV was designed to be used primarily for spacecraft delivery, retrieval, boost, deboost, and close proximity visual observation beyond the operating range of the Space Shuttle. The vehicle would extend the reach of the Shuttle up to approximately 2,400 kilometers.

Concept definition studies were completed in 1983, and development began toward a flight demonstration of the ability to refuel propellant tanks of an orbiting satellite. In 1984, an in-flight demonstration of hydrazine fuel transfer took place successfully on STS 41-G. System definition studies were completed in 1985, and in June 1986, TRW was selected by NASA for negotiations leading to the award of a contract to develop the OMV. The Preliminary Requirements Review took place in 1987, and the Preliminary Design Review was held in 1988, with the Marshall Space Flight Center managing the effort.

NASA planned for the OMV to be available for its first mission in 1993, when it would be remotely controlled from Earth. In the early years of use, NASA envisioned that the OMV would be deployed from the Space Shuttle for each short-duration mission and returned to Earth for servicing. Later, the vehicle would be left parked in orbit for extended periods, for use with both the Shuttle and the space station. However, the OMV was the victim of budget cuts, and the contract with TRW was canceled in June 1990.

Tethered Satellite System

The Tethered Satellite System (TSS) program was a cooperative effort between the government of Italy and NASA to provide the capability to perform science in areas of space outside the reach of the Space Shuttle. The TSS would enable scientists to conduct experiments in the upper atmosphere and ionosphere while tethered to the Space Shuttle as its operating base. The system consisted of a satellite anchored to the Space Shuttle by a tether up to 100 kilometers long. (Tethers are long, superstrong tow lines joining orbiting objects together.)

The advanced development stage of the program was completed in 1983, and management for the TSS moved to the Space Transportation and Capability Development Division. In 1984, a study and laboratory program was initiated to define and evaluate several applications of tethers in space. Possible applications included power generation, orbit raising in the absence of propellants, artificial gravity, and space vehicle constellations. In 1986, the Critical Design and Manufacturing Reviews were conducted on the satellite and the deployer. In 1988, manufacture and qualification of the flight subsystems continued. The twelve-meter deployer boom, reel motor, and on-board computer were all qualified and delivered. Also, manufacture of the deployer structure was initiated, and the tether control mechanisms were functionally tested. A test program was completed for the satellite structural and engineering models. The flight satellite structure was due for delivery in early 1989. The development of the scientific instruments continued, with delivery of flight satellite instruments scheduled for early 1989. The first TSS mission was scheduled for 1991.

Advanced Launch System

The Advanced Launch System, a joint NASA-DOD effort, was a systems definition and technology advanced development program aimed at defining a new family of launchers for use after 2000, including a new heavy-lift vehicle. President Reagan signed a report to Congress in January 1988 that officially created the program. Within this DOD-funded program, NASA managed the liquid engine system and advanced development efforts.

Next Manned Launch Vehicle

In 1988, attention was focused on examining various next-generation manned launch vehicle concepts. Three possible directions were considered: Space Shuttle evolution, a personnel launch system, and an advanced manned launch system. The evolution concept referred to the option of improving the current Shuttle design through the incorporation of upgraded technologies and capabilities. The personnel launch system would be a people carrier and have no capability to launch payloads into space. The advanced manned launch system represented an innovative crewed transportation system. Preliminary studies on all three possibilities progressed during 1988.

Shuttle-C

Shuttle-C (cargo) was a concept for a large, uncrewed launch vehicle that would make maximum use of existing Space Shuttle systems with a cargo canister in place of the orbiter. This proposed cargo-carrying launch vehicle would be able to lift 45,454.5 to 68,181.8 kilograms to low-Earth orbit. This payload capacity is two to three times greater than the Space Shuttle payload capability.

In October 1987, NASA selected three contractors to perform the first of a two-phase systems definition study for Shuttle-C. The efforts focused on vehicle configuration details, including the cargo element's length and diameter, the number of liquid-fueled main engines, and an operations concept evaluation that included ground and flight support systems. A major purpose of the study was to determine whether Shuttle-C would be cost effective in supporting the space station. Using Shuttle-C could free the Space Shuttle for STS-unique missions, such as solar system exploration, astronomy, life sciences, space station crew rotation, and logistics and materials processing experiments. Shuttle-C also would be used to launch planetary missions and serve as a test bed for new Shuttle boosters.

The results of the Shuttle-C efforts were to be coordinated with other ongoing advanced launch systems studies to enable a joint steering group, composed of DOD and NASA senior managers. The purpose of the steering group was to formulate a national heavy-lift vehicle strategy that best accommodated both near-term requirements and longer term objectives for reducing space transportation operational costs.

Advanced Upper Stages

Advanced missions in the future would require even greater capabilities to move from low- to high-Earth orbit and beyond. During 1988, activity in the advanced upper stages area focused on the space transfer vehicle (STV) and the possibility of upgrading the existing Centaur upper stage. The STV concept involved a cryogenic hydrogen-oxygen vehicle that could transport payloads weighing from 909.1 to 8,636 kilograms from low-Earth orbit to geosynchronous orbit or the lunar surface, as well as for unmanned planetary missions. The STV concept could potentially lead to a vehicle capable of supporting human exploration missions to the Moon or Mars.

Advanced Solid Rocket Motor

The Advanced Solid Rocket Motor (ASRM) was an STS improvement intended to replace the RSRM that was used on STS-26. The ASRM would be based on a better design than the former rocket motor, contain more reliable safety margins, and use automated manufacturing techniques. The ASRM would also enhance Space Shuttle performance by offering a potential increase of payload mass to orbit from 5454.5 kilograms to 9090.9 kilograms for the Shuttle. In addition, a new study on liquid rocket boosters was conducted that examined the feasibility of replacing SRMs with liquid engines.

In March 1988, NASA submitted the "Space Shuttle Advanced Solid Rocket Motor Acquisition Plan" to Congress. This plan reviewed procurement strategy for the ASRM and discussed implementation plans and schedules. Facilities in Mississippi would be used for production and testing of the new rocket motor. In August 1988, NASA issued an request for proposals to design, develop, test, and evaluate the ASRM. Contract award was anticipated for early 1989, and the first flight using the new motor was targeted for 1994.

Table 2–1. Appropriated Budget by Launch Vehicle and Launch-Related Component (in thousands of dollars)

Vehicle/Year	1979	Supp. Appr.	1980	Supp. Appr.	1981	1982	1983
Atlas E/F	—		*a*		—	—	—
Atlas Centaur	*b*		*c*		5,600	—	—
Delta	*b*		*d*		47,900	30,400	42,800
Scout	*b*		*e*		900	800	—
Space Shuttle Main Engine (SSME) Design, Development, Test, and Evaluation (DDTE)	*b*	*f*	*g*	*h*	145,700	127,000	262,000
SSME Production	*b*	*f*	*g*	*h*	121,500	105,000	—
Solid Rocket Booster (SRB)	*b*	*i*	*j*	*h*	14,000	17,000	*k*
External Tank	*b*	*l*	*m*	*h*	48,000	25,000	*n*
STS Upper Stages (STS Operations Capability Development)	*b*	—	*o*	—	29,000	75,000 *p*	*q*
Upper Stages Operations (STS Operations)	*b*	—	*o*	—	30,900	40,000 *p*	—
Orbital Maneuvering Vehicle	Program did not begin until 1983 when it was incorporated into Advanced Programs.						*r*
Tethered Satellite System	Program did not begin until 1982 when it was incorporated into Advanced Programs.					*r*	*r*
Advanced Programs	*b*	—	*s*	—	*t*	8,800	11,900

Table 2–1 continued

Vehicle/Year	1984	1985	Supp. Appr.	1986	1987	1988
Atlas E/F	*u*	*v*	—	*v*	*v*	—
Atlas Centaur	*u*	*v*	—	*v*	*v*	—
Delta	*u*	*v*	—	*v*	*v*	28,000
Scout	*u*	*v*	—	*v*	*v*	—
SSME	*w*	*x*	—	*y*	*z*	*aa*
SRB (Propulsion System)	*w*	*x*	—	*y*	*z*	*aa*
Solid Rocket Booster (Flight Hardware)	*w*	*x*		*y*	*z*	
External Tank (Propulsion System)	*w*	*x*	—	*y*	*z*	*z*
External Tank (Flight Hardware)	*w*			*y*	*z*	*aa*
Upper Stages	143,200 *bb*	92,400	40,000	122,000	202,100	159,700
Orbital Maneuvering Vehicle	*r*	*r*	—	10,000	45,000	55,000
Tethered Satellite System	3,300	18,200	—	10,000	10,600	7,300
Advanced Programs	15,000	20,500	—	21,000	16,600	30,900

a Undistributed. Only total 1980 R&D appropriation specified: $4,091,086,000. (Authorization for Atlas F = $2,000,000.)
b Undistributed. Total 1979 R&D appropriation = $3,477,200,000.
c Undistributed. Only total 1980 R&D appropriation specified: $4,091,086,000. (Authorization for Atlas Centaur = $18,300,000.)
d Undistributed. Only total 1980 R&D appropriation specified: $4,091,086,000. (Authorization for Delta = $43,100,000.)
e Undistributed. Only total 1980 R&D appropriation specified: $4,091,086,000. (Authorization for Scout = $7,300,000
f Supplemental appropriation specified for overall R&D activities = $185,000,000. (Authorization for SSME = $48,000,000.)
g Undistributed. Only total 1980 R&D appropriation specified: $4,091,086,000. (Authorization for SSME DDT&E = $140,600,000; production = $109,000,000.)
h Undistributed. Total Space Shuttle supplemental appropriation = $285,000,000. No specific Shuttle elements listed.

Table 2–1 continued

i Supplemental appropriation specified for overall R&D activities = $185,000,000. (Authorization for SRB = $36,700,000.)

j Undistributed. Only total 1980 R&D appropriation specified: $4,091,086,000. (Authorization for SRB = $57,500,000.)

k No budget item listed. Supporting committee documentation includes SRB in Space Shuttle Production category with no amount specified. Total Production appropriation = $1,636,600,000.

l Supplemental appropriation specified for overall R&D activities = $185,000,000. (Authorization for external tank = $27,100,000.)

m Undistributed. Only total 1980 R&D appropriation specified: $4,091,086,000. (Authorization for external tank = $68,400,000.)

n No budget item listed. Supporting committee documentation includes external tank in Space Shuttle Production category with no amount specified. Total Production appropriation = $1,636,600,000.

o No specific funding.

p Included in narrative for Public Law 97–101, December 23, 1981, 97th Cong.

q Includes $140,000,000 for Centaur upper stage development (from Appropriations Conference Report to accompany H.R. 6956). Total Space Flight Operations appropriation = $1,796,000,000.

r Included in Advanced Planning/Programs.

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

t Undistributed. Included in R&D appropriation of $4,396,200 (modified by General Provision, Sec. 412, to $4,340,788).

u No budget submission, authorization, or appropriation for specific expendable launch vehicles (ELVs). Total undistributed ELV submission = $50,000,000; authorization = $50,000,000; and appropriation = $50,000,000. ELV appropriation removed from R&D and placed in Space Flight, Control & Data Communications (SFC&DC) (Office of Space Transportation Systems) appropriation. NASA Budget Estimate for FY 1984 shows $50,000,000 for Delta ($0 for Scout) but specific appropriation for Delta not confirmed by congressional committee documentation.

v FY 1985–1987—no appropriation for ELVs. All ELV costs would be completely funded on a reimbursable basis.

w No specific appropriation for SSME, external tank, or SRB. Appropriation for Space Shuttle activities of $1,545,000,000 moved from R&D to SFC&DC. Amount of $427,400,000 remained in R&D for upper stages, Spacelab, engineering and technology base, planetary operations and support equipment, Advanced Programs, Tethered Satellite System, and Teleoperator Maneuvering System. NASA Budget Estimate documents indicate estimated amount of $280,700,000 for SSME, $108,400,000 for SRB, and $83,100,000 for external tank under Propulsion Systems/Shuttle Production and Capability Development category. According to NASA Budget Estimate documents, the Shuttle Production and Capability Development /Propulsion Systems "provides for the production of the Space Shuttle's main engines and the development of the capability to support operational requirements established for the main engine, solid rocket booster, and external tank." Congressional documents also state that the category includes continuing "capability development tasks for the orbiter, main engine, external tank, and SRB, . . ." and "the development of the filament wound case (FWC) SRB." Some launch system–related appropriated funding is included in the Flight Hardware/Shuttle Operations category (also in SFC&DC) undistributed, included in Shuttle Operations appropriation = $1,520,600,000. NASA Budget Estimate documents indicate estimated amount of $336,200,000 for external tank and $353,200,000 for SRB under Flight Hardware/Shuttle Operations category.

Table 2–1 continued

x Production and residual development tasks for the orbiter, SSME, external tank, and SRB fall under Space Production and Operational Capability, Propulsion Systems. SRBs and external tank procurement (production) falls under Space Transportation Operations, Flight Hardware. No breakdown is provided for individual Space Shuttle propulsion components. The 1985 appropriation for Propulsion Systems = $599,000,000; Flight Hardware appropriation = $758,000,000.

y No breakdown for individual Space Shuttle propulsion components. The 1986 appropriation for Propulsion Systems = $454,000,000; no Flight Hardware appropriation in 1986.

z No breakdown for individual Space Shuttle propulsion components. The 1987 appropriation for Propulsion Systems = $338,400,000; appropriation for Flight Hardware = $646,200,000.

aa No breakdown for individual Space Shuttle propulsion components. The 1988 appropriation for Propulsion Systems = $249,300,000; appropriation for Flight Hardware = $923,100,000.

bb Includes funding for modification of the Centaur for use in the Shuttle.

Source: NASA Chronological History Fiscal Years 1979–1983 Budget Submissions.

Table 2–2. Atlas E/F Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1980	2,000[a]	2,000	[b]	1,200
1981	No direct funds authorized or appropriated; no proposed use of Atlas E/F after 1980 by NASA			—
1982	No budget line item			—
1983	Reimbursable only			—
1984	No budget line item for specific ELVs [c]			—
1985 [d]	There were no direct appropriated fund requirements for the			—
1986 [e]	ELV program. DOD and NOAA continued to use the Delta,			—
1987 [f]	Scout, Atlas, and Atlas—Centaur ELVs on a fully reimbursable basis.			—
1988	Atlas E/F not in use by NASA			—

a Atlas F only.

b Undistributed. Included in 1980 R&D appropriation of $4,091,086,000.

c No budget submission, authorization, or appropriation for specific ELVs. Total undistributed ELV submission = $50,000,000; authorization = $50,000,000; and appropriation = $50,000,000. ELV appropriation removed from R&D and placed in Space Flight, Control & Data Communications (SFC&DC) (Office of Space Transportation Systems) appropriation.

d No budget line item for ELVs. Support for ELVs paid for as part of Space Transportation Operations Program. Budget data for Space Transportation Operations Program found in Chapter 3 budget tables.

e No budget line item for ELVs. Support for ELVs paid for as part of Space Transportation Operations Program. Budget data for Space Transportation Operations Program found in Chapter 3 budget tables.

f Included in Flight Hardware category. Budget data for Flight Hardware found in Chapter 3 budget tables.

Table 2–3. Atlas-Centaur Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	21,500	*a*	*b*	17,320
1980	18,300	18,300	*c*	18,000
1981	5,600	5,600	5,600	5,600 *d*
1982		Reimbursable only		—
1983		Reimbursable only		—
1984		No budget line item for specific ELVs *e*		—
1985 *f*		There were no direct appropriated fund requirements for the,		—
1986 *g*		ELV program. DOD and NOAA continued to use the Delta		—
1987 *h*		Scout, Atlas, and Atlas-Centaur ELVs on a fully reimbursable basis.		—
1988		Atlas-Centaur not in use by NASA		—

a Not distributed by vehicle—total 1979 ELV authorization = $74,000,000.

b Not distributed by vehicle—1979 R&D appropriation = $3,477,200,000.

c Undistributed. Included in R&D appropriation of $4,091,086,000.

d Based on anticipated closeout of the NASA program by the end of 1981.

e No budget submission, authorization, or appropriation for specific ELVs. Total undistributed ELV submission = $50,000,000; authorization = $50,000,000; and appropriation = $50,000,000. ELV appropriation removed from R&D and placed in Space Flight, Control & Data Communications (SFC&DC) (Office of Space Transportation Systems) appropriation.

f No budget line item for ELVs. Support for ELVs paid for as part of Space Transportation Operations Program. Budget data for Space Transportation Operations Program found in Chapter 3 budget tables.

g No budget line item for ELVs. Support for ELVs paid for as part of Space Transportation Operations Program. Budget data for Space Transportation Operations Program found in Chapter 3 budget tables.

h Included in Flight Hardware category. Budget data for Flight Hardware found in Chapter 3 budget tables.

Table 2–4. Delta Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	38,600	*a*	*b*	45,680
1980	43,100	43,100	*c*	43,100
1981	47,900	47,900	47,900	47,900
1982	30,400	30,400	30,400	30,400
1983	42,800	42,800	42,800	83,000
1984		No budget line item for specific ELVs *d*		50,000 *e*
1985 *f*		No budget line item for ELVs		—
1986 *g*		No budget line item for ELVs		—
1987 *h*		No budget line item for ELVs		—
1988	28,000 *i*	60,000 *i*	28,000 *i*	28,000 *i*

a Not distributed by vehicle—total 1979 ELV authorization = $74,000,000.

b Not distributed by vehicle—1979 R&D appropriation = $3,477,200,000.

c Undistributed. Included in R&D appropriation of $4,091,086,000.

d No budget submission, authorization, or appropriation for specific ELVs. Total undistributed ELV submission = $50,000,000; authorization = $50,000,000; and appropriation = $50,000,000. ELV appropriation removed from R&D and placed in SFC&DC (Office of Space Transportation Systems) appropriation. Congressional supporting documentation indicates that $50,000,000 is for "continued procurement of the Delta ELVs in FY 1984."

e NASA budget summary data do not specifically indicate that programmed amount was for the Delta. However, the narrative that accompanies congressional committee reports describes programs that use the Delta as the launch vehicle.

f No budget line item for ELVs. Support for ELVs paid for as part of Space Transportation Operations Program. It was anticipated that the NASA ELV program would be completely funded on a reimbursable basis in 1985.

g No budget line item for ELVs. Support for ELVs paid for as part of Space Transportation Operations Program. It was anticipated that the NASA ELV program would be completely funded on a reimbursable basis in 1986.

h Included in Flight Hardware category. It was anticipated that the NASA ELV program would be completely funded on a reimbursable basis in 1987.

i Vehicle not specified in budget figures but indicated in supporting congressional committee documentation, which specifies two Delta II vehicles for 1990 and 1991 launches.

Table 2–5. Scout Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	16,400	*a*	*b*	10,600
1980	7,300	7,300	*c*	5,100
1981	2,200	2,200	900 *d*	900
1982	800	800	800	800
1983	No budget line item (Scout not in use by NASA after 1982)			—

a Not distributed by vehicle—total 1979 ELV authorization = $74,000,000.

b Not distributed by vehicle—1979 R&D appropriation = $3,477,200,000.

c Undistributed. Included in R&D appropriation of $4,091,086,000.

d Basic appropriation of $2,200,000. Effect of General Provision, Sec. 412 (Public Law 96–526), reduced funding level to $900,000.

e No budget submission, authorization, or appropriation for specific ELVs. Total undistributed ELV submission = $50,000,000; authorization = $50,000,000; and appropriation = $50,000,000. ELV appropriation removed from R&D and placed in Space Flight, Control & Data Communications (SFC&DC) (Office of Space Transportation Systems) appropriation.

f No budget line item for ELVs. Support for ELVs paid for as part of Space Transportation Operations Program. It was anticipated that the NASA ELV program would be completely funded on a reimbursable basis in 1985.

g No budget line item for ELVs. Support for ELVs paid for as part of Space Transportation Operations Program. It was anticipated that the NASA ELV program would be completely funded on a reimbursable basis in 1986.

h Included in Flight Hardware category. It was anticipated that the NASA ELV program would be completely funded on a reimbursable basis in 1987.

Table 2–6. Space Shuttle Main Engine Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979 DDT&E	176,700	176,700	*a*	172,700
Production	18,000	*b*	*a*	264,500
Suppl. Appropriation	*c*	48,000 *d*	*e*	
1980 DDT&E	140,600	140,600	*f*	140,600
Production	109,900	109,900	*f*	123,600
Suppl. Appropriation *g*				
1981 DDT&E	145,700	145,700	145,700	134,000
Production	121,500	121,500	121,500	779,000
1982 DDT&E	127,000	127,000	127,000	*h*
Production	105,000	105,000	105,000	163,300
1983	262,000	262,000	262,000	355,700
1984	*i*	*i*	*i*	418,100
1985	*j*	*i*	*i*	419,000
1986	*k*	*k*	*k*	394,400
1987	*l*	*l*	*l*	432,700
1988	*m*	*m*	*m*	395,900

a Not distributed by element/vehicle—1979 R&D appropriation = $3,477,200,000.
b No SSME Production category broken out. Total Production amount = $458,000,000.
c No breakout of Supplemental Appropriation submission; included in general R&D supplemental appropriation submission.
d Breakdown of supplemental authorization not provided in budget request or public law. Breakdown provided in supporting documentation for authorization only.
e Supplemental appropriation specified for overall R&D activities = $185,000,000.
f Undistributed. Included in R&D appropriation of $4,091,086,000.
g Supplemental appropriation for Space Shuttle in response to amended NASA budget submission of $300,000,000. No authorization activity. Supplemental appropriation of $285,000,000 approved with no distribution to individual components.
h Programmed amount for SSME DDT&E in 1982 not indicated.

Table 2–6 continued

i No specific authorization for SSME, external tank, or SRB. According to congressional reports, the Space Transportation and Capability Development program supported the production of the SSME, SRB, and external tank, in addition to providing for critical spares (as well as other items). The total authorization for this category = $2,009,400,000. Category also included continuing "capability development tasks for the orbiter, main engine, external tank, and SRB, . . ." and "the development of the filament wound case (FWC) SRB." Appropriation for Space Shuttle activities of $1,545,000,000 moved from R&D to SFC&DC. Some Space Shuttle funding was included in the Flight Hardware category: submission = $848,400,000; authorization undistributed, included in Shuttle Operations authorization = $1,495,600,000; and appropriation (moved to SFC&DC) undistributed, included in Shuttle Operations appropriation = $1,520,600,000. Amount of $427,400,000 remained in R&D for other activities.

j SSME production and residual development tasks for the orbiter, SSME, external tank, and SRB fell under Space Production and Operational Capability, Propulsion Systems. SRBs and external tank procurement (production) fell under Space Transportation Operations, Flight Hardware. No breakdown for individual Space Shuttle propulsion components. The 1985 amounts for Propulsion Systems were: submission = $599,000,000; authorization = $599,000,000; and appropriation = $599,000,000. Flight Hardware submission = $758,000,000; authorization = $758,000,000; and appropriation = $758,000,000.

k No breakdown for individual Space Shuttle propulsion components. The 1986 amounts for Propulsion Systems were: submission = $454,000,000; authorization = $454,000,000; and appropriation = $454,000,000. No Flight Hardware budget category in 1986.

l No breakdown for individual Space Shuttle propulsion components. The 1987 amounts for Propulsion Systems were: submission = $338,400,000; authorization = $338,400,000; and appropriation = $338,400,000. Flight Hardware submission = $646,200,000; authorization = $879,100,000; and appropriation = $646,200,000.

m No breakdown for individual Space Shuttle propulsion components. The 1988 amounts for Propulsion Systems were: submission = $552,100,000; authorization = $552,100,000; and appropriation = $249,300,000. Flight Hardware submission = $923,100,000; authorization = $923,100,000; and appropriation = $923,100,000.

Table 2–7. Solid Rocket Boosters Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	63,500	63,500	*a*	115,400
Suppl. Appropriation	*b*	36,700 *c*	*d*	
1980	57,500	57,500	*e*	65,200
Suppl. Appropriation *f*	—	—	—	
1981	14,000	14,000	14,000	50,500
1982 Propulsion Systems *g*	17,000	17,000	17,000	22,000
Flight Hardware *g*				156,200
1983 Propulsion Systems *g*	*h*	*h*	*h*	102,300
Flight Hardware *g*				309,200
1984 Propulsion Systems	*i*	*i*	*i*	140,500
Flight Hardware	*i*	*i*	*i*	341,200
1985 Propulsion Systems	*j*	*j*	*j*	105,100
Flight Hardware	*j*	*j*	*j*	298,600
1986 Propulsion Systems	*k*	*k*	*k*	328,500
Flight Hardware	*k*	*k*	*k*	335,000
1987 Propulsion Systems	*l*	*l*	*l*	322,100
Flight Hardware	*l*	*l*	*l*	144,300
1988 Propulsion Systems	*m*	*m*	*m*	161,200
Flight Hardware	*m*	*m*	*m*	200,500

a Not distributed by element/vehicle—1979 R&D appropriation = $3,477,200,000.
b No breakout of Supplemental Appropriation submission; included in general R&D request of $185,000,000.
c Breakdown of supplemental authorization not provided in budget request or public law. Breakdown provided in supporting documentation for authorization only.
d Supplemental Appropriation for general R&D activities.
e Undistributed. Included in 1980 R&D appropriation of $4,091,086,000.

Table 2–7 continued

f Supplemental appropriation for Space Shuttle in response to amended NASA budget submission of $300,000,000. No authorization activity. Supplemental appropriation of $285,000,000 approved with no distribution to individual components.

g Propulsion Systems and Flight Hardware budget categories were not used in NASA's budget prior to 1984. However, programmed amounts used these categories to be consistent with categories used in estimates for the future years.

h No budget item listed. Supporting committee documentation included SRB in Space Shuttle Production category with no amount specified. Total Production amount: submission = $1,585,500,000; authorization = $1,670,500,000; and appropriation = $1,636,600,000.

i No specific authorization for SSME, external tank, or SRB. According to congressional reports, the Space Transportation and Capability Development program supported the production of the SSME, SRB, and external tank, in addition to providing for critical spares (as well as other items). The total authorization for this category = $2,009,400,000. Category also included continuing "capability development tasks for the orbiter, main engine, external tank, and SRB, . . ." and "the development of the filament wound case (FWC) SRB." Appropriation moved from R&D to SFC&DC = $1,545,000,000. Some Space Shuttle funding was included in the Flight Hardware category (see above for definition): submission = $848,400,000; authorization undistributed, included in Shuttle Operations authorization of $1,495,600,000; and appropriation (moved to SFC&DC) undistributed, included in Shuttle Operations appropriation = $1,520,600,000. Appropriation moved from R&D to SFC&DC = $1,545,000,000.

j SSME production and residual development tasks for the orbiter, SSME, external tank, and SRB fell under Space Production and Operational Capability, Propulsion Systems. SRB and external tank procurement (production) fell under Space Transportation Operations, Flight Hardware. No breakdown for individual Space Shuttle propulsion components. The 1985 amount for Propulsion Systems was: submission = $599,000,000; authorization = $599,000,000; and appropriation = $599,000,000. Authorization for submission = $758,000,000. Procurement of external tank, solid rocket motor, and SRB hardware included in Space Transportation Operations Program, Flight Hardware amount of $758,000,000; appropriation = $758,000,000. SSME production and residual development tasks for the orbiter, SSME, external tank, and SRB fall under Space Production and Operational Capability, Propulsion Systems. SRB and external tank procurement (production) fell under Space Transportation Operations, Flight Hardware. Flight Hardware submission = $758,000,000; authorization = $758,000,000; and appropriation = $758,000,000.

k No breakdown for individual Space Shuttle propulsion components. The 1986 amounts for Propulsion Systems were: submission = $454,000,000; authorization = $454,000,000; and appropriation = $454,000,000. No Flight Hardware budget category in 1986.

l No breakdown for individual Space Shuttle propulsion components. The 1987 amounts for Propulsion Systems were: submission = $338,400,000; authorization = $338,400,000; and appropriation = $338,400,000. Flight Hardware submission = $646,200,000; authorization = $879,100,000; and appropriation = $646,200,000.

m No breakdown for individual Space Shuttle propulsion components. The 1988 amounts for Propulsion Systems were: submission = $552,100,000; authorization = $552,100,000; and appropriation = $249,300,000. Funds deleted from Propulsion Systems; $302,800,000 appropriated moved to Launch and Mission Support category. Flight Hardware submission = $923,100,000; authorization = $923,100,000; and appropriation = $923,100,000.

Table 2–8. External Tank Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	80,500	80,500	*a*	104,800
Suppl. Appropriation	*b*	27,100	*c*	
1980	68,400	68,400	*d*	79,400
Suppl. Appropriation *e*	—	—	—	
1981	48,000	48,000	48,000	63,500
1982 Propulsion Systems *f*	25,000	25,000	25,000	45,700
Flight Hardware *f*				176,200
1983 Propulsion Systems *f*	*g*	*g*	*g*	97,600
Flight Hardware *f*	*g*	*g*	*g*	269,400
1984 Propulsion Systems	*h*	*h*	*h*	74,400
Flight Hardware	*h*	*h*	*h*	242,700
1985 Propulsion Systems	*i*	*i*	*i*	60,500
Flight Hardware	*i*	*i*	*i*	267,000
1986 Propulsion Systems	*j*	*j*	*j*	63,200
Flight Hardware	*j*	*j*	*j*	285,100
1987 Propulsion Systems	*k*	*k*	*k*	51,700
Flight Hardware	*k*	*k*	*k*	251,400
1988 Propulsion Systems	*l*	*l*	*l*	36,000
Flight Hardware	*l*	*l*	*l*	286,600

a Undistributed. No amount specified for external tank appropriation. Included in total R&D appropriation of $3,477,200,000.

b No breakout of supplemental appropriation submission; included in R&D submission of $185,000,000.

c Supplemental Appropriation of $185,000,000 specified for general R&D activities.

d Undistributed. Included in R&D appropriation of $4,091,096,000.

e Supplemental appropriation for Space Shuttle in response to amended NASA budget submission of $300,000,000. No authorization activity. Supplemental appropriation of $285,000,000 approved with no distribution to individual components.

Table 2–8 continued

f Propulsion Systems and Flight Hardware budget categories were not used by NASA prior to FY 1984. However, programmed amounts used these categories in FY 1982 and FY 1983 to be consistent with categories used in estimates for future years.

g No budget item listed. Supporting committee documentation included external tank in Space Shuttle Production with no amount specified. Total Production amount: submission = $1,585,500,000; authorization = $1,670,500,000; and appropriation = $1,636,500,000.

h No specific authorization for SSME, external tank, or SRB. According to congressional reports, the Space Transportation and Capability Development program supported the production of the SSME, SRB, and external tank, in addition to providing for critical spares (as well as other items). The total authorization for this category = $2,009,400,000. Some Space Shuttle funding was included in the Flight Hardware category (see above for definition): submission = $848,400,000; authorization undistributed, included in Shuttle Operations authorization = $1,495,600,000; and appropriation (moved to SFC&DC) undistributed, included in Shuttle Operations appropriation = $1,520,600,000.

i SSME production and residual development tasks for the orbiter, SSME, external tank, and SRB fell under Space Production and Operational Capability, Propulsion Systems. SRB and external tank procurement (production) fell under Space Transportation Operations, Flight Hardware. No breakdown for individual Space Shuttle propulsion components. The 1985 amounts for Propulsion Systems were: submission = $599,000,000; authorization = $599,000,000; and appropriation = $599,000,000. Authorization for submission = $758,000,000. Procurement of external tank, solid rocket motor, and SRB hardware included in Space Transportation Operations Program, Flight Hardware amount of $758,000,000; appropriation = $758,000,000. SSME production and residual development tasks for the orbiter, SSME, external tank, and SRB fell under Space Production and Operational Capability, Propulsion Systems. SRB and external tank procurement (production) fell under Space Transportation Operations, Flight Hardware. Flight Hardware submission = $758,000,000; authorization = $758,000,000; and appropriation = $758,000,000.

j No breakdown for individual Space Shuttle propulsion components. The 1986 amounts for Propulsion Systems were: submission = $454,000,000; authorization = $454,000,000; and appropriation = $454,000,000. No Flight Hardware budget category in 1986.

k No breakdown for individual Space Shuttle propulsion components. The 1987 amounts for Propulsion Systems were: submission = $338,400,000; authorization = $338,400,000; and appropriation = $338,400,000. Flight Hardware submission = $646,200,000; authorization = $879,100,000; appropriation = $646,200,000.

l No breakdown for individual Space Shuttle propulsion components. The 1988 amounts for Propulsion Systems were: submission = $552,100,000; authorization = $552,100,000; and appropriation = $249,300,000. Funds deleted from Propulsion Systems; $302,800,000 moved to Launch and Mission Support category. Flight Hardware submission = $923,100,000; authorization = $923,100,000; and appropriation = $923,100,000.

Table 2–9. Upper Stages Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979 STS Upper Stages	*a*	*a*	*a*	19,300
Upper Stage Operations				6,300
1980 STS Upper Stages	*b*	*b*	*b*	18,300
Upper Stage Operations	*b*	*b*	*b*	18,700
1981 STS Upper Stages	*c*	*c*	*c*	38,300
Upper Stage Operations	*c*	*c*	*c*	30,900
1982 *d*	—	—	—	106,700
1983 *e*	—	—	—	167,000
1984 *f*	143,200	143,200	143,200	143,200
1985 *g*	92,400	92,400	92,400	137,400
Suppl. Appropriation		40,000 *h*		
1986	122,000	122,000	122,000	122,000
1987	202,100 *i*	200,100 *j*	202,100 *k*	156,100
1988	159,700	159,700	159,700	

a No specific funding. Submission for Space Transportation System Operations Capability Development = $110,500,000; authorization for Space Transportation System Operations Capability Development by Senate committee = $110,500,000 (no final authorization); and appropriation for Space Transportation System Operations Capability Development was undistributed. Total R&D appropriation = $3,477,200,000. Submission for Space Transportation System Operations = $33,400,000. Authorization for Space Transportation System Operations by Senate committee = $33,400,000 (no final authorization). Appropriation undistributed.

b No specific funding for Upper Stages.

c Upper Stages were included in the Space Flight Operations Space Transportation Systems Operational Capability budget line item. House Committee documentation indicated that NASA submission, as well as congressional authorization, for upper stage activities was $29,000,000; Public Law 96–526 report referred to both STS Upper Stages and STS Operations Upper Stages: appropriation = $29,000,000 for STS Upper Stages and $30,900,000 for STS Operations Upper Stages.

d No NASA submission, final authorization, or appropriation for Upper Stages indicated.

e Upper Stages included in Space Flight Operations, but no amount specified. Total Space Flight Operations: submission = $1,707,000,000; authorization = $1,699,000,000; and appropriation = $1,796,000,000.

Table 2–9 continued

f Included modification of the Centaur for use in the Shuttle.

g Included development of Transfer Orbit Stage for use in launching the Mars geoscience/climatology orbiter in 1990. Also included joint development program between NASA and DOD for use of the Centaur as an STS upper stage. Procurement would be initiated in FY 1985 for two Centaur G vehicles to support the Venus Radar Mapper mission planned for 1988 and the TDRS-E mission.

h Supplemental Appropriation added $40,000,000 to initial appropriation for Upper Stages for total of $132,400,000

i Amended budget submission increased amount from $85,100,000 to $202,100,000.

j Figure reflects authorization act, which was vetoed.

k Figure reflects Appropriation Conference Committee action, which was subsequently included in the Omnibus Appropriation Act of 1987 (Public Law 99–591).

Table 2–10. Orbital Maneuvering Vehicle Funding History (in thousands of dollars)

Year (Fiscal)	**Submission**	**Authorization**	**Appropriation**	**Programmed (Actual)**
1983		Included in Advanced Programs		
1984		Included in Advanced Programs		
1985		Included in Advanced Programs		
1986	25,000	13,000	10,000	5,000
1987	45,000 *a*	50,000 *b*	45,000 *c*	45,000
1988	80,000	75,000	55,000	

a Reflects revised budget submission, which decreased amount from $70,000,000 to $45,000,000

b Figure reflects authorization act, which was vetoed.

c Figure reflects Appropriation Conference Committee action, which was subsequently included in the Omnibus Appropriation Act of 1987 (Public Law 99–591).

Table 2–11. Tethered Satellite System Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979		Included in Advanced Programs		
1980		Included in Advanced Programs		
1981		Included in Advanced Programs		
1982		Included in Advanced Programs		
1983		Included in Advanced Programs		
1984	3,300	3,300	3,300	3,300
1985	18,200	18,200	18,200	15,800
1986	21,000	14,000	21,000	15,000
1987	10,600 *a*	11,600 *b*	10,600 *c*	10,600
1988	7,300	7,300	7,300	

a Figure reflects $1,000,000 reduction from initial budget submission.
b Figure reflects authorization act, which was vetoed.
c Figure reflects Appropriation Conference Committee action, which was subsequently included in the Omnibus Appropriation Act of 1987 (Public Law 99–591).

Table 2–12. Advanced Programs/Planning Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed (Actual)
1979	5,000	*a*	*b*	7,000
1980	13,000	*c*	*d*	13,000
1981	8,800	13,800 *e*	f	11,800
1982	8,800	12,800 *g*	8,800	9,700
1983	11,900	h	11,900	12,600
1984	15,000	25,000 *i*	15,000	21,500
1985	14,500	14,500	20,500	20,500
1986	21,000	21,000	21,000	19,400
1987	16,600	16,600 *j*	16,600 *k*	33,600
1988	24,900	24,900	30,900	

a Undistributed. Included in Space Flight Operations Program authorization of $315,900,000.
b Undistributed. Included in R&D appropriation of $3,477,200,000.
c Undistributed. Included in Space Flight Operations Program authorization of $463,300,000.
d Undistributed. Included in R&D appropriation of $4,091,086,000.
e Increased authorization recommended by House Committee to support enhanced Phase B definition studies and technical development for the power extension package (PEP) and the 25-kilowatt (kW) power module.
f Undistributed. Included in R&D appropriation of $4,396,200,000 (modified by General Provision, Sec. 412, to $4,340,788).
g House recommended additional authorization of $5,000,000 for PEP, 25-kW power module, space platforms, space operations definition studies, and advanced technical development. Conference Committee reduced additional authorization to $12,800,000.
h Undistributed. Included in Space Flight Operations authorization of $1,699,000,000.
i House authorized additional $10,000,000 for space station studies and space platform. Senate authorized additional $5,000,000 for space station studies. Conference Committee authorized additional $10,000,000 for space station studies.
j Figure reflects authorization act, which was vetoed.
k Figure reflects Appropriation Conference Committee action, which was subsequently included in the Omnibus Appropriation Act of 1987 (Public Law 99–591).

Table 2–13. ELV Success Rate by Year and Launch Vehicle for NASA Launches

Year (Fiscal)	Atlas-Centaur	Atlas E/F	Delta	Scout	Total
1979	2/2	1/1	3/3	3/3	9/9
1980	3/3	0/1	1/1	—	1/1
1981	4/4	1/1	5/5	1/1	11/11
1982	2/2	—	7/7	—	9/9
1983	1/1	1/1	8/8	1/1	11/11
1984	0/1	1/1	4/4	1/1	6/7
1985	3/3	—	—	2/2	5/5
1986	1/1	1/1	1/2	1/1	4/5
1987	0/1	—	2/2	1/1	3/4
1988	—	1/1	1/1	4/4	6/6
Total	**16/18 (88.9%)**	**6/7 (85.7%)**	**34/35 (97.1%)**	**14/14 (100%)**	**70/74 (94.6%)**

Table 2–14. NASA Atlas E/F Vehicle Launches

Atlas-E/F Vehicle	**Date**	**Mission**	**Atlas Successful** *a*
Atlas F	June 27, 1979	NOAA-6	Yes
Atlas F	May 29, 1980	NOAA-B	No. Launch vehicle malfunctioned; failed to place satellite into proper orbit.
Atlas F	June 23, 1981	NOAA-7	Yes
Atlas E	March 28, 1983	NOAA-8	Yes
Atlas E	Dec. 12, 1984	NOAA-9	Yes
Atlas E	Sept. 17, 1986	NOAA-10	Yes
Atlas E	Sept. 24, 1988	NOAA-11	Yes

a One failure out of seven attempts (85.7% success rate).

Table 2–15. Atlas E/F Characteristics

	1-1/2 Stages (Booster & Sustainer)	Apogee Kick Motor	Fairing
Length	21.3 meters (m)	—	7.0 m
Overall Length	Up to 28.3 m including fairing		
Diameter	3.05 m		2.1 m
Gross Weight (Liftoff)	121,000 kilograms (kg)	47.7 kg (weight of motor)	735 kg assembly case after depletion of fuel)
Fuel Weight	112,900 kg	666 kg	
Engine Type/Name	MA-3 system consisting of LR 89-NA-5 booster, LR 105-NA-5 sustainer, LR 101-NA-7 vernier engines	TE-M-364-15	
Number of Engines	2 booster engines, 1 sustainer engine, & 2 vernier engines (VE)	1	
Propellant	LOX & RJ-1-1	Solid	
Burn Time (Avg.)	120-sec booster, 309-sec. sustainer	45 sec.	
Liftoff Thrust	1,743,000 newtons		
Avg. Thrust per Engine	1,470,000 newtons (boosters); (267,000 newtons (sustainer); 3,000 newtons (each VE)	650,800 newtons	
Max. Payload	2,090 kg in 185-km orbit from polar launch with dual TE-364 4 engines; 1,500 kg in 185-km orbit from polar launch with single TE 374-4 engine		

Table 2–15 continued

	1-1/2 Stages (Booster & Sustainer)	**Apogee Kick Motor**	**Fairing**
Prime Contractor	General Dynamics		
Contractors	Rocketdyne	Thiokol	
How Utilized	To launch meteorological satellites		
Remarks	The Atlas E/F series was originally deployed as ICBMs. By the late 1970s, the remaining Atlas E/Fs were converted for space launch. During 1979–1988, they were used only to launch meteorological satellites. On particular missions, the fairings were lengthened to 7.4 m to accommodate additional equipment—for instance, search-and-rescue equipment on NOAA missions.		

Table 2–16. NASA Atlas-Centaur Vehicle Launches

Atlas-Centaur Vehicle Serial Number	Date	Mission	Atlas-Centaur Successful [a]
AC-47	May 4, 1979	FltSatCom 2	Yes
AC-53	Sept. 20, 1979	HEAO 3	Yes
AC-49	Jan. 17, 1980	FltSatCom 3	Yes
AC-52	Oct. 30, 1980	FltSatCom 4	Yes
AC-54	Dec. 6, 1980	Intelsat V-A F-2	Yes
AC-42	Feb. 21, 1981	Comstar 4	Yes
AC-56	May 23, 1981	Intelsat V-B F-1	Yes
AC-59	Aug. 6, 1981	FltSatCom 5	Yes
AC-55	Dec. 15, 1981	Intelsat V F-3	Yes
AC-58	Mar. 4, 1982	Intelsat V-D F-4	Yes
AC-60	Sept. 28, 1982	Intelsat V-E F-5	Yes
AC-61	May 19, 1983	Intelsat V-F F-6	Yes
AC-62	June 9, 1984	Intelsat V-G F-9	No. Vehicle failed to place satellite in useful orbit.
AC-36	Mar. 22, 1985	Intelsat V-A F-10	Yes
AC-64	June 29, 1985	Intelsat V-A F-11	Yes
AC-65	Sept. 28, 1985	Intelsat V-A F-12	Yes
AC-66	Dec. 4, 1986	FltSatCom 7	Yes
AC-67	Mar. 26, 1987	FltSatCom 6	No. Telemetry lost shortly after launch; destruct signal sent at 70.7 seconds into flight. An electrical transient, caused by lightning strike on launch vehicle, was most probable cause of loss.

a Two failures out of eighteen attempts (88.9% success rate).

Table 2–17. Atlas-Centaur Characteristics

	Atlas Booster & Sustainer SLV-3D	**Centaur Stage D-1A**
Length	21.1 meters (m)	9.1 m without fairing; 18.6 m (with payload fairing)
Overall Length	40.8 m including fairing	
Diameter	3.05 m	3.05 m
Engine Type/Name	MA-5 system consisting of 2 boosters 1 sustainer, and 2 vernier engines	RL-10
Prime Contractor	General Dynamics	
Contractors	Rocketdyne	Pratt & Whitney Aircraft
Number of Engines	5 (2 booster engines, 1 thrust sustainer engine, 2 vernier engines)	2 thrust engines and 14 small hydrogen peroxide thrusters
Liftoff Thrust (Avg.)	1,931,000 newtons (at sea level) using two 828,088-newton-thrust booster engines, one 267,000-newton-thrust sustainer engine, and two vernier engines developing 3,006 newtons each	133,440 newtons (vacuum) using two 67,000-newton-thrust RL-10 engines and 14 small hydrogen peroxide thrusters
Burn Time	174-sec. booster, 226-sec. sustainer	450 sec.
Propellant	LOX as the oxidizer and RP-1	LOX and LH_2
Max. Payload	6,100 kilograms (kg) in 185-km orbit; 2,360 kg in geosynchronous transfer orbit; 900 kg to Venus or Mars	
Launch Weight	128,934 kg	17,676 kg
How Utilized	Primarily to launch communications satellites	
Remarks	Unlike earlier Atlas-Centaur combinations, the SLV-3D and later models were integrated electronically with the Centaur D-1A upper stage. The Intelsat V-A F-10, Intelsat V-A F-11, Intelsat V-A F-12, FltSatCom 5, and FltSatCom 6 missions used the Atlas G configuration. The Atlas stage on the “G” configuration is 2.06 m longer than the SLV-3D, and its engine provided 33,600 newtons more thrust than the SLV-3D engines.	

Table 2–18. Chronology of Delta Vehicle Launches

Delta Vehicle Type	**Date**	**Mission**	**Delta Successful** *a*
2914/148	Jan. 30, 1979	SCATHA	Yes
2914/149	Aug. 9, 1979	Westar-C	Yes
3914/150	Dec. 6, 1979	RCA-C	Yes
3910/151	Feb. 14, 1980	Solar Max Mission	Yes
3914/152	Sept. 9, 1980	GOES 4	Yes
3910-PAM/153	Nov. 15, 1980	SBS-A (first use of PAM)	Yes
3914/154	May 22, 1981	GOES 5	Yes
3913/155	Aug. 3, 1981	Dynamic Explorer DE-A/B	Yes
3910-PAM/156	Sept. 24, 1981	SBS-B	Yes
2310/157 b	Oct. 6, 1981	SME/Uosat	Yes
3910-PAM/158	Nov. 20, 1981	RCA-D	Yes
3910-PAM/159	Jan. 15, 1982	RCA-C	Yes
3910-PAM/160	Feb. 25, 1982	Westar IV	Yes
32910-PAM/161	Apr. 10, 1982	Insat-1A	Yes
3915/162	June 8, 1982	Westar-V	Yes
3920/163	July 16, 1982	Landsat-D	Yes
3920-PAM/164	Aug. 26, 1982	(Telesat-F) Anik-D-1	Yes
3924/165	Oct. 27, 1982	RCA-E	Yes
3910/166	Jan. 25, 1983	IRAS/PIX II	Yes
3924/167	Apr. 11, 1983	RCA-F	Yes
3914/168	Apr. 28, 1983	GOES F	Yes
3914/169	May 26, 1983	EXOSAT	Yes
3920-PAM/170	June 28, 1983	Galaxy-A	Yes
3920-PAM/171	July 28, 1983	Telstar-3A	Yes

Table 2–18 continued

Delta Vehicle Type	Date	Mission	Delta Successful *a*
3924/172	Sept. 8, 1983	Satcom-IIR (RCA-G)	Yes
3920-PAM/173	Sept. 22, 1983	Galaxy-B	Yes
3920/174	Mar. 1, 1984	Landsat-D/Uosat	Yes
3924/175	Aug. 16, 1984	AMPTE	Yes
3920-PAM/176	Sept. 21, 1984	Galaxy-C	Yes
3914/177	Nov. 13, 1984	NATO-IIID	Yes
3914/178	May 3, 1986	GOES G	No. Vehicle failed.
3920/180	Sept. 5, 1986	SDI	Yes
3924/179	Feb. 26, 1987	GOES H	Yes
3920-PAM/182	Mar. 20, 1987	Palapa-B2P	Yes
3910/181	Feb. 8, 1988	SDI	Yes

a One failure out of thirty-five attempts (97.1% success rate).

b Three strap-on engines.

Table 2–19. Delta 2914 Characteristics

	Strap-on	**Stage I**	**Stage II**	**Stage III**
Length		21.3 m	6.4 m	1.4 m
Overall Length	35.5 m including spacecraft shroud			
Diameter	Overall basic diameter of 2.4 m			
Engine Type/Name	TX-354-5 Castor II	RS-27 extended long tank Thor	8-foot-diameter TR-201	TE-364-4
No. of Engines	9	1 main and 2 vernier	1	1
Thrust (per Engine) (Avg.)	233,856 newtons	911,840 newtons	45,800 newtons	66,586 newtons
Liftoff Thrust	1,765,315 newtons (includes 6 of 9 strap-ons, which are ignited at liftoff)			
Burn Time	37 sec.	209 sec.	335 sec.	44 sec.
Propellant	Solid	RP-1/LOX	N_2O_4 & aerozine-50	Solid
Fuel Weight	18,084 kg each strap-on	80,264 kg	4,593 kg	1,039 kg
Liftoff Weight	40,320 kg	84,330 kg	6,125 kg	1,120 kg
Prime Contractor	McDonnell Douglas			
Contractors	Thiokol	Rocketdyne	TRW	Thiokol
How Utilized	Medium-weight payloads			
Remarks	Only three Deltas in the 2900 series were used between 1979 and 1988. Two were 2914s and one was a 2310, which had only three strap-on motors and two stages.			

Table 2–20. Delta 3910/3914 Characteristics

	Strap-on	**Stage I**	**Stage II**	**Stage III**
Overall Length	35.5 m including spacecraft shroud			
Length	11.3 m	21.3 m	6.0 m *a*	1.8 m *a*
Diameter	Overall 2.4 m max.			
Engine Type/Name	Castor IV/TX-526-2	RS-27 modified long tank Thor booster	TR-201	Thiokol TE-364-3 or TE-364-4
No. of Engines	9	1 main and 2 vernier	1	1
Burn Time (Avg.)	57 sec.	224 sec.	320 sec.	44 sec.
Specific Impulse (Avg.)	229.9 sec.	262.4 sec.	319 sec.	283 sec.
Thrust	377,165 newtons	911,887 newtons	43,815 newtons	TE 364-3 engine: 42,169 newtons TE 364-4 engine: 66,586 newtons
Propellant	Solid TP-H-8038	LOX and RP-1 (hydrazine) or LOX and RJ-1 (liquid hydrocarbon) *b*	N_2O_4 and aerozine-50	Solid
Fuel Weight	9,373 kg	80,264 kg	4,593 kg	1,039 kg
Gross Weight	10,840 kg each	85,076 kg	6,115 kg	1,158 kg
Prime Contractor	McDonnell Douglas			
Contractors	Thiokol	Rocketdyne	TRW	Thiokol
How Utilized	Medium-weight payloads			
Remarks	With the exceptions noted below in notes *a* and *b*, the 3910 was identical to the 3914 but had only two stages. For launches from the Eastern Space and Missile Center, six strap-on motors were ignited at liftoff and jettisoned approximately nine seconds after ignition of the second set of three strap-on motors. The remaining three motors were jettisoned at approximately 126 seconds after liftoff. For the Western Space and Missile Center, the six ground-ignited motors were jettisoned at a later time for range safety considerations.			

a The length of the second stage on the 3910 equaled the sum of the lengths of the second and third stages on the 3914. The lengths of the individual stages did not include the length of the spacecraft shroud.

b The 3910 used LOX and RP-1 propellant; the 3914 used LOX and RJ-1 propellant.

Table 2–21. Delta 3920/3924 Characteristics

	Strap-on	Stage I	Stage II	Stage III
Length		21.3 m	6m	1.8m
Overall Length	35.5 m including spacecraft shroud			
Diameter	Overall 2.4 m max.			
Engine Type/Name	Castor IV TX-526-2 solid boosters	RS-27 modified long tank Thor booster	Improved Transtage Injector Program	TE-364-4
No. of Engines	9	1 main & 2 vernier	1	1
Specific Impulse (Avg.)	229.9 sec.	262.4 sec.	319 sec.	283.6 sec.
Thrust (Avg.)	377,165 newtons	911,007 newtons	44,000 newtons	66,586 newtons
Burn Time	57 sec.	224 sec.	320 sec.	44 sec.
Propellant	Solid TP-H-8038	RP-1 and LOX	Aerozine-50 and N_2O_4 oxide	Solid
Fuel Weight	9,373 kg	79,380 kg	4,593 kg	1,039 kg
Max Payload	3,045 kg in 185-km orbit with due east launch; 1,275 kg in geosynchronous transfer orbit with due east launch; 2,135 kg in circular Sun-synchronous orbit with polar launch; 2,180 kg in 185-km orbit with polar launch			
Gross Weight	10,840 kg	85,076 kg	6,920 kg	1,122 kg
Prime Contractor	McDonnell Douglas			
Contractors	Thiokol	Rocketdyne	Aerojet	Thiokol
How Utilized	Mid-size communication and meteorological satellite			
Remarks	The length of the second stage of the 3920 equalled the combined lengths of the second and third stages of the 3924. Lengths of individual stages did not include length of the spacecraft shroud.			

Table 2–22. NASA Scout Launches

Scout Vehicle	Date	Mission	Scout Successful
S-202	Feb. 18, 1979	SAGE	Yes
S-198	June 2, 1979	UK-6	Yes
S-203	Oct. 30, 1979	Magsat	Yes
S-192	May 14, 1981	NOVA-I	Yes
S-205	June 27, 1983	Hilat	Yes
S-208	Oct. 11, 1984	NOVA-III	Yes
S-209	Aug. 2, 1985	SOOS-1	Yes
S-207	Dec. 12, 1985	AFITV	Yes
S-199	Nov. 13, 1986	AF Polar BEAR	Yes
S-204	Sept. 16, 1987	SOOS-2	Yes
S-206	Mar. 25, 1988	San Marco-DL	Yes
S-211	Apr. 25, 1988	SOOS-3	Yes
S-213	June 15, 1988	NOVA-II	Yes
S-214	Aug. 25, 1988	SOOS-4	Yes

All of attempted launches were successful.

Table 2–23. Scout Characteristics (G-1)

	First Stage	Second Stage	Third Stage	Fourth Stage
Length	9.94 m	6.56 m	3.28 m	1.97 m
Overall Length	22.86 m including transition and payload sections			
Weight	14,255 kg	4,424 kg	1,395 kg	302 kg
Diameter	1.01 m max.			
Engine Type/ Name	Algol IIIA	Castor IIA	Antares IIIA *a*	Altair IIIA/ Star 31
Thrust (Avg.)	481,000 newtons	281,000 newtons	83,100 newtons	25,593 newtons
Fuel	Solid	Solid	Solid	Solid
Fuel Weight	12,684 kg	3,762 kg	1,286 kg	275 kg
Launch Weight	14,215 kg	4,433 kg	1,394 kg	301 kg
Burn Time (Avg.)	90 sec.	46 sec.	48.4 sec.	30 sec.
Payload Capacity	227.2 kg payload to a 480-km Earth orbit			
Prime Contractor	Vought Corp. (LTV Corp.)			
Contractors	United Technologies	Thiokol	Thiokol	Thiokol
How Utilized	Smaller payloads			
Remarks	An optional fifth stage used the Alcyone IA engine, with a thrust of approximately 26,230 newtons, a burn time of 8.42 sec., and a total weight of 98.2 kg.			

a Missions prior to Magsat (SAGE and UK-6) used the Antares II third stage engine.

Table 2–24. STS-Launched Missions

Vehicle	Mission	Deployed Payload	Date
Columbia	STS-1	First test flight, no deployable payload	Apr. 12–14, 1981
Columbia	STS-2	Second test flight, no deployable payload	Nov. 12–14, 1981
Columbia	STS-3	Third test flight, no deployable payload	Mar. 22–30, 1982
Columbia	STS-4	Fourth and final test flight; DOD payload 82-1	June 27–July 4, 1982
Columbia	STS-5	SBS-C/PAM-D, Anik C-3/PAM-D (Telesat-E) (Canada)	Nov. 11–16, 1982
Challenger	STS-6	Tracking and Data Relay Satellite (TDRS)-1/IUS	Apr. 4–9, 1983
Challenger	STS-7	Telesat 7 (Anik C-2)/PAM-D (Canada)/PAM-D, Palapa B-1 (Indonesia)/PAM-D	June 18–24, 1983
Challenger	STS-8	INSAT-1B/PAM-D (India)	Aug. 30–Sept. 5, 1983
Columbia	STS-9	Spacelab-1 (no satellites deployed)	Nov. 28–Dec. 8, 1983
Challenger	STS 41-B	Palapa-B2/PAM-D (Indonesia), Westar VI/PAM-D	Feb. 3–11, 1984
Challenger	STS 41-C	Long Duration Exposure Facility (LDEF-1)	Apr. 6–13, 1984
Discovery	STS 41-D	Syncom IV-2 (Leasat 2)/Unique Upper Stage*, Telstar 3-C/PAM-D, SBS-D/PAM-D	Aug. 30–Sept. 5, 1984
Challenger	STS 41-G	Earth Radiation Budget Satellite (ERBS)	Oct. 5–13, 1984
Discovery	STS 51-A	Syncom IV-1 (Leasat 1)/Unique Upper Stage*, Anik (Telesat-H)/PAM-D	Nov. 8–16, 1984
Discovery	STS 51-C	DOD classified payload/IUS	Jan. 24–27, 1984
Discovery	STS 51-D	Anik C-1 (Telesat-I)/PAM-D, Syncom IV (Leasat 3)/Unique Upper Stage*	Apr. 12–19, 1985
Challenger	STS 51-B	Spacelab 3, NUSAT, GLOMR (failed to deploy)	Apr. 29–May 6, 1985
Discovery	STS 51-G	Morelos-A/PAM-D (Mexico), Arabsat-A/PAM-D, Telstar 3-D/PAM-D, Spartan-1/MPESS	June 17–24, 1985

Table 2–24 continued

Vehicle	Mission	Deployed Payload	Date
Challenger	STS 51-F	Spacelab 2 (no satellites deployed)	July 29–Aug. 6, 1985
Discovery	STS 51-I	ASC-1/PAM-D, Aussat-1/PAM-D (Australia), Syncom IV (Leasat-4)/Unique Upper Stage*	Aug. 27–Sept. 3, 1985
Atlantis	STS 51-J	DOD Mission	Oct. 3–7, 1985
Challenger	STS 61-A	GLOMR GAS (DOD classified mission)	Oct. 30–Nov. 6, 1985
Atlantis	STS 61-B	Morelos-B/PAM-D (Mexico), Aussat-2/PAM-D (Australia), Satcom Ku-2/PAM-DII (RCA)	Nov. 26–Dec. 3, 1985
Columbia	STS 61-C	Satcom Ku-1/PAM-DII (RCA)	Jan. 12–18, 1986
Challenger	STS 51-L	TDRS-B/IUS and Spartan 203 (carried but not deployed because of the destruction of *Challenger*)	Jan. 28, 1986
Discovery	STS-26	TDRS-3/IUS	Sept. 29–Oct. 3, 1988
Atlantis	STS-27	DOD payload	Dec. 2–6, 1988

* Unique Upper Stage—Minuteman missile third stage used as a solid propellant perigee motor.

Table 2–25. Space Shuttle Main Engine Characteristics

Number of Engines	Three on each Shuttle
Thrust	2,000,000 newtons each
Operating Life	7.5 hours and 55 starts
Range of Thrust Level	65%–109% of rated power level
Propellant	LOX/LH_2
Nominal Burn Time	522 sec.
Prime Contractor	Rockwell International

Table 2–26. Main Engine Development and Selected Events

Date	Event
June 1980	Surpassed original goal of achieving 80,000 seconds of engine test time before the first orbital flight.
Feb. 20, 1981	Flight readiness firing (20-second firing of all three SSMEs), *Columbia* (OV-102) at Kennedy Space Center.
Feb. 28, 1982	Completed main propulsion test program, National Space Technology Laboratories (NSTL), Mississippi.
1983	Phase II program began for improvements to SSMEs for increased margin and durability.
Dec. 1983	Completed certification of main engines at 109 percent of present rated power level to full power level. Certification process included 400 tests of more than 40,000 seconds of static firing operation.
June 26, 1984	Launch of STS 41-D postponed indefinitely because of shutdown of SSMEs 3 and 2 at T-4 seconds caused by slow opening SSME 3 main fuel valve. SSME 1 never received a start command.
Aug. 30, 1984	STS 41-D conducted successfully.
July 12, 1985	STS 51-F launch scrubbed at T-3 seconds and shutdown of SSMEs because of loss of redundancy (channel A) on SSME 2 chamber coolant valve.
July 29, 1985	STS 51-F conducted successfully.
July 16, 1986	250-second test conducted successfully at NSTL. The test was the first in a series to verify a modification designed to extend the operational service life of turbine blades on the engine’s high-pressure oxidizer turbopump.
Aug. 13, 1986	NASA announced selection of Pratt & Whitney for alternate turbopump development contract, which would provide extended life capability and enhance safety margins.
Dec. 1986	Ground test program initiated.
Dec. 1986-Dec. 1987	151 tests and 52,363 seconds of operation (equivalent to 100 Shuttle missions) were performed at NSTL (Mississippi) and Rockwell International’s Rocketdyne Division (California).
Aug. 1987–Jan. 1988	Acceptance tests at Stennis Space Center (formerly NSTL).
Sept. 1987	Beginning of acceptance testing of main engines to be used on STS-26 at NSTL. A number of improvements were made on the engines as a result of an extensive, ongoing test program.
Jan. 6, 1988	Engine 2016 arrived at Kennedy.
Jan. 10, 1988	Engine 2106 installed in number one position on *Discovery.*
Jan. 15, 1988	Engine 2022 arrived at Kennedy.
Jan. 21, 1988	Engine 2028 arrived at Kennedy.
Jan. 24, 1988	Engine 2022 installed in number-two position and Engine 2028 installed in number-three position on *Discovery*.
Aug. 10, 1988	Conducted a 22-second flight readiness firing of *Discovery*’s main engine. Verified that the entire Shuttle system was ready for flight

Table 2–27. Space Shuttle External Tank Characteristics

Propellants	LH_2, LOX
Length	46.8 m
Diameter	8.4 m
Weight of Propellant	700,000 kg
Gross Liftoff Weight	750,980 kg
Inert Weight of Lightweight Tank	30, 096 kg
Liquid Oxygen Max. Weight	617,774 kg
Liquid Oxygen Tank Volume	542,583 liters
Liquid Oxygen Tank Diameter	8.4 m
Liquid Oxygen Tank Length	15 m
Liquid Oxygen Tank Weight	5,454.5 kg empty
Liquid Hydrogen Max. Weight	103, 257 kg
Liquid Hydrogen Tank Diameter	8.4 m
Liquid Hydrogen Tank Length	29.46 m
Liquid Hydrogen Tank Volume	1,458,228 liters
Liquid Hydrogen Tank Weight (Empty)	13,181.8 kg
Intertank Length	6.9 m
Intertank Diameter	8.4 m
Intertank Weight	5,500 kg
Prime Contractor	Martin Marietta Aerospace

*Table 2–28. External Tank Development and Selected Events**

Date	Event
Mar. 19, 1979	First external tank leaves Marshall Space Flight Center for Kennedy Space Center.
June 25, 1979	First external tank ready for flight.
Feb. 28, 1980	Successful completion of full duration test of MPTA-098.
June 30, 1980	NASA awards contract for external tank to Martin Marietta Corp.
Oct. 8, 1980	"All Systems Test" conducted.
Nov. 3, 1980	First external tank mated to SRBs for STS-1.
Nov. 11, 1980	External tank and SRBs mated to orbiter for STS-1.
Dec. 2, 1980	Assembly of first lightweight tank begins.
Jan. 17, 1981	Static firing at NSTL. External tank test without anti-geyser line to verify feasibility of eventually removing it from later external tank versions.
Jan. 22 and 24, 1981	External tank liquid hydrogen load of *Columbia* at Kennedy.
Apr. 12, 1981	First tank flown successfully.
Nov. 12, 1981	Second tank flown successfully.
Oct. 1981	Third tank delivered to Kennedy.
1981	Major welding and structural assembly completed on the first production version of a lightweight tank.
Apr. 4, 1983	First lightweight tank (LWTR 1) flown on STS-6 mission; design changes reduced weight of external tank by 4,000 kg, permitting heavier payload.
Aug. 1, 1988	Wet Countdown Demonstration Test held; external tank loaded with liquid oxygen and liquid hydrogen.

* Relatively few events were associated with the development of the external tank, and there were no events over a five-year period from April 1983 to August 1988. The external tank performed successfully on the STS missions during this period and required little attention.

Table 2–29. Space Shuttle Solid Rocket Booster Characteristics

Length	45.5 m
Diameter	3.7 m
Outside Diameter of Nozzle and Thrust	12.4 feet
Vector Control System	
Weight at Launch (Each)	589,680 kg
Propellant Weight (Each)	500,000 kg
Inert Weight (Each)	87,273 kg
Propellant Mixture	Ammonium perchlorate, aluminum, iron oxide, a polymer, an epoxy curing agent
Thrust (Sea Level) of Each Booster in Vacuum	14,409,740 newtons at launch
Separation Motors	Four motors in the nose frustum and four motors in the aft skirt
Length	0.8 m
Diameter	32.5 cm
Thrust of Separation Motors	98,078 newtons each
Inert Weight	87373.6 kg
Burn Time (Nominal)	123 sec.
Prime Contractors	SRB motors: Morton Thiokol Corp. SRB assembly, checkout, and refurbishment for all non–solid rocket motor components and for SRB integration: Booster Production Co.
NASA Lead Center	Marshall Space Flight Center
Remarks	Structural modifications following the Challenger accident added approximately 204 kg to the weight of each SRB.

Table 2–30. Chronology of Selected Solid Rocket Booster Development Events

Date	Event
Jan. 30, 1979	Began orbiter/external tank/SRB burnout mated vertical ground vibration test at Marshall Space Flight Center.
Feb. 17, 1979	Fourth SRB firing at Thiokol, Utah.
June 15, 1979	First SRB qualification firing, Thiokol, 122 seconds; nozzle extension severed at end of run as in actual mission; full cycle gimbal.
July 23, 1979	*Enterprise* (OV-101), external tank, and SRBs transported on mobile launcher platform from Launch Complex 39-A to Vehicle Assembly Building at Kennedy Space Center.
Aug. 1979	Second SRB qualification firing, Thiokol.
Feb. 14, 1980	Final qualification firing SRB, Thiokol.
Aug. 4, 1980	*Columbia* mated with SRBs and external tank for STS-2.
Nov. 3, 1980	External tank mated to SRBs in Vehicle Assembly Building, Kennedy, for STS-1.
Nov. 5, 1980	External tank mated to SRBs at Kennedy.
Nov. 26, 1980	Mating of *Columbia* (OV-102) to external tank and SRBs in Vehicle Assembly Building for STS-1, Kennedy.
Apr. 20, 1981	SRB stacking began on mobile launcher platform for STS-2, Kennedy.
July 30, 1981	Start mating of external tank to SRBs on mobile launcher platform for STS-2, Kennedy.
Apr. 12, 1981, Nov. 12, 1981	STS-1 and STS-2 flights verified reusability of SRBs; some redesign of aft skirts indicated.
Sept. 9, 1981	*Columbia* mated with SRBs and external tank in preparation for STS-5.
Nov. 23, 1981	Start SRB stacking on mobile launcher platform for STS-3, Kennedy.
Dec. 19, 1981	Start mating of external tank to SRBs on mobile launcher platform for STS-3, Kennedy.
Apr. 16, 1982	Complete mating of SRBs and external tank for STS-4 in Vehicle Assembly Building, Kennedy.
Apr. 4, 1983	New lightweight SRB case first flown on STS-6.
Aug. 30, 1983	First high-performance solid-fueled rocket motor flown on STS-8.
Aug. 2, 1984	*Discovery* (OV-103) transported from Orbiter Processing Facility to Vehicle Assembly Building for remate with original 41-D SRBs and external tank, Kennedy.
Dec. 19, 1985	STS 61-C, seventh flight of *Columbia* (OV-102), launch scrubbed at T-13 seconds because of righthand SRB auxiliary power unit turbine system B overspeed.

Table 2–30 continued

Date	Event
Jan. 6, 1986	STS 61-C launch scrubbed at T-31 seconds because of a launch facility liquid oxygen replenish valve problem.
Jan. 7, 1986	STS 61-C launch scrubbed at T-9 seconds because of adverse weather conditions.
Jan. 12, 1986	STS 61-C launch conducted successfully.
Jan. 28, 1986	STS 51-L launched. Destruction of *Challenger* and all crew aboard.
Mar. 25, 1986	Formation of Solid Rocket Motor Redesign Team to requalify the SRB motor.
July–Aug. 1986	Preliminary Requirements Reviews held.
Aug. 22, 1986	NASA announced the beginning of a series of tests designed to verify the ignition pressure dynamics of the Space Shuttle solid rocket motor (SRM) field joint. The series was conducted over the next year at Thiokol's facility and at Marshall.
Sept. 5, 1986	Study contracts awarded to five aerospace firms for conceptual designs of an alternative or Block II Space Shuttle SRM.
Sept. 1986	Preliminary Design Review held to assess design requirements.
Oct. 2, 1986	NASA announced the decision to test-fire the redesigned SRM in a horizontal attitude to best simulate the critical conditions on the field joint that failed during the 51-L mission.
Oct. 9, 1986	Transfer of *Atlantis* (OV-104) mated, minus SSMEs, from the Vehicle Assembly Building to Launch Complex 39-B for weather protection fit checks, payload bay operations, SRB flight readiness test, terminal countdown demonstration test, and emergency egress simulation, Kennedy.
Oct. 16, 1986	NASA announced it would proceed with constructing a second horizontal test stand for redesign and certification of the Space Shuttle SRM at the Thiokol facility. The new test stand was designed to simulate, more closely than the existing SRM stand, the stresses on the SRM during an actual Shuttle launch and ascent.
Oct. 1986	Design requirements baselined.
1987	Primary design changes made to the SRM field joints, nozzle-to-case joints, case insulation, and seals.
Jan. 1987	Results of studies relating to innovative change to the existing (pre-*Challenger*) SRM joint design and design of new concepts for improved SRM performance were reported to Congress.
Mar. 1987	SRM Acquisition Strategy and Plan submitted to Congress. Plan indicated that NASA proposed to initiate Phase B (Definition) studies for an Advanced Solid Rocket Motor (ASRM); SRM redesign team evaluated design alternatives that would minimize the redesign time but ensure adequate safety margins. The team conducted analyses and tests of the redesign baseline.

Table 2–30 continued

Date	Event
May 22, 1987	First in a series of test firings conducted at Thiokol's facility. Objectives of the test, called the Nozzle Joint Environment Simulator test, included diversified motor system operations, such as evaluating and characterizing the SRM nozzle-to-case joint, obtaining information on the joint deflection data, and validating the test article in its original design.
May 27, 1987	An engineering test motor (ETM) was test-fired at Thiokol's facility in Utah as part of the Shuttle motor redesign program. The extensively instrumented ETM-1A was successfully fired for 120 seconds, a full-duration test.
Aug. 29, 1987	First full-duration test firing of the redesigned SRM at Thiokol. Designated DM-8, the 2-minute test evaluated the performance of the major features of the redesigned motor and completed several tests of case and nozzle-to-case joints with intentionally flawed insulation and O-rings.
Aug. 1987	Five solid propulsion contractors were awarded contracts for 9-month preliminary design and definition studies of both a monolithic and segmented ASRM that would permit performance increases of up to 5,443 kg of payload.
Oct. 1987	Critical Design Review—final design was approved.
Dec. 19, 1987	Second full-duration test firing of the redesigned Space Shuttle SRM at Thiokol.
Mar. 1, 1988	Redesigned SRM segments began arriving at Kennedy.
Mar. 28, 1988	Began stacking of *Discovery*'s SRM segments beginning with left aft booster.
Apr. 1988	Full-duration test firing of redesigned solid rocket motor (RSRM) at Thiokol's facility in Utah.
May 5, 1988	Began stacking lefthand booster segments.
May 28, 1988	Complete stacking of *Discovery*'s SRBs.
June 1988	Full-duration test firing of RSRM at Thiokol's facility in Utah.
June 10, 1988	SRBs and external tank are mated for STS-26; interface test between boosters and external tank conducted to verify connection.
July 1988	Solid Propulsion Integrity Program conducted most highly instrumented SRM nozzle test up to that time.
Aug. 1988	Full-duration test firing of RSRM. For this test, production verification motor-1 was extensively flawed to demonstrate the fail-safe characteristics of the redesign.
Aug. 1988	RFP issued for design, development, test, and evaluation of a Space Shuttle ASRM to replace the current RSRM in the mid-1990s. Contract award was anticipated for the spring of 1989.
Sept. 29, 1988	STS-26 returns Shuttle to operational status.

Table 2–31. Upper Stage Development

Date	Event
1979	DOD's detailed design of the two-stage Inertial Upper Stage (IUS) configuration completed.
1979	Detailed design of the NASA three-stage IUS configuration initiated.
1979	Designs completed and qualification program initiated for the PAM.
1979	Most PAM flight hardware manufactured and ready for assembly.
1979	NASA ordered PAM-As for Comsat's Intelsat V communications satellite missions.
Nov. 15, 1980	First flight of PAM-D on the Delta launched the SBS 1 spacecraft.
Sept. 1981	SBS 2 used PAM-D on Delta vehicle.
Nov. 1981	RCA-Satcom 3-R launched using PAM-D.
1982	PAM-A qualification and production halted, pending definition of spacecraft needs and launch schedules.
1982	PAM-D completed qualification and verification tests.
1982	PAM-D flew six commercial flights as third stage of Delta ELV.
May 1982	Transfer Orbit Stage (TOS) conceptual studies initiated.
Oct. 30, 1982	First IUS flown on DOD mission.
Dec. 1982	NASA/Orbital Sciences Corp. TOS Memorandum of Understanding.
Apr. 4, 1983	First IUS launched from Space Shuttle on STS-6, carrying the Tracking and Data Relay Satellite (TDRS). Second stage failed to place satellite in final geosynchronous orbit. Additional maneuvers placed TDRS 1 in its required functional orbit. NASA-Air Force team determined the IUS problem was in the gimbal mechanism of the second stage.
1983	PAM-D launched nine communications satellites, three from the Space Shuttle's cargo bay and six from ELVs.
Apr. 1983	NASA and Orbital Sciences signed a joint agreement for commercial development of the TOS.
May 1983	TOS design studies initiated.
Oct. 1983	TOS full-scale development initiated.
Feb. 3, 1984	PAM failed to boost Westar 6 and Palapa B-2 to proper orbit on STS 41-B mission.
May 1984	TOS Preliminary Design Review.
June 1984	Laser initial navigation system development begun by Honeywell for use in upper stages.
Dec. 1984	Orbital Sciences and Martin Marietta sign a development contract for TOS/Apogee Maneuvering Stage.

Table 2–31 continued

Date	Event
Mar. 1985	TOS Critical Design Review.
June 1985	Contract awarded to Orbital Sciences for the laser initial navigation system.
Aug. 1985	TOS Production Readiness Review; factory rollout of first TOS upper stage.
Nov. 26, 1985	PAM DII used on STS 61-B.
Jan. 12, 1986	PAM DII used on STS 61-C.
Feb. 1986	Boeing Aerospace selected to provide upper stage for TDRS-E and -F.
Mar. 1986	Mars Observer TOS contract selection.
June 19, 1986	Termination of Centaur upper stage development.
Nov. 26, 1986	NASA announced the selection of the IUS as the baseline option for three planetary missions: Galileo, Magellan, and Ulysses.
Nov. 26, 1986	The TOS was selected to place the Mars Observer spacecraft into the proper interplanetary trajectory.
1989	Martin Marietta and Boeing chosen to conduct studies on space transfer concepts, successor to the Orbital Transfer Vehicle.
July 14, 1993	Advanced Communications Technology Satellite (ACTS) launched from Shuttle with TOS for transfer to higher orbit.

Table 2–32. Transfer Orbit Stage Characteristics

Length	3.3 m
Weight With Full Propellant Load	10,886 kg
Airborne Support Equipment Weight	1,450 kg
Payload to Geotransfer Orbit	6,080 kg from Shuttle
Payload to Planetary and High-Energy Orbits	5,227 kg from Titan III and IV
Propulsion System	Orbis 21 solid rocket motor and attitude control system
Capacity	1,360 kg to 3,175 kg capacity