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THESIS

THE SPACE SHUTTLE: AN ATTEMPT AT
LOW-COST, ROUTINE ACCESS
TO SPACE

by

Jeffery D. Wonch

September 1990

Thesis Advisor Donald A. Lacer

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This thesis examines the Space Shuttle's purpose of low-cost, routine access to space and how the lessons learned during the Space Shuttle program have affected the thinking on new heavy-lift launch systems. The thesis objective is to show the Space Shuttle was an attempt at developing a routine, low-cost access to space but, because of Shuttle-unique capabilities, cost-effective operations may never be realized with the Shuttle system. The Space Shuttle concept definition is addressed and the impact on design by DOD influence. The Space Shuttle developmental history is presented, and how budgetary constraints, coupled with NASA's desire to build a low-cost system resulted in over-runs in schedule and costs. The thesis looks at the operational period of the Space Shuttle, the use of Government subsidies to keep the price of a Shuttle launch artificially low, and the difficulties experienced by NASA in maintaining the planned launch schedule. The *Challenger* accident resulted in restructure of U.S. space policy as well as how the Shuttle will be used in the future. In conclusion, lessons learned from the Space Shuttle program are presented that the next generation of space transportation systems can build upon.

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The Space Shuttle: An Attempt at Low-Cost, Routine Access to Space

by

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Lieutenant, United States Navy
B.S., University of Michigan, 1983

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This thesis examines the Space Shuttle's purpose of low-cost, routine access to space and how the lessons learned during the Space Shuttle program have affected the thinking on new heavy-lift launch systems. The thesis objective is to show the Space Shuttle was an attempt at developing a routine, low-cost access to space but, because of Shuttle-unique capabilities, cost-effective operations may never be realized with the Shuttle system. The Space Shuttle concept definition is addressed and the impact on design by DOD influence. The Space Shuttle developmental history is presented, and how budgetary constraints, coupled with NASA's desire to build a low-cost system resulted in over-runs in schedule and costs. The thesis looks at the operational period of the Space Shuttle, the use of Government subsidies to keep the price of a Shuttle launch artificially low, and the difficulties experienced by NASA in maintaining the planned launch schedule. The *Challenger* accident resulted in restructure of U.S. space policy as well as how the Shuttle will be used in the future. In conclusion, lessons learned from the Space Shuttle program are presented that the next generation of space transportation systems can build upon.

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I. INTRODUCTION

The Mercury, Gemini, and Apollo space programs of the 1960's excited the American people who were being readied for a new space frontier. But almost 30 years after John Glenn's historic space flight, the frontier is still remote. Access to space is the problem. The United States is unable to routinely, and at a low cost, launch payloads into orbit. Many space analysts believe that once this access barrier is overcome, the real proliferation of space travel will begin.

In the late 1960's, NASA envisioned a space vehicle that routinely and at a low cost would be able to launch payloads into space. Additionally, this vehicle would be manned so satellite repair or retrieval could be accomplished. The secret to low cost access to space, NASA believed, was in the use of a reusable launch vehicle. This vehicle became the Space Shuttle which NASA believed would be the United States' "space truck" to earth orbit.

This thesis will examine the Space Shuttle's purpose of low cost, routine access to space, and how the lessons learned during the Space Shuttle program have affected the direction of new heavy-lift launch systems.

The developmental history of the Shuttle will be examined from the post-Apollo period through the finalized Shuttle configuration in 1982. Many influences affected the final Shuttle design including its relationship with the space station as well as a manned mission to Mars. Additionally, Department of Defense and political influences impacted Shuttle design.

The Space Shuttle development during the 1970's was undertaken in fiscally lean times for NASA. Budget constraints had an enormous effect on the Shuttle schedule, developmental costs, and operational costs. NASA developed management styles that allowed them to produce the Shuttle under meager budget conditions. Shuttle cost growth and the delay of the First Manned Orbital Flight were two results of the budgetary constraints of the 1970's. When the Shuttle flew its first test flight in April 1981, it was experiencing a two year delay in development and cost over runs of almost 2 billion dollars.

After a series of four test flights, NASA declared the Space Shuttle operational and started to market the Shuttle worldwide as providing a low cost, routine access to space. NASA envisioned a 24 flight per year capability that started to appear, in the early 1980's, overly ambitious. NASA experienced problems trying to launch the Space Shuttle on schedule. This resulted in DOD seeking additional launch capabilities that would guarantee access to space. By 1985, space users were beginning to doubt the "routine" capabilities of the manned Shuttle.

The pricing structure that NASA incorporated for the Shuttle in the initial operating period did not cover Shuttle operational costs. Moreover, the pricing structure, which was U.S. Government subsidized, resulted in commercial launch services becoming less competitive with the Shuttle.

The Space Shuttle saw 24 successful flights before the *Challenger* accident in January of 1986. The tragedy caused space officials to rethink the Shuttle's role in accessing space as well as causing a revision in space transportation policy. The resulting policy called for a mixed fleet of expendable launch vehicles (ELVs) and the Space Shuttle, but the Shuttle was to be used only in cases requiring Shuttle-unique capabilities. No longer would the Shuttle be used to launch payloads that could be easily launched on an ELV.

The grounded period of the Shuttle fleet was over two and one half years. During this time, many revisions to the Shuttle program took place. When the Shuttle resumed flying in September 1988, NASA felt the Shuttle was a safer, more capable launch vehicle. However, the efficiency of the Snuttle had further decreased because of additional safeguards making low-cost, routine access to space unattainable for the Shuttle system.

Many lessons can be learned from the Shuttle program in pursuing new launch systems. The National Security Launch Strategy signed by President Reagan in February 1985 initiated a joint study by NASA and DOD on the development of a second-generation space transportation system. [Ref. 1: p. 1] This thesis will examine some of the findings of the joint DOD / NASA study regarding existing launch systems as well as the direction for future launch systems. The two proposed systems currently under investigation are the Advanced Launch System (ALS) and the Shuttle-derived cargo vehicle or Shuttle-C.

The objective of the thesis is to show that the Space Shuttle was an attempt at developing a routine, low-cost access to space, but because of Space Shuttle unique qualities, cost-effective operations will never be realized.

The thesis concludes that next generation space transportation systems must learn from as well as build upon what is learned from the Space Shuttle program.

II. DEVELOPMENTAL HISTORY

A. POST-APOLLO PERIOD

By mid 1969, the United States space program was at a crossroads. NASA was finishing up a successful Apollo program and, desiring to continue this momentum, advocating endorsement by the nation of new manned space ventures:

> The next logical step for us to make in space will be to create permanent manned space stations in Earth and lunar orbits with low cost access by reusable chemical and nuclear rocket transportation systems, and to utilize these systems in assembling our capacity to explore the planet Mars with men thereby initiating man's permanent occupancy of outer space. [Ref. 2: p. 6]

These recommendations by President Nixon's newly formed Space Task Group (STG) were characteristic of NASA's direction for post-Apollo activity.

The STG was made up of Vice President Spiro Agnew as Chairman, Secretary of Defense Melvin Laird, Presidential Science Advisor Lee Dubridge, and NASA Administrator Thomas Paine. The STG made public in September 1969 three new alternatives the Nation could undertake in space:

- Establish a 50-man space station orbiting the earth, an orbiting lunar space station, a lunar surface base, and a manned flight to Mars by 1985. A reusable carrier would be needed to "shuttle" between the earth's surface and the earth orbiting station, and a reusable space tug would be needed to service the lunar orbiting station.
- Establish the earth orbiting station, along with the reusable shuttle but eliminate the lunar projects and postpone the manned Mars launch until 1986.
- Develop the earth orbiting space station and the shuttle, but defer any decision of the Mars mission, keeping it only as a goal to be realized before the end of the century. [Ref. 2: p. 1]

The first two options carried fiscal price tags in 1969 of $10 billion and $8 billion annually, respectively, while option three would still require a $5 billion annual NASA budget over the same time frame. [Ref. 3: p. 180]

Critics in the Congress, the media, and in the public generally opposed the magnitude of the space program plans presented in the STG report, to say nothing of the funds necessary to meet the program goals. [Ref. 4: p. 540]

In his 1968 election campaign, President Nixon pledged to curtail NASA operations until the economy could afford more funding. After entering office, as part of a general anti-inflation, multi-billion dollar government spending curb, President Nixon cut the NASA fiscal year 1970 budget request (submitted by President Johnson) by $45 million to $3.772 billion dollars, nearly a quarter of a billion dollars less than the 1969 appropriation.

Although interested in seeing a continuation of large space projects, the aerospace industry was not united as to which specific projects should have priority. While several companies had special interests due to specific space capabilities, industry as a whole favored the Department of Defense over NASA because of the shrinking NASA funding and the magnitude of its business with the military. Additionally, Vietnam, the economy, domestic unrest, state of the welfare program, and other issues commanded more attention than new space ventures. [Ref. 3: p. 181]

These concerns were reflected in the administration's fiscal year 1971 budget request to Congress, submitted in January 1970. NASA's budget was cut to $3.377 billion, $372 million below the fiscal year 1970 appropriation. [Ref. 5: pp. 8-11]

After President Nixon was in office only one year, NASA was forced to announce several major program changes. In February 1970, the Apollo applications program was renamed Skylab and, while originally planned to coincide with the lunar landing flights, was rescheduled to 1973 - 1974. In addition, instead of seven crews being sent to two space stations, only three crews would be sent to a single space station. [Ref. 4: pp. 430-431] NASA also announced the last lunar landing mission (Apollo 20) was being cancelled, and by September 1970 the Apollo 18 and 19 missions were cancelled, too. [Ref. 3: p. 182]

The President's space policy statement of 7 March 1970 was anticipated by the space community in light of the fiscal activity over the preceding 13 months. The statement reflected the political realities and the mood of Congress and the public:

> Space expenditures must take their proper place within a rigorous system of national priorities ... what we do in space from here on in must become a normal and regular part of our national life and must therefore be planned in conjunction with all of the other undertakings which are also important to us. [Ref.6: p. 3]

While the President's announcement did not back the new large projects as proposed by the STG, the statement did identify three "general purposes which should guide our space program -- exploration, scientific knowledge, and practical applications." President Nixon considered the space program to be of low priority in 1970, not justifying increased investment or the initiation of large new efforts as recommended by the STG. [Ref. 3: p. 182]

NASA was left with identifying a project that would both gain enough political support for approval and be sizeable enough to keep its development engineers occupied during the 1970's.

The "Space Shuttle" emerged as that project. NASA promised a variety of Shuttle capabilities, the primary one being low cost, routine transportation to space. NASA realized DOD was projected to be one of the larger users of space and very much needed DOD support for the Shuttle. According to a 1970 President's Science Advisory Committee (PSAC) report, the Space Shuttle was projected to solve both NASA and DOD needs:

> (a) Replacing twelve existing launch vehicles "with a STS (Space Transportation System) used jointly by both DOD and NASA as a national transportation capability."
> (b) "Provision for national security contingencies by the ready availability of transportation to orbit on short notice, with sufficient maneuverability and cross range capability for a variety of missions." [Ref. 7]

It was these two objectives -- replacing all existing launch vehicles with a more economical system and meeting DOD requirements for particular national security missions -- that drove Shuttle design during 1970 - 1971 and led NASA to resist suggestions that a smaller manned system would be an adequate U.S. space initiative for the 1970's. [Ref. 8: p. 1100]

NASA's fiscal funding downward trend did not stop at the $3.377 billion dollar level, however. By December 1970, Congress passed the fiscal year 1971 appropriation bill which cut an additional $64 million from NASA's budget. This pattern would repeat itself through fiscal year 1974 when NASA suffered its lowest budget in over 12 years, $3.040 billion dollars. The corresponding figure in relative buying power, or constant year 1967 dollars, was just over $2 billion dollars, and would remain there throughout the decade. [Ref. 5: pp. 8-11]

B. SPACE SHUTTLE CONCEPT

As early as the 1950's, conceptual design for a multi-regime aircraft were seriously considered. Such aircraft were conceived to be capable of operating in space, reentering the earth's atmosphere, and maneuvering and landing as conventional aircraft. Because of the state of knowledge of reentry heating and hypersonic aerodynamics, as well as relatively inefficient propulsion, such designs were shelved in favor of more conventional rocket technology. [Ref. 9: p. 1]

With the advent of the Mercury, Gemini, and Apollo programs, propulsion technology was significantly advanced and substantial information was obtained on reentry of spacecraft into the Earth's atmosphere. These developments coupled with substantially new technology in spacecraft systems allowed the consideration of earlier concepts for a reusable earth-to-orbit transportation system. [Ref. 9: p. 1]

Five aerospace companies began conducting studies for NASA in 1969 to determine the most practical approach for a Space Shuttle design: Lockheed Missles and Space

Company, North American Rockwell Corporation, General Dynamics Corporation, Martin Marietta Corporation, and McDonnell Douglas Astronautics Company. [Ref. 5: p. 114]

In May 1970, NASA awarded North American Rockwell and General Dynamics, working together as a spacecraft-launch vehicle team, an eleven-month contract to define more fully their shuttle concept. McDonnell Douglas and Martin Marietta were chosen to submit a competitive design. Also chosen to conduct feasibility studies of alternate designs were Grumman Aerospace Corporation, Lockheed, and Chrysler Corporation. [Ref. 5: p. 114]

C. THE DESIRE FOR A MANNED ORBITER

The Shuttle would have a unique feature that existing Expendable Launch Vehicles (ELVs) did not have. Not only did the Shuttle promise to be less expensive but, because astronauts were aboard, functions that could not be normally performed on satellites in space could now be executed.

Among the features a manned launcher promised were:

- Satellite services in space. Replacing components or refueling for example. This promised to extend satellite lifetime, or make operational a satellite in distress.
- Satellite retrieval. If satellite repair in space was beyond the Shuttle and crew capabilities then the Shuttle could simply place the ailing satellite in the large cargo bay and return it to earth for refurbishing and later launch.
- Scientific experiments could be performed by Shuttle personnel in the zero gravity environment of space.
- Because the Shuttle was carrying personnel to space, the ride to orbit promised to be much more gentle than existing ELVs. This would allow satellite designers to be more lenient on satellite launch requirements.
- Astronauts on board the Shuttle would allow for human judgement and flexibility in space, as well as benefits not yet realized.

Additionally, manned space ventures have a leadership aspect. This was perhaps the single most important element that gained presidential support. NASA argued that "the United States can not forego its responsibility -- to itself and to the free world -- to have a part in manned space flight ... for the U.S. not to be in space, while others do have men in space, is unthinkable, and a position that America can not accept." This kind of argument reportedly appealed to President Nixon, who saw astronauts as representing the very best of American values and said, "we must be on the leading edge of this kind of technological development." [Ref. 8: p. 1104]

D. DOD INPUT TO SHUTTLE DESIGN

During NASA's Shuttle analyses it was clear that any economic justification depended crucially on the Shuttle "capturing" all U.S. missions likely to be flown during the 1980's. In particular, NASA had to gain the agreement of the national security community to use the Shuttle to launch all military and intelligence payloads, which were projected to be some 34% of future space traffic. DOD support of the Shuttle was crucial on both political and economic grounds. [Ref. 8: p. 1100]

Accommodating DOD missions required a Shuttle that could handle payloads up to 60 feet long, could launch up to 40,000 pounds into polar orbit and 5,000 pounds into geosynchronous orbit (this translates to a 65,000 pound maximum payload into a due east, 100 mile low earth orbit), and could maneuver to land at the same location from which it was launched after only one orbit of the earth. Of the major design parameters of the Shuttle, only the maximum payload width, 15 feet, was based primarily on a NASA requirement, although NASA as well as DOD projected the need for 60 foot long and 65,000 pound payloads. [Ref. 8: p. 1101]

Perhaps the military requirement with the most impact on Shuttle design was for high cross range or the ability to maneuver upon reentry to either side of the vehicle's ground track. The Air Force wanted 1100 to 1500 mile cross-range capability allowing for a quick return from orbit to military air fields. In particular, the Air Force wanted to be able to launch the Shuttle into polar orbit from Vandenburg Air Force Base on the California coast, have it rendezvous with an already orbiting payload, and return after a single orbit to Vandenburg. The landing strip would have moved east some 1100 miles as the earth rotated during the approximately 110-minute Shuttle orbit. [Ref. 8: p. 1101]

In order to achieve this cross range capability, NASA designed a delta-wing for the Shuttle, which in turn made the vehicle heavier. Maneuvering during high-speed reentry also exposed the vehicle to higher temperatures for longer periods as compared to a "straight in" approach, and required doubling the weight of the thermal protection system. These increases in orbiter weight made it difficult to meet payload lifting requirements and placed extra demands on the Shuttle's propulsion systems. [Ref. 8: p. 1101]

Even though DOD drove many aspects of the Shuttle design, it was not clear how much military interest there was in the Shuttle or how accurate were the projections of future military and intelligence missions on which the DOD requirements were based. Secretary of the Air Force and once former top NASA official Robert Seamans saw "no pressing need" for the Shuttle, but characterized it as "a capability the Air Force would like to have." Although most high ranking Air Force Officers favored the shuttle, most were satisfied with the service's own large expendable Titan rocket. [Ref. 8: p.1101]

The military's only significant share of Shuttle development costs were those used to create a launch facility at Vandenburg Air Force Base. DOD agreed in 1971 not to develop any new launch vehicles of its own, and leaders of the national security community did communicate their support of the Shuttle program both to the White House and to Congress. Many believe the military potential of the Shuttle was another key factor in Nixon's decision to approve the Shuttle in 1972.

NASA had its own list of military missions that the Shuttle might perform. For example:

> The shuttle could be maintained on ready alert, making possible rapid responses to foreseeable and unexpected situations and greatly increase flexibility and timeliness of responses to military or technological surprises, such as: (a) rapid recovery and replacement of a faulty or failed spacecraft essential to national security; (b) examination of unidentified and suspicious orbiting objects; (c) capture, disablement, or

destruction of unfriendly spacecraft; (d) rapid examination of crucial situations developing on earth or in space whenever such events are observable from orbiting spacecraft; and (e) rescue or relief of stranded or ill astronauts. [Ref. 8: p. 1104]

It apparently was Shuttle capabilities such as these that were attractive to President Nixon. Top Nixon advisor John Erlichman remembered that "a strong influence was what the [illegible] could do with a large cargo bay in terms of the uses of satellites" and "the capa[illegible] capturing satellites, or recovering them." These factors weighed heavily in Nixon's approval of the Space Shuttle. [Ref. 8: p. 1104]

E. EMPLOYMENT FACTOR

NASA spent some time in developing the Shuttle program employment impact, partic[illegible]arly in view of the then-depressed state of the aerospace industry and the upcoming 1972 presidential election. NASA Administrator Fletcher told the White House that "an accelerated start on the Shuttle would lead to a direct employment of 8,800 by the end of 1972, and 24,000 by the end of 1973." This was "a very important consideration in Nixon's mind," according to Erlichman. The White House found that "when you look at the employment numbers and key them to battleground states, the space program has an importance out of proportion to its budget." [Ref. 8: p. 1104]

F. SPACE SHUTTLE APPROVAL

President Nixon gave the go-ahead for the Space Shuttle in January 1972 for mainly the following reasons:

- It would further the United States' manned presence in space.
- It promised to drastically reduce launching and operational costs through reuse of vehicles.
- It was of value to the Department of Defense.
- It would employ some 40,000 aerospace workers by the mid-1970's. [Ref. 8: pp. 1101-1104]

NASA's contractors spent the next [illegible] months refining their designs and adjusting their ideas to more realistic budgets and flight schedules. Shortly after receiving President Nixon's blessing on the Shuttle program, NASA was ready for a Request For Proposal (RFP) for the development and fabrication of a Space Shuttle Orbiter. Four companies responded to the March 1972 request -- Rockwell, McDonnell Douglas, Grumman, and Lockheed -- and delivered their proposals to the Manned Spacecraft Center in Houston on 12 May 1972. [Ref. 5: p. 114]

On 25 July 1972, NASA announced that North American Rockwell (later named Rockwell International) would be responsible for the design, development, and production of the Orbiter. The value o the contract that was awarded on 9 August 1972 was estimated at $2.6 billion over the next six years. [Ref. 5: p. 114] Rockwell International was responsible for the Orbiter as well as integration of all Space Shuttle system components. The prime contractor for the Space Shuttle Main Engines was the Rockwell International Rocketdyne Division in Canoga Park, California. The Morton Thiokol Corporation in Brigham City, Utah, is the prime contractor for the Solid Rocket Motors. The Martin Marietta Corporation, Michoud Operations, Michoud, Louisiana, is the prime contractor for the External Tank. [Ref. 10: p. 13]

NASA faced five major technological hurdles in Space Shuttle development:

- To use a recoverable, inexpensive solid propellant booster.
- To reduce the design weight of the Shuttle so as not to decrease the 65,000 pound payload capability.
- To develop a new thermal protection system since the heat shield principles of previous manned systems were inadequate for a reusable shuttle.
- To design and test new high performance rocket engines for the orbiter.
- To solve the requirement for an on-board, self-contained flight control system. [Ref. 3: pp. 185-186]

G. SPACE SHUTTLE CONFIGURATION

1. Space Shuttle Design Evolution

The Shuttle program saw many evolutionary design changes in the beginning. The first design was based on a "fly back" concept in which two stages, each manned, would fly back to a horizontal, airplane-like landing. The first stage was a huge, winged, rocket-powered vehicle that would carry the smaller second stage "piggy back". The carrier would provide the thrust for lift off and flight through the atmosphere, release the orbiting vehicle, and return to the Earth. The Orbiter, carrying the crew and the payload, would continue into space under its own rocket power, complete its mission and then fly back to Earth. [Ref. 11: p. 2]

The Orbiter vehicle was designed to be considerably larger than the Orbiter of today. It carried its rocket propellants internally, had a flight deck sufficiently large to seat twelve space-station-bound passengers and a cargo bay big enough to accommodate space station modules. The Orbiter size put enormous lifting and thrust-generating demands on the first-stage. [Ref. 11: p. 2]

This two-stage, fully reusable design represented the optimum Space Shuttle in terms of routine access to space, however, it was less than optimum in terms of the funding required, so NASA had to rethink their designs. [Ref. 11: pp. 2-3]

NASA finally found the design that would gain them the green light in development -- the Space Shuttle of today.

2. Space Shuttle Components

See Figure 1 for the current Space Shuttle configuration. The Space Shuttle is a combination of three major components: the delta-winged Orbiter, a pair of solid propellant boosters, and a large external liquid propellant tank.

The Orbiter is the principal part of the Shuttle. Designed to last 100 flights, this winged vehicle is part spacecraft, part aircraft. It carries payloads in a 15 by 60 foot cargo bay in the middle of the fuselage. Forward of the cargo bay is the crew compartment where the astronauts live during a space flight. Aft of the cargo bay are three main orbiter engines that help propel the orbiter during launch. The Thermal Protection System on the Orbiter's exterior enables it to survive the searing heat of atmospheric reentry. After reentry, the vehicle becomes a glider as it makes an unpowered approach and landing on a runway. On-board auxiliary power units provide power for the hydraulic system that operates the control surfaces during the atmospheric flight. Hydrogen and oxygen are combined in fuel cells to provide electricity and water. [Ref. 12: p. 13-6]

The three engines on the aft end of the orbiter, called the Space Shuttle Main Engines (SSMEs), are advanced liquid fuel rocket engines. They burn liquid hydrogen and liquid oxygen under high pressure to create the maximum thrust needed to augment the launch. Each SSME has a rated thrust of 375,000 pounds (1.6 million newtons) at sea level. The thrust can be varied from 65% to 109% of this rated value. [Ref. 12: p. 13-6]

Propellants for the SSMEs are contained in the large External Tank (ET). The tank, made of aluminum, is 154 feet (47 meters) long and 27.5 feet (8 meters) in diameter. It is the largest single Space Shuttle component and the only component that is not reused. When the contents of the ET are depleted, it is allowed to reenter the atmosphere to break apart and burn up over the Indian Ocean. Two large conduits feed propellants into the Orbiter's aft fuselage from the ET. [Ref. 12: p. 13-9]

At launch, two large solid-propellant rockets are attached to the tank, one on each side. These are the Solid Rocket Boosters (SRBs), which provide most of the power to lift the Shuttle off the pad and propel it during the first two minutes of flight. After their propellants are consumed, the empty boosters separate from the Shuttle and descend by parachutes and land in the ocean. These empty motor casings are recovered and reused. The Solid Rocket Boosters are 149 feet (45 meters) long and 12.4 feet (3.5 meters) in diameter, and are the first ever designed for reuse. [Ref. 12: p. 13-10]

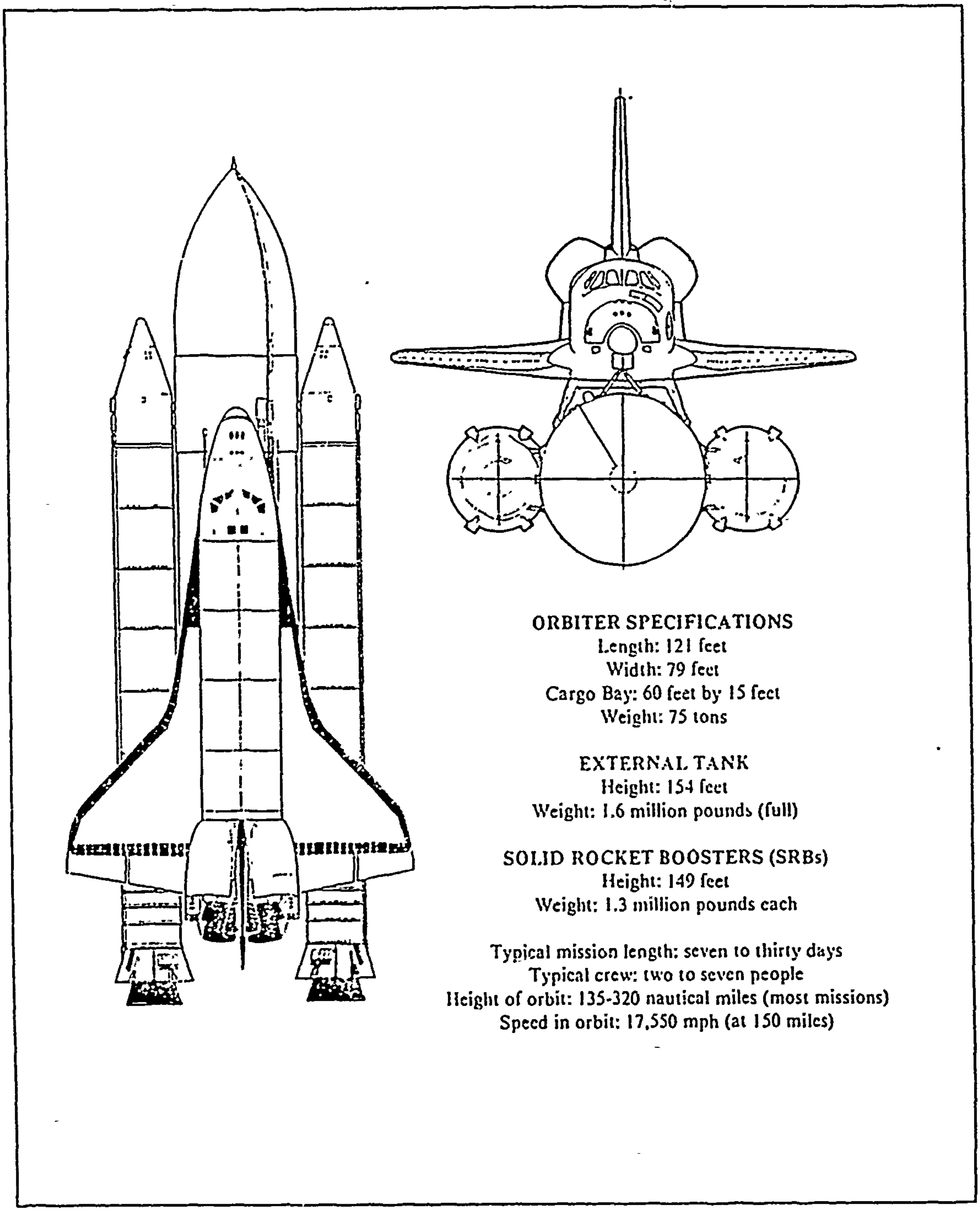

Figure 1. Space Shuttle Configuration

III. SPACE SHUTTLE DEVELOPMENT

A. SPACE SHUTTLE MANAGEMENT

NASA divided managerial responsibility for the Shuttle program among three of its field centers. Johnson Space Center, Houston, Texas was assigned management for the Orbiter. Marshall Space Flight Center, Huntsville, Alabama was made responsible for the Orbiter's main engines, the External Tank, and the Solid Rocket Boosters. Kennedy Space Center, Merrit Island, Florida, was given the job of assembling the Space Shuttle components, checking them out, and conducting launches. [Ref. 11: p. 4] See Figure 2 below for Space Shuttle management organization.

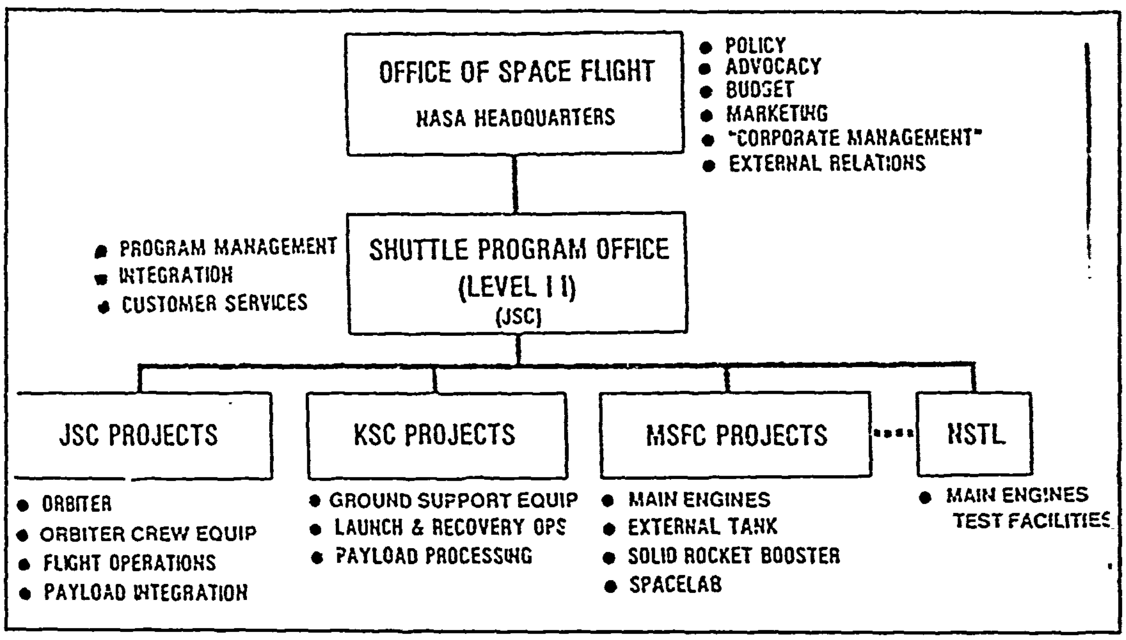

Figure 2. Space Shuttle Management Organization

B. SPACE SHUTTLE MANAGEMENT PHILOSOPHY

NASA and the Space Shuttle prime contractors use the term "constraint management" to characterize the management philosophy which was used for the Space Shuttle

Program. The objectives of this technique were to minimize total costs, as well as minimizing fiscal year funding requirements. In implementing this management philosophy, contingency funds were identified and eliminated at all levels from subcontractor to prime contractor to NASA Field centers, and at NASA Headquarters program reserves were consolidated and maintained. This management approach was in sharp contrast to the Apollo era when money constraints were essentially nonexistent. [Ref. 10: pp. 58-59] While this approach had limited success in minimizing the funding for any given fiscal year, the constraints did not control program cost growth and schedule changes.

In the early years, the "constraint management" approach eliminated contingency funds and forced managers to employ innovative, cost effective techniques for accomplishing the stated objectives. Deferral of work to future years was both necessary due to funding constraints by the Office of Budget and Management (OMB) and feasible from a cost and schedule point of view, although there was an increase in cost and schedule risk. [Ref. 10: p. 59]

After fiscal year 1976, and beginning with the fabrication of major test and flight hardware, continued deferral of work to future years significantly increased the cost and schedule risk. When work was added to a given fiscal year for unanticipated or anticipated changes, NASA program managers had four options to cover the additional work:

- Defer some other work to the next fiscal year;
- Delete some other work;
- Attempt to "fit the added work in"; and
- Cover the additional work with reserves which were maintained by NASA Headquarters. [Ref. 10: pp. 59-60]

Attempting to "fit the added work in" and deferral of work to the following fiscal year were used extensively to accommodate significant amounts of added work. This resulted in major management efforts at the end of the fiscal year to "live" within the fiscal year funding constraints which was referred to as "managing to get out of the fiscal year." [Ref. 10: p. 60]

Work deferral to the following year resulted in more effort with a greater value and different schedule for the following year. The complexity of the cumulative effect of a large number of deferrals was greatly under-estimated by NASA management.

At the end of the fiscal year, the Shuttle managers' time and attention were repeatedly dominated by efforts to get out of the fiscal year, leaving inadequate opportunity to address the equally important job of estimating "budget year" funding requirements. [Ref. 10: p. 60]

C. BUDGET CHRONOLOGY (1972 - 1979)

In March 1972, NASA committed to development of the Space Shuttle using reusable Solid Rocket Boosters for a total cost of $5.15 billion (1971 dollars), a First Manned Orbital Flight (FMOF) scheduled for March 1978, and an Initial Operational Capability (IOC) scheduled for March 1979. [Ref. 10: p. 47]

When the Space Shuttle program was first authorized, the plan called for an Orbiter fleet size of five vehicles with launch site capabilities at both Kennedy Space Center and Vandenberg Air Force Base. The Space Shuttle Program included two phases. The Design, Development, Test, and Evaluation (DDT&E) Phase called for the fabrication of Orbiter 101 for testing, including the approach and landing tests, and full scale vibration tests; the fabrication of Orbiter 102 in a flight configuration; and a refurbishment of Orbiter 101 to a flight configuration after the use of the vehicle for testing. The second phase or Production Phase called for the fabrication of Orbiter 103, Orbiter 104, and Orbiter 105.

With the submission of the fiscal year 1974 budget and as a result of an $85 million reduction by the Office of Management and Budget (OMB) to NASA's budget request, NASA announced a 6 to 9 month delay in the First Manned Orbital Flight (FMOF) schedule with no change in the Space Shuttle Program cost estimate at completion. [Ref. 10: p. 47]

During fiscal year 1975 budget negotiations, OMB once again made a reduction in the NASA budget request amounting to $89 million, which NASA announced would delay the FMOF by an additional 6 months until June 1979 and would increase the total DDT&E program costs by $50 million (1971 dollars). [Ref. 10; p. 47]

NASA's fiscal year 1976 budget request was also reduced $45 million by OMB, although NASA did not reflect a change in program run-out cost or schedule.

For fiscal year 1977, NASA's funding request was reduced by $15 million in DDT&E and $85 million in production which NASA assessed would increase DDT&E total program costs by $20 million with no change in schedule of the FMOF. [Ref. 10: p. 47]

In September 1977, at the time of submission of the fiscal year 1979 budget to OMB, NASA announced that due to technical and cost problems in fabrication and test activities the total program estimate increased by 4% based on experience in building Orbiter 101. [Ref. 10: p. 47]

In May 1979, NASA announced additional cost growth resulting from cumulative effects of technical problems, increased fabrication and assembly efforts on Orbiter 102, technical changes to the external tank, and problems during certification testing of the main engines and solid rocket boosters. The effect of these problems was estimated to increase the total production cost by $250-$350 million in 1971 dollars and delay the FMOF until early 1980. [Ref. 10: p. 47]

The NASA fiscal year 1979 budget request submitted to the Congress in January, 1978 did not include any funds for a fifth orbital vehicle. During the fiscal year 1979 authorization hearings, NASA stated that during formulation of the budget, they were specifically given approval for a four Orbiter fleet operating from the east and west coasts, with the understanding that additional Orbiters would be considered for funding in future years in the event that projected flight rates, actual operating experience, or the loss of an Orbiter warranted augmentation of the Orbiter fleet. However, funds for long lead items for a fifth Orbiter were both authorized and appropriated to provide flexibility for exploitation of the Space Transportation System (STS) capabilities and to provide a backup for any unforseen loss of an orbiter vehicle. Additionally, considerable economy could be realized if production was initiated in fiscal year 1979. [Ref. 10: p. 47]

Many program observers believed the key problem for the Shuttle was in the fact that it was under-funded from its inception. At the time of Shuttle approval, President Nixon did not allow for NASA's 20% contingency reserve fund that was needed for developing the new technology. Most NASA management personnel agree that it was that basic shortfall at the Shuttle birth that has bred the major difficulties of today. [Ref. 13: p. 518]

In addition, the Shuttle agreement was made in 1972 to provide NASA with a level budget each year so that rational plans could be made, and this was not the case. Hence, each year Shuttle management had to meet a reduced budget level that was handed down by the administration -- after yearly work plans were laid out. This required a replanning of work usually after work already begun. This is a very disruptive and inefficient approach for NASA, their contractors, and the subcontractors. Shuttle work required continual reprogramming. More people were sometimes required for replanning work than were doing the work. This was the inevitable result of the Shuttle Program when it started out under-funded. [Ref. 13: p. 518]

Under-budgeting became de facto Space Shuttle policy rapidly, and a key job became meeting a reduced annual budget level. Also, it became de facto Space Shuttle policy to borrow funds or take funds from the operational phase of the Shuttle program.

NASA was forced to substitute schedule contingency for dollar contingency. [Ref. 13: p. 518]

Then Deputy Director of the NASA Ames Research Center, A. Thomas Young, summarized the Shuttle funding in a report given to the Subcommittee on Space Science and Applications:

> Space Shuttle funding on a fiscal year basis has been less than that required to meet established schedules. This has been accepted as the 'way of life' by Shuttle management who have evolved management techniques to cope with limited funding situation. Demanding work plans have been utilized in an effort to apply pressure to maximize accomplishments for available funds. A direct consequence is a work plan that is inconsistent with the budget. In the absence of adequate funding reserves, schedule has been used as a reserve for delaying work that could not be funded. This approach has forced a focus on the near-term with frequent significant adjustments in the work plan to assure remaining within the fiscal year funding limitations. The principal management objective appears to have been to conduct the First Manned Orbital Flight (FMOF) as soon as feasible with available funds and to allow production orbiter schedule delays as required. [Ref. 13: p. 420]

D. COST GROWTH

Fiscal years 1977, 1978, 1979, and 1980 saw an increased infusion of funds into the Shuttle DDT&E program. In fiscal year 1977, an increase of funds of $55 million went to DDT&E. Twenty-five million was from the economic Stimulus Appropriations Act of 1977 and $30 million from the space flight operations budget, $27 million of which was residual Apollo-Soyuz test project funds. This increased funding was used for technical problems encountered in the Orbiter, SSMEs, Solid Rocket Booster, and External Tank, as well as additional manpower needed and subcontractor buildup. [Ref. 14: p. 141]

In fiscal year 1978, $100 million of funds were transferred from production to DDT&E to provide for increased effort resulting from deferrals and delays from fiscal year 1977 and 1978. These funds were applied to the Orbiter, Solid Rocket Booster, and External Tank in areas of testing, subcontractor cost growth, and increased manufacturing costs. [Ref. 14: p. 142]

In fiscal year 1979, additional funds were identified from a requested $185 million supplemental appropriation from Congress. Also an additional $10 million was reprogrammed from the Teleoperator Retrieval System (TRS) project and a $70 - $90 million transfer from Shuttle production funds. These funds were used in solving technical problems in all major components of the Space Shuttle system as well as providing funds needed for the launch and landing aspect of the system. [Ref. 14: p. 143]

NASA felt that Space Shuttle production funding in fiscal year 1979 was constrained due to the uncertainty of the fiscal year 1979 supplemental request submitted to Congress. This funding constraint, together with technical problems, resulted in schedule delay of production orbiters. Because of this constrained buildup, NASA felt that it was not possible or productive to use the full $458 million that was allotted in fiscal year 1979 for production. So NASA felt that a $70 to $90 million reallocation of these production funds to development would have no further impact on production schedule. [Ref. 14: p. 119]

By June 1979, NASA said that the original estimate of $5.15 billion in 1971 dollars had grown to almost $6.0 billion dollars -- a total cost growth of about 15 percent. (See Table 1.) Seventy million dollars of this increase was caused by schedule stretch-outs resulting from OMB budget limitations. The balance of the increase resulted from technical problems encountered during development and test. [Ref. 14: p. 417]

NASA was seeking a $220 million budget amendment for fiscal year 1980. This additional amount was to be used for development and would alleviate the need to reallocate money from production assuming the cost projections were accurate and no additional unexpected technical problems occur. NASA felt the $220 million would allow the orbiter production program to proceed at a pace to support projected launch needs. [Ref. 14: p. 121]

In both the fiscal year 1979 supplemental ($185 million) and fiscal year 1980 budget amendment ($220 million) cases, the additional funding estimates were developed to allow the continuation of the pace of development, test and manufacturing activities necessary to meet the projected launch requirements. The specific estimates were a result of program status evaluations in the late summer of 1978 and spring of 1979, respectively. These program evaluations took into consideration schedule status and the need for additional resources to compensate for technical problems, design changes, schedule delays and the underestimate of work efforts subsequent to the estimate provided in the applicable Congressional budgets. The need for additional funding represented the best judgment at the particular time of the program requirements, allowing a minimal reserve for unanticipated changes and growth. NASA knew the additional resources would not provide the program with the funding flexibility to accommodate major unforeseen problems and growth. [Ref. 14: p. 160]

In February 1982, months after the FMOF of the Shuttle system, NASA estimated the DDT&E completion figure at $10 billion. In terms of 1971 dollars, this equated to approximately $6.8 billion dollars or a 31% increase over the original $5.15 billion dollar figure. (See Table 1.) [Ref. 15: p. 1256]

Ironically, the official cost target for Shuttle development was fixed by the White House in January, 1972, at the lower end of a 20% ($1 billion) range in the estimated probable costs submitted by NASA at the time. This indicated to both the space agency and the presidential review committees that Shuttle costs have actually been as predicted in 1972, including the need up to 1979 for an additional $1 billion to finish the development. [Ref. 16: p. 21]

Table 1. NASA SPACE SHUTTLE DDT&E CHRONOLOGY

Budget Year	First Manned Orbital Flight	Initial Operating Capability	Total DDT&E Cost ($1971, billions)	Change ($1971, billions)
FY 1973	March 1978	March 1979	$5.150	---
FY 1974	Dec. 1978	Dec. 1979	$5.150	---
FY 1975	June 1979	June 1980	$5.200	+ $0.050
FY 1976	Same	Same	Same	---
FY 1977	Same	Same	$5.220	+ $0.020
FY 1978	Same	Aug. 1980	Same	---
FY 1979	Same	Aug. 1980	$5.430	+ $0.210
FY 1980	Dec. 1979	May 1981	$5.654	+ $0.224
Actual	Apr. 1981	Feb. 1984	$6.800	+ $1.146

E. SCHEDULE

The Space Shuttle Program was initiated as a fiscal program in 1971. An important consideration was to scope the program such that NASA could continue a balanced aeronautics and space program within a strained total budget level. In the first few years of the Shuttle Program, fiscal year funding of the Shuttle was less than that requested from OMB. With a limited budget and a lean technical program, the only alternative was to use the near-term schedule as the flexible element of the program. The importance of the FMOF milestone was recognized, and its schedule was given priority throughout the program. By necessity, the production Orbiters were allowed to slip in schedule as required to meet the funding requirements. [Ref. 13: p. 433]

As of February 1977, Orbiter 102 (*Columbia*), the first orbital flight vehicle, was scheduled for delivery to Kennedy Space Center in August 1978. Orbiter 101 (*Enterprise*), following its use in the mated ground vibration tests at Marshall Space

Flight Center, was to be refurbished and delivered to Kennedy Space Center in June, 1981. Orbiters 103 (*Discovery*) and Orbiter 105 (cut from the fiscal year 1979 budget) were to be delivered to the Western Test Range in March, 1982, and March 1984, respectively. Orbiter 104 (*Atlantis*) was scheduled for delivery to Kennedy Space Center in March, 1983. Internal schedule adjustments in the Fall of 1977 called for delivery of Orbiter 102 to Kennedy Space Center in October, 1978, a slip of two months. Further, NASA decided to modify the structural test article for use as the second flight vehicle with a delivery date to Kennedy Space Center of February, 1981. Delivery of Orbiters 103 and 105 would each slip six months from the February, 1977 schedule. This plan did not include the use of Orbiter 101 as an operational vehicle. [Ref. 17: p. 5]

In September 1978, NASA reported that an internal Shuttle program review was completed to permit an accurate, updated assessment of cost, schedule, and performance. As a result of this review, NASA determined that all program elements could be ready for a September, 1979 FMOF if all planned tests were successful. Recognizing the possibility of unforseen problems and tests which are not entirely successful, NASA stated at that time there was a good probability of flying the first Shuttle flight in Calender Year 1979. NASA further stated that the current plan was to schedule the first operational flight for February, 1981. NASA reported that these changes would impact both cost and schedule as well as the funding requirements for fiscal year 1979 and fiscal year 1980. [Ref. 17: p. 6]

In September 1978, NASA announced that additional technical problems including the SSMEs, the Thermal Protection System, necessary design changes, and an additional engine test stand would result in a six month delay for the FMOF until September 1979. In January 1979, NASA announced that the FMOF would occur on 9 November 1979. This date was selected for planning and scheduling purposes. These delays resulted in an additional 4 percent increase in total cost estimates. [Ref. 17: p. 6]

Due to funding constraints in production funding in fiscal year 1979 and with associated technical problems, NASA was led to announce in June of 1979 delivery impacts on production Orbiters. Preliminary schedule impacts on production orbiters were estimated at approximately six to twelve months on Orbiters 099, 103 and 104. [Ref. 14: p. 119] (See Table 2 for 1979 production Orbiter delivery dates.)

Table 2. PRODUCTION ORBITER DELIVERY DATES AS OF FY 1979

Orbiter	Projected Delivery Date
Columbia, OV-102	First flight Orbiter
Challenger, OV-099	March 1982
Discovery, OV-103	Summer 1983
Atlantis, OV-104	Fall 1984
OV-105	Cut From Budget

1. Production Orbiters

Since that original estimate, planning for the implementation of the Orbiter fleet was impacted by budget reductions, Orbiter delivery schedule adjustments, revised estimates (based on experience in the developmental phase), and new requirements identified as development neared completion.

Some examples of the above included:

- the fiscal year 1977 budget decision to defer the start of production;
- schedule adjustments related to NASA's realignment of program funding between DDT&E and production in fiscal years 1978 and 1979;
- the fiscal year 1979 budget decision to delay proceeding with a fifth orbiter;
- the actual Orbiter and main engine fabrication and assembly experience on development hardware;
- the delivery schedule stretch-out included in the fiscal year 1980 and 1981 budget plans;

- the identification of new requirements, such as the orbiter weight reduction program and systems engineering support.

Based on the combined effects of these varied impacts, the estimated 1981 figure to produce the fleet of operational Orbiters was $3.556 billion in 1981 dollars. This estimate provided for modifying Orbiter 102 after its use for the Orbital flight test program and early operational flights, upgrading the Orbiter structural test article (Orbiter 099), and the fabrication and assembly of two additional Orbiters and associated main engines. [Ref. 15: p. 3374]

2. First Manned Orbital Flight (FMOF)

By Summer 1979 NASA was facing a seventh month delay in the FMOF which in turn caused a delay in the first operational flight. NASA estimated Initial Operating Capability (IOC) to be late Summer 1981. This permitted NASA to fly only one mission in fiscal year 1981 and ten missions in fiscal year 1982. This also reduced the flight rate from twenty-three to eleven in fiscal year 1981-82. NASA felt the lower flight rate would make it possible to reduce fiscal year 1980 funding requirements for flight hardware procurement. However, NASA feared the loss of reimbursements due to cancellation of reimbursable flights may offset this reduction. [Ref. 14: p. 124]

NASA was also concerned that the delay in the FMOF and the consequent rescheduling of the first operational flight may cause some commercial and foreign users to consider an expendable launch vehicle (ELV) instead of the Shuttle. However, a survey conducted by NASA of the early customers at that time indicated little interest in launching on the more expensive expendable systems. [Ref. 14: p. 127]

NASA planned for some time to support up to six Delta and one Atlas/Centaur launch vehicles as potential back-ups in case the Shuttle was not available for customer mandatory launch dates. These vehicles could be requested by the user up to the FMOF of the Shuttle; after that, the user must wait for Shuttle availability. [Ref. 14: p. 127]

NASA believed that since utilization of the Shuttle by DOD did not commence until late 1982, DOD requirements would be satisfied in accordance with requested launch dates, providing no further Shuttle delays were experienced. Delay of the FMOF, therefore, apparently did not have a significant impact on DOD requirements as far as NASA could determine in June 1979. [Ref. 14: p. 128]

The operational date slip caused by the delay in the FMOF generally moved all operational missions a similar period. NASA attempted to hold important missions with mandatory launch windows to the then present schedules at the expense of lower priority, non-scheduled constrained missions. This arrangement was recognized to affect primarily NASA missions only.

In addition, cargo manifests were revised to take full advantage of available cargo bay space as well as Shuttle weight and turn-around capabilities. These changes were felt to minimize the impact of the FMOF delay. [Ref. 14: p. 129]

The number of planned Space Shuttle developmental Orbital flight tests were reduced from six to four. Although NASA planned to specify that the Space Shuttle would be considered operational on the fifth flight, in reality the Shuttle would require research and development activities for some time. [Ref. 17: p. X]

By January 1980 NASA projected the launch cost to have increased from early projections of $10.5 million per flight to $15.2 million per flight in 1971 dollars. To minimize these costs, NASA placed increased emphasis on production activities particularly with regard to reducing the unit costs of the External Tank and the Solid Rocket Boosters. [Ref. 17: p. XI]

F. DEVELOPMENTAL TECHNICAL CONCERNS

As of November 1979 some major Space Shuttle Milestones were reached. These included:

- The basic detailed design of the system was completed.

- Virtually all wind tunnel testing and scaled vehicle testing were successfully completed.
- The Orbiter *Enterprise* (OV-101) and the Orbiter structural test article *Challenger* (OV-099) completed their testing.
- Fifteen of the Shuttle Main Engines were produced, and the three SSMEs for the first orbital flight test were at the launch sight and installed.
- The successful Approach and Landing Test Flight series was completed. This consisted of eight captive flights coupled with a Boing 747, and five free flights released from a Boing 747.
- The full scale mated vertical ground vibration tests were successfully completed utilizing the Orbiter *Enterprise,* a flight type external tank, and inert solid rocket boosters.
- The *Enterprise,* external tank, and inert Solid Rocket Boosters were successfully utilized to verify the launch facilities at Kennedy Space Center.
- The Orbiter *Columbia* (OV-102) was delivered to the launch site and, despite problems with the thermal protection system, was progressing on remaining subsystem checkout activities.
- The first flight External Tank was delivered to the launch site and was undergoing checkout.
- All Solid Rocket development motor firings plus two qualification motor firings were successfully completed. One remaining qualification motor firing was scheduled for early 1980.
- The Solid Rocket Motor for the first orbital flight test were delivered to the launch site in November 1979.
- The first launch and landing facilities at Kennedy Space Center and Dryden Flight Research Center were essentially ready for first flight. [Ref. 17: pp. 15-16]

As of November 1979, the most significant remaining concerns to NASA regarding the Shuttle Program and the FMOF included:

- Overall Main Engine development leading to certification.
- The Orbiter thermal protection system.

1. The Space Shuttle Main Engines (SSMEs)

The Space Shuttle Main Engine (SSME) development program experienced a mixture of accomplishments and major setbacks following a 1980 Congressional review. Delays in the program and changes in testing and certification schedules increased the work effort and program costs. [Ref. 17: p. 19]

Space Shuttle Main Engine progress was substantially slowed during the latter part of 1979 due to delays in restarting the Main Propulsion Test (MPT) after a July 1979 MPT incident involving failure of the Main Fuel Housing. The Main Fuel Valve Housing was subsequently modified and incorporated into field units. An attempted main propulsion test was again aborted on November 4, 1979, due to failure of the high pressure oxygen turbopump seal and rupture during engine shutdown of the hydrogen fuel line. The resulting design modification caused further delays.

Also discovered at that time was the use of incorrect welding wire used in critical areas of SSMEs. There are about 1800 welds on a SSME of which 200 are considered critical. Each individual weld on every SSME was inspected and corrected on a case by case basis. [Ref. 17: pp. 19-20]

The SSME production schedule was also changed following a May-June 1979 Congressional review. Production engine fabrication was accelerated and three new engines were added to the program to provide five SSME flight sets. These changes impacted the funding requirements in fiscal year 1981. [Ref. 17: p. 21]

2. Orbiter Thermal Protection Tiles

After the Orbiter *Columbia* was delivered to the Orbiter Processing Facility, it was discovered, by testing, that some load conditions imposed during the ascent phase of the flight could over stress the TPS (Thermal Protection System) tiles. As a consequence, an extensive testing program was instituted to proof load approximately 24,000 tiles and replace or install approximately 10,000. This effort proved to be very labor intensive and was completed around March 1980.

The primary area of concern or doubt was in the testing of two particular types of tiles installed on the upper surface of the Orbiter. Due to testing techniques, these tiles required more time and effort than was actually planned. [Ref. 17: p. 18]

G. FLIGHT TESTS

The first Shuttle test flights were conducted at Dryden Flight Research Facility, California, in 1977. The test craft was the Orbiter *Enterprise*, a full size vehicle that lacked engines and other systems needed for orbital flight. The purpose of these tests were to check out the aerodynamic and flight control characteristics of the Orbiter in atmospheric flight.

Mounted piggyback atop a modified Boing 747, the *Enterprise* was carried to altitude and released for a gliding approach and landing at the Mojave Desert Test Center. Five such flights were made. They served to validate the Orbiter's computers and other systems. They also demonstrated the craft's subsonic handling qualities, in particular its performance in the precise unpowered landings that would be required on all Shuttle flights. [Ref. 11: p. 4]

By early 1981, the Space Shuttle was ready for the Orbital flight test program. This was designed to include more than 1,000 tests and data collection procedures. All flights were to be launched from Kennedy Space Center, and terminate at Edwards Air Force Base, where the Dryden Flight Research Facility is located.

Originally intended for a six mission program, the Orbital test series was reduced to four flights:

- STS-1 (Space Transportation System - First Flight). April 12 - 14. 1981. Orbiter *Columbia*. was a two-day demonstration of the Orbiter's ability to go into orbit and return to Earth safely. Its main payload was a flight instrumentation pallet containing equipment for recording temperatures. pressures and acceleration levels at various points around the Orbiter. In addition, there were checkouts of the cargo bay doors, attitude control system and orbital maneuvering system.
- STS-2. November 12-14, 1981. Orbiter *Columbia*, marked the first test of the Remote Manipulating System and carried a payload of Earth survey instruments. This was the first time any spacecraft had flown twice. Failure of a fuel cell shortened the flight by about three days.
- STS-3. March 22-30, 1982. Orbiter *Columbia*, was the longest of the initial test series. staying aloft for eight days. Activities included a special test of the manipulator in which the robot arm removed a package of instruments from the payload bay but did not release it into space. The flight included experiments in materials processing.

- STS-4, June 27 - July 4, 1982, Orbiter *Columbia*, featured another test of the robot arm, which extended a scientific payload over the side of the payload bay, then re-stowed it. Materials processing experiments were conducted, as were a number of scientific investigations. This flight carried the first DOD payload. [Ref. 11: pp. 4-5]

With the landing of STS-4, the Orbital flight test program came to an end with 95 percent of its objectives accomplished. The interval between flights was trimmed from seven months to four, then three. NASA declared the Space Shuttle "operational." Many erroneously believed that the Shuttle had attained an airline-like degree of routine operation, when in reality much was still to be learned about the Shuttle. Since the Shuttle was considered operational, NASA placed payload requirements over spacecraft testing, which required larger crews. [Ref. 11: p. 5]

H. SPACE SHUTTLE OPERATIONS

By the early 1980's the Shuttle was the most complex space launch vehicle ever built with specialized capabilities never before seen in access to space. The launch and landing profiles are an example of this.

1. Launch Profile

See Figure 3 for a typical launch profile. (Source: Ref. 18) Most prelaunch checks are performed by computer, but special crews board the Orbiter five hours prior to launch to ensure all controls are properly set. The astronauts board the Orbiter at approximately two hours prior to lift-off and perform additional preflight checks. [Ref. 18: p. 1.6]

At 3.8 seconds prior to launch or T-3.8, the computers command the SSMEs to fire. The first SSME fires at T-3.46 seconds, followed by the other two at 120 millisecond intervals. This in turn causes the Shuttle to lurch forward about 40 inches toward the ET.

The SSME's builds up to 90% thrust by T-0, and a timer set for 2.46 seconds starts. When it reaches zero, the Solid Rocket Boosters ignite. The 2.46 second delay

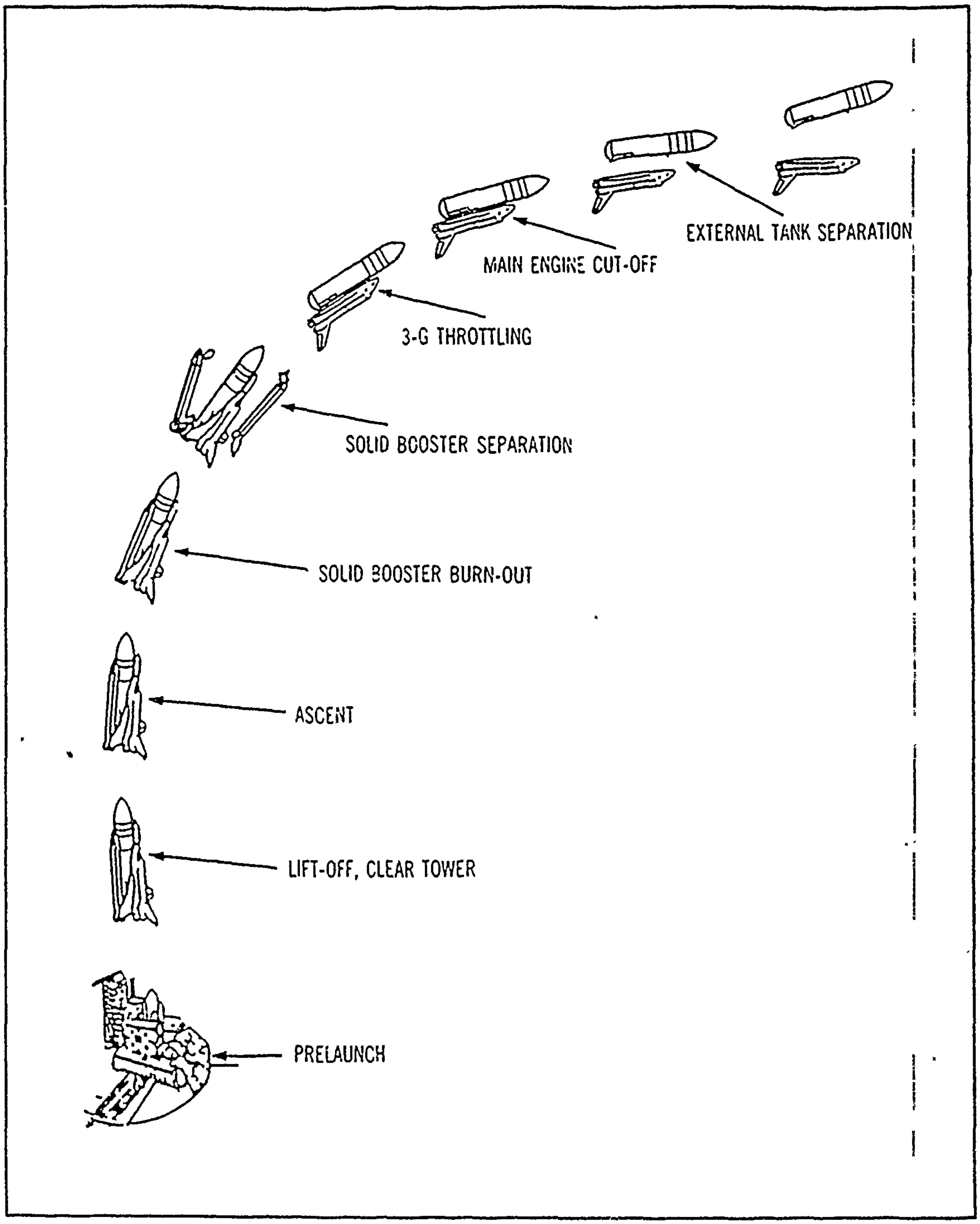

Figure 3. Space Shuttle Launch Profile

allows the Shuttle to be upright at solid-booster ignition as it sways away from the initial lurch toward the ET. [Ref. 18: p. 1.6]

Thrust from the SRBs builds up quickly and the vehicle lifts off at T+3.0 seconds. Eight seconds after launch the Shuttle rolls 120 degrees to the right, and assumes a "heads down" position. During ascent the thrust of the SRBs decreases and the SSMEs are throttled to keep acceleration below 3 g (three times earth gravity). [Ref. 18: p. 1.6]

About 50 seconds into the flight the Shuttle reaches the speed of sound, Mach 1. By time the SRBs consume their propellants (T+2 minutes and 12 seconds) the Shuttle has reached Mach 4.5 and an altitude of 28 miles (45 kilometers). The empty SRB casings separate from the vehicle and land in the ocean via parachute. They are retrieved, refurbished, and later reused. [Ref. 18: p. 1.6]

At this point of the flight, the Shuttle consists of the Orbiter and External Tank. It continues to gain speed and altitude; at 6.5 minutes into the flight, the speed is approximately 15 times the speed of sound at an altitude of 80 miles (130 kilometers). The Shuttle now performs a long shallow dive to 72 miles (120 kilometers). Near the end of this dive, 8.5 minutes after liftoff, the SSMEs are shut down. The External Tank is discarded twenty seconds later to splash down in a remote ocean area. [Ref. 18: p. 1.6]

Following ET separation, the Orbital Maneuvering System (OMS), consisting of two 6,000-pound-thrust (26,700 newton) engines, fires to place the Orbiter in a low elliptical orbit. Half an earth orbit later, about 45 minutes after launch, the OMS engines fire again to place the Orbiter in a higher circular orbit, generally 250 miles (400 kilometers) in altitude. [Ref. 18: p. 1.7]

One of the first tasks of the Shuttle crew is to open the cargo bay doors. This is necessary because there are radiators located on the inside surface of the doors that dissipate heat accumulated within the Orbiter. If this heat is not discarded, the mission is aborted. [Ref. 18: p. 1.7]

2. Landing Profile

See Figure 4 for a typical landing profile. (Source: Ref. 18) Near the end of the mission, the cargo bay doors are closed and the Orbiter is maneuvered so that the tail section is flying "first". About 60 minutes prior to landing (L-60), the OMS engines fire to slow the vehicle so it will enter the atmosphere. A pitch maneuver configures the Orbiter with nose pointed forward and up at an angle of 28 to 38 degrees. Atmospheric entry begins at an altitude of 400,000 feet (122,000 meters) and a distance of about 5,000 miles (8,000 kilometers) from the landing sight. [Ref. 18: p. 1.7]

During entry, the tremendous energy of the Orbiter (which begins entry at a speed of 16,500 miles per hour) is dissipated by atmospheric drag. This generates enormous heat - portions of the Orbiter exterior reach 1510 degrees centigrade (2,750 degrees fahrenheit). The heat ionizes air molecules near the spacecraft, so from about L-25 minutes to L-12 minutes the vehicle is enveloped in a sheath of electrically charged particles that blocks radio signals between the spacecraft and the ground. This "communication blackout" occurs at a critical portion of the flight. However, all maneuvers can be performed by either on-board computers or the Shuttle pilot without ground communications. [Ref. 18: p. 1.7]

Rate of descent and range are controlled by bank angles; the steeper the bank angle, the greater the descent rate (and also greater heating rate). The Orbiter's nose swings left and right as several hypersonic banks are made to control the flight path. At around L-20 minutes, maximum heating occurs. [Ref. 18: p. 1.8]

As the craft descends, it becomes a glider - an extremely large heavy one. The transition from control by spacecraft reaction control jets to aerodynamic-control surfaces is made in stages. When a speed of Mach 3.5 is reached as well as an altitude of

45,000 feet (13,700 meters) the rudder becomes effective and the control jets are shut down. [Ref. 18: p. 1.8]

Descending at a rate of 10,000 feet (3,000 meters) per minute, the 100-ton (90,000 kilogram) Orbiter is on a glideslope of about 20 degrees.

At an altitude of 1,750 feet (530 meters), the nose is pulled up in a "preflare" maneuver to reduce the glideslope to 1.5 degrees. By the time this maneuver is complete, the altitude is 135 feet (41 meters).

The landing gear extends when the Orbiter is below 90 feet (27 meters), 14 seconds before landing. After the gear extend and lock, a final flare is made to reduce airspeed to 215 mph (345 kph). The Orbiter lands first on its main aft gear then drops onto the nose wheels. It rolls to a stop and is met by a convoy of ground servicing vehicles. [Ref. 18: p. 1.8]

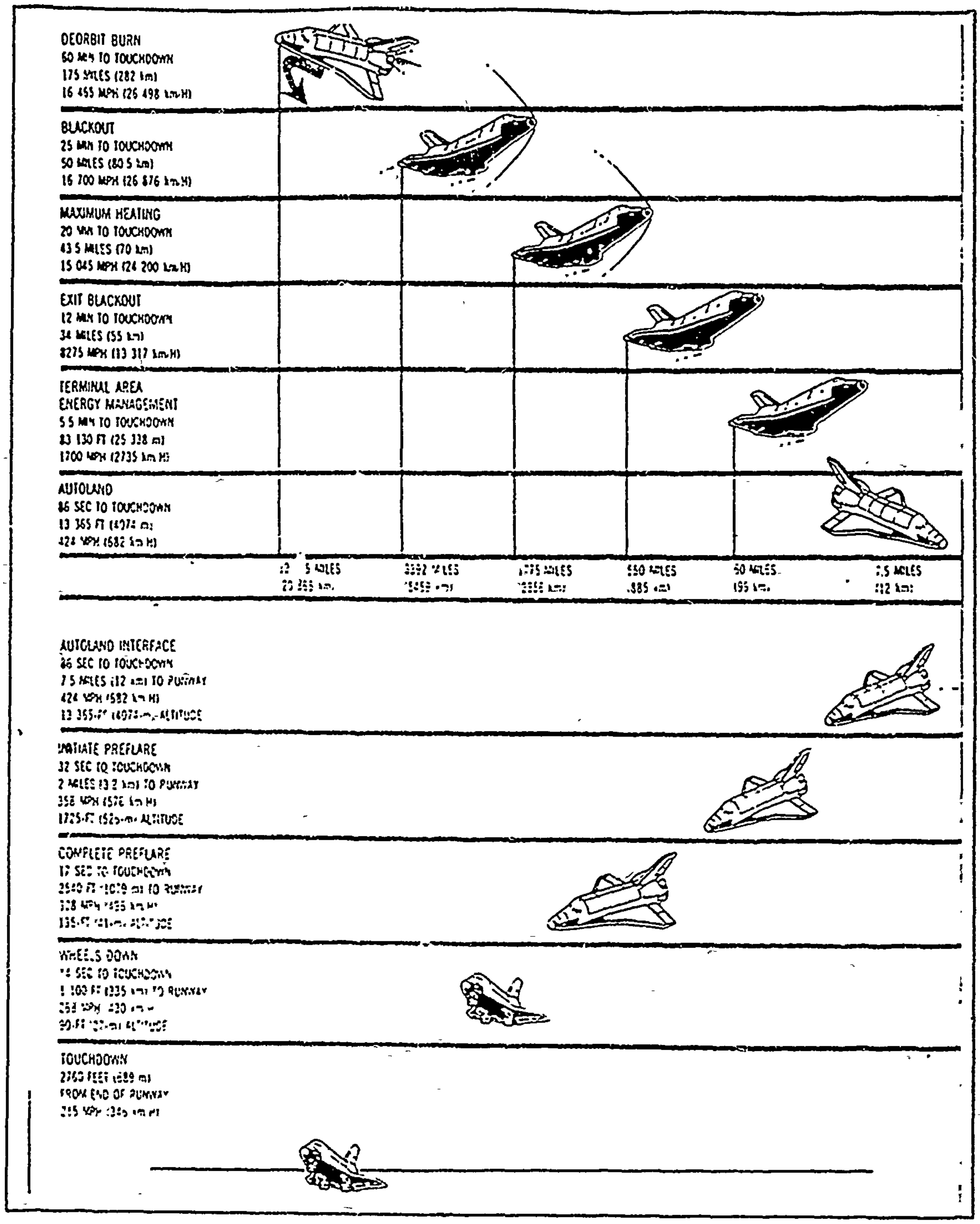

Figure 4. Space Shuttle Landing Profile

IV. OPERATIONAL SPACE SHUTTLE

With the ending of the four flight orbital test series, the Space Shuttle was considered operational by NASA; however, since the original estimate, planning for the implementation of the operational Orbiter fleet was impacted by factors such as:

- budget reductions;
- Orbiter delivery schedule adjustments;
- revised estimates based on experience in the developmental phase;
- new requirements identified during the development test flight program;
- the FY 1977 budget decision to defer the start of production;
- schedule adjustments related to NASA's realignment of program funding between DDT&E and production in FY 1978 and FY 1979;
- the FY 1979 budget decision to delay proceeding with a fifth Orbiter;
- the actual Orbiter and main engine fabrication and assembly experience on development hardware;
- the delivery schedule stretch-out included in the FY 1980 and FY 1981 budget plans; and
- the identification of new requirements such as the Orbiter weight reduction program and systems engineering support.

Based on the combined effects of these varied impacts, the 1981 estimate to design, develop, test, and procure the fleet of operational Orbiters was $3.5 billion, was equivalent to $1.6 billion in FY 1971 dollars. [Ref. 19: p. 76]

Additionally, the resulting Space Shuttle in 1981 did not have the originally planned capabilities as the Space Shuttle in 1971. (See Table 3.)

Table 3. COMPARISON OF PROPOSED AND PROJECTED SPACE SHUTTLE

Item	Originally Proposed in 1971	Projected Capability in 1981
Payload Launch Capability	65,000 lbs	65,000 lbs
Flight Rate	60/year	24/year
Max On-Orbit time	30 days	10 days
Cost per Flight ($mil, 1982)	34.5	83.3
Orbiter Turnaround Time	160 hours	35 days
Max Altitude	600 nautical miles	400 nautical miles

A. SPACE SHUTTLE MISSION HISTORY (PRIOR TO CHALLENGER ACCIDENT)

After the ninth Space Shuttle flight (STS-9), NASA changed the method for numbering missions. Each flight was designated by two numbers and a letter. The first digit indicated the fiscal year of the scheduled launch (e.g., 4 for 1984). The second digit identified the launch site (1 is the Kennedy Space Center, 2 is Vandenburg Air Force Base). The letter corresponds to the alphabetical sequence for the fiscal year (e.g., B is the second mission scheduled). [Ref. 11: p. 5]

Including the initial orbital tests, the Shuttle flew 24 successful missions over a 57 month period prior to the *Challenger* accident in January of 1986. *Columbia* made seven trips into space, *Discovery* six and *Atlantis* two. *Challenger* flew most frequently -- nine times -- prior to the accident. [Ref. 11: p. 6] (See Table 4.)

Table 4. SPACE SHUTTLE OPERATIONAL MISSION HISTORY (NOV. 1982 TO JAN. 1986)

Flight Number	Date	Vehicle	Highlights
STS-5	Nov. 11-16, 1982	*Columbia*	Launched two communication satellites, first operational flight
STS-6	Apr. 4-9, 1983	*Challenger*	First EVA, NASA communications satellite deployed
STS-7	Jun. 18-24	*Challenger*	Remote Manipulator tested, first retrieval of an orbital object
STS-8	Aug. 30-Sep. 6, 1983	*Challenger*	Robot Arm tests
STS-9	Nov. 28-Dec. 8, 1983	*Columbia*	First Spacelab. Return of *Columbia* after one year mod.
41-B	Feb. 3-11, 1984	*Challenger*	Two Satellites fail to reach orbits due to Perigee/Apogee motors
41-C	Apr. 6-13, 1984	*Challenger*	Retrieval,repair, and redeploy. of Solar Max.
41-D	Aug. 30-Sep. 5, 1984	*Discovery*	3 communication satellites deployed
41-G	Oct. 5-13, 1984	*Challenger*	Earth observations
51-A	Nov. 8-16, 1984	*Discovery*	Retrieved two satellites from flight 41-B
51-C	Jan.24-27, 1985	*Discovery*	DOD payload
51-D	Apr.12-19, 1985	*Discovery*	Two commercial satellites deployed
51-B	Apr. 29-May 6, 1985	*Challenger*	Second Spacelab mission
51-G	Jun. 17-24, 1985	*Discovery*	Three communication satellites deployed

51-F	Jul. 29-Aug. 6, 1985	*Challenger*	Third Spacelab mission
51-I	Aug. 27-Sep. 3, 1985	*Discovery*	Three communication satellites deployed. LEASAT-3 retrieved, repaired, and redeployed
51-J	Oct. 3-10, 1985	*Atlantis*	DOD mission
61-A	Oct. 30-Nov. 6, 1985	*Challenger*	Fourth Spacelab mission
61-B	Nov. 26-Dec. 3, 1985	*Atlantis*	Astronaut assembly of structures in orbit
61-C	Jan. 12-18, 1986	*Columbia*	Satellite deployment. Pictures of Comet Halley
51-L	Jan. 28, 1986	*Challenger*	The accident

B. SHUTTLE FLIGHT PLANNING

By late 1979, NASA created the Space Transportation System Operations Office. This office is charged with the responsibility for planning, implementing, and conducting integrated STS operations after conclusion of the Orbital Flight Test Program. This responsibility includes transition planning; development of financial plans and pricing structures; coordinating activities with DOD; and providing all necessary services to potential users of the STS. [Ref. 20: p. 12]

The management concept selected for STS Operations has three interrelated areas:

1. Operations Management which involves mission planning, flight planning, payload integration, flight operations, and launch/landing operations.

2. Business and Customer Service Management which encompasses budgeting, cost accounting, pricing, customer relations, launch service agreement preparation, flight assignment determination, and cargo manifesting.

3. Flight Hardware Management which is concerned with the procurement of external tanks, refurbished solid rocket boosters, and spares for flight and ground equipment, sustaining engineering and logistic support. [Ref. 20: pp. 12-13]

The key document governing relations between NASA and the user is the Launch Service Agreement which all users sign and which describes the services (and conditions of the services) to be provided by NASA. The agreement is based on published U.S. Government policy and regulations. In addition, the Launch Service Agreement contains all financial arrangements, termination clauses, launch schedules, description of proprietary rights, insurance provisions, and other important information the user must know including a Payload Integration Plan (PIP) which contains detailed, technical launch service specifications. [Ref. 20: p. 18]

1. Shuttle Services

Standard Shuttle services, which are uniform for all civilian users, includes a basic Shuttle launch for a one-day mission to a standard altitude and azimuth, a crew of three, and standard support services.

Optional Shuttle services, which must be requested by the user, include special hardware, analysis, testing, use of Kennedy Space Center facilities and services, and special orbital operations. [Ref. 20: p. 18]

NASA feels one of the most important aspects of preparing for mature STS operations is the development of a pricing structure and pricing policies which permit maximum use of the STS while meeting NASA's goal of recovering total operational costs over a twelve year period. The policies would be updated as experience and need dictated. [Ref. 20: p. 15]

NASA published Shuttle civil reimbursement policies in 1977 that incorporated the fundamental principles upon which user charges for all STS elements are based. These concepts included:

- no distinction between international and U.S. commercial pricing;
- fixed prices for three years;
- escalation clauses for inflation;
- reduced prices for exceptional payloads;

- standby payloads;
- provisions for cancellations and postponements; and
- small, self-contained payloads. [Ref. 20: p. 15]

NASA pointed out that these policies would most certainly be amended to further clarify a number of issues as well as defining such further defining terms and clauses.

2. Initial Scheduling

NASA identified the principal users of the Space Transportation System: NASA, DOD, other U.S. government agencies, commercial enterprises, and foreign governments and organizations. In 1979, NASA's traffic forecasts indicated that, over the next twelve years, NASA payloads would represent approximately 37% of all payloads, DOD about 29%, and all others 34%. [Ref. 20: p. 20]

NASA's plan is to accommodate user requirements as much as possible on a first-come-first-served basis. In the case of conflicting requirements, missions affecting national security are given top priority. Missions involving significant science and technology objectives, and reimbursable payloads are given preference over routine science and technology experiments. [Ref. 20: p. 20]

In 1979, approximately 29% of all Shuttle traffic was earmarked for Department of Defense missions. In accordance with prior NASA agreements, DOD is responsible for launch and recovery operations at Vandenburg Air Force Base and DOD payload integration and planning. DOD reimbursement principles are embodied in an agreement which stipulates that Kennedy Space Center and Johnson Space Center flight operation services for DOD missions are exchanged for Vandenburg Air Force Base launch services for all non-DOD missions from Vandenburg. [Ref. 20: p. 16]

By 1979, NASA had commitments for the first 38 operational flights, representing 15 different customers (including NASA). These payloads represented commercial, foreign, DOD, and civil (U.S. Government and NASA) customers. [Ref. 20: p. 21]

C. SPACE SHUTTLE PROCESSING

Since the Shuttle Orbiter is designed to be reused, launch processing includes recovering and refurbishing the orbiter and the Solid Rocket Boosters.

At Kennedy Space Center (KSC), Shuttle processing is carried out by contractors monitored by NASA employees. Approximately 6,500 contractors and 640 NASA employees directly support Shuttle launch operations at KSC. Johnson Space Center has responsibility for on-orbit mission operations and some launch operations, which involve about 5,675 contractors and 1,065 NASA employees. Marshall Space Flight Center contributes engineering expertise for Shuttle modifications and supports the Shuttle with approximately 1,000 NASA employees and 11,000 prime contractor employees. [Ref. 21: p. 40]

1. Shuttle Payload Processing

Payloads for the Shuttle can be installed either horizontally or vertically. Horizontal payloads, such as Spacelab, are installed in the orbiter while it is still in the Orbiter Processing Facility, prior to being mated to the External Tank and the Solid Rocket Boosters. Vertical payloads are installed in the orbiter's payload bay after the fully assembled Shuttle arrives at the launch pad. [Ref. 21: p. 40]

Payload owners have five options for processing payloads, ranging from minimum KSC involvement, where the payload is ready for launch and can be installed in the orbiter 2 to 50 days before launch with no servicing, to maximum involvement, where all flight experiments and component hardware must be delivered up to a year before launch for technicians to assemble, integrate and test. [Ref. 21: p. 41]

2. Orbiter Processing

Orbiter processing constitutes the critical limit to the achievable flight rate. For example, refurbishing the orbiter *Columbia* for the second Shuttle flight consumed nearly 200 work days. By late 1984, the turnaround time was reduced to 55 workdays. [Ref. 21: p. 41]

In the Orbiter Processing Facility, NASA contractors check and refurbish every major system in the orbiter after each flight, including the avionics brakes, electrical system, and windows. They inspect the Shuttle Main Engines while completely replacing the bearings and turbines. The 31,000 ceramic tiles are individually inspected and replaced as needed. Any modifications that are needed to the orbiter are done at this time. [Ref. 21: p. 41]

D. PROJECTED SPACE SHUTTLE LAUNCH CAPABILITIES

In 1981, NASA anticipated that the launch capability of the Space Shuttle by the late 1980's would be at least 24 missions per year. NASA was concerned with total launch capability -- that is, both foreign and U.S. launchers as well as launch demand. NASA projected that the European Ariane launch vehicle family would be capable of 10 to 12 missions per year by the end of the 1980's, which NASA equated to five or six Shuttle flights. Some market analysts in 1981 projected a launch demand in the vicinity of 35 to 50 Shuttle equivalent flights in the same time frame. These figures pleased NASA. If NASA could make the Shuttle attractive enough to potential Ariane users, manifests could be full for years. [Ref. 22: p. 19]

NASA studies indicated that a fifth orbiter vehicle would be needed to reach and sustain a launch rate of forty flights per year by the 1990's. NASA based the forty flight projection on a single Shuttle being able to fly eight to ten times per year. [Ref. 22: p. 19]

Original NASA planning at the time of Shuttle program approval in 1972 envisioned a five orbiter fleet supporting a projected mission model of 572 flights over a twelve year period. This five orbiter fleet was to be made up of two DDT&E vehicles and three production vehicles. During f- ' year 1977 budget preparations, OMB and NASA concluded that five orbiters were necessary but, due to funding constraints, orbiter procurements were stretched out. By fiscal year 1979 budget hearings, the fifth Orbiter was deferred. However, Congress concluded that the fifth Orbiter option should be kept open and added funds for fifth Orbiter long lead items. [Ref. 23: pp. 1243-1244]

The fiscal year 1980 NASA budget request to the administration contained funds for a fifth orbiter. These funds were deleted after program review within the administration. [Ref. 23: p. 1244]

E. SPACE TRANSPORTATION SYSTEM (STS) PRICING

The STS pricing structure is based on the concept of a firm-fixed price, designed to encourage potential users to make an early commitment to fly on the Space Shuttle. In 1979, the price for civil users was $18.0 million in 1975 dollars. (See Table 5.) This figure was developed from cost data based on an anticipated manifest of 487 flights in twelve years, and was predicated on recovery of all operations costs over the twelve year period. [Ref. 20: p. 19]

Commercial and foreign users, except the European Space Agency (ESA) and Canada, would be charged a fee of $4.3 million for the use of U.S. government facilities and $270,000 for reflight insurance. [Ref. 20: p. 19]

The 1975 fixed price of $18.0 million was escalated to $25.8 million in fiscal year 1979 dollars, in accordance with Bureau of Labor Statistics inflation rates. Studies done by NASA at that time (1979) indicated that by fiscal year 1985, user charges would have to be raised an additional 15 to 20%. [Ref. 20: p. 19]

The price for a civil or foreign Shuttle launch prior to 1988 was $38 million plus fees for capital facilities and insurance. (See Table 5.) This was set by NASA in 1977 to recover all operating and production costs, including orbiters and related equipment (in 1982 dollars).

By the early 1980's, the market for launch services proved substantially smaller than expected, forcing NASA to spread its operational costs over a smaller number of flights. Accordingly in 1982, when NASA revised the pricing policy for launches in the years 1986 through 1988, the price was significantly higher. But at $71 million, it still did not recover all the operational costs of the Shuttle system.

The price for the period 1989 through 1991 -- $87 million per flight -- called for the recovery of an averaged operational cost only. The user price remained significantly less than that called for by the original pricing policy which sought to recover all operating costs. [Ref. 19: pp. 795-796]

Table 5. SPACE SHUTTLE PRICE / LAUNCH

Fiscal Year	User Fee in 1975 $ (million)	User fee in 1982 $ (million)
1983	18	38
1984	18	38
1985	18	38
1986	38	71
1987	38	71
1988	38	71

NASA's plan in 1982 was to increase Shuttle prices to users by 1986. NASA's 1982 preliminary assessment of the price increase was on the order of 75% to 100% higher than the established fixed price. The price increase was due to rising costs. NASA felt even though there was to be a considerable price increase, Shuttle prices would remain competitive within the launch market. [Ref. 24: p. 301]

During the fiscal year 1986 NASA authorization hearings, Shuttle funding requirements increased as a result of the net effect of:

- reduction in the amount of anticipated reimbursements, both from the DOD and foreign and commercial users,
- and the savings which could be realized from changes of the flight mission schedule and other cost reduction activities. [Ref. 19: p. 48]

NASA developed a cost model for the post-1988 period that permitted the establishment of prices for various users, depending on the pricing policy that applies. (See Table 6.) The cost, based on a traffic model of 24 flights per year (two flights per month), included all direct and indirect costs as well as allocation of institutional support costs associated with Space Shuttle operations. Excluded were costs for Space Shuttle research and development. [Ref. 19: p. 1330]

Table 6. SPACE SHUTTLE PRICE PER FLIGHT POST-1988 (1982, $ MILLION)

Fiscal Year 1989	Fiscal Year 1990	Fiscal Year 1991	Average
$83.9	$83.6	$82.5	$83.3

Launch costs in 1979 for DOD were fixed for six full fiscal years at $12.2 million in 1975 dollars. This price was intended to recover material and service costs and would be adjusted to actual costs annually after the initial six year period. [Ref. 20: p. 16]

DOD Shuttle use prices in FY 1975 $ for materials and services for all launches in FY 1984 and FY 1985 was $16 million. DOD's rate was fixed at $29.8 million (FY 1975 $) per DOD Launch for FY 1986 through FY 1988. NASA felt that these prices provided the framework and conditions for appropriate reimbursements by DOD for STS flight charges. They were developed in recognition of the major investment (Vandenburg Air Force Base) DOD made in the STS program. [Ref. 25: p. 594]

In 1983, NASA stated that the amount of paid reservations, signed launch agreements, joint endeavors, and number of customers making progress payments increased significantly since the FMOF of April 1981. NASA expected this trend to continue as the Shuttle proved itself operationally since launch agreements are generally made three years or more prior to launch. [Ref. 23: p. 1245]

However, to discourage people from cancelling their reservations on the Shuttle or from considering other vehicles (Ariane, for example), NASA formulated cancellation fees for users. [Ref. 23: pp. 1245-1246]

F. EXPENDABLE LAUNCH VEHICLES (ELVS)

1. NASA's Atlas and Delta ELVs

By 1983, after STS-5 and the Shuttle was considered operational, NASA was only producing the Atlas-Centaur and Delta launch vehicles for users who previously made reservations for those vehicles. (See Figure 5 for the Atlas and Delta configurations.)

NASA terminated work on the Delta launch vehicle and eliminated the last six Delta launches to conform with known launch requirements and in anticipation of STS operations. Production of the Delta launch vehicle terminated in 1983 although the vehicle would be used through 1986 to accommodate the launch of NOAA spacecraft. [Ref. 23: p. 40]

Atlas-Centaur vehicles were being produced on firm customer requirements only and its termination was slated for 1985. DOD planned to use the Atlas through 1987, with the last launch of an Atlas vehicle scheduled for early 1987. [Ref. 23: p. 40]

For the Delta and Atlas-Centaur program, a minimum on going rate of three to four vehicles per year production and launch is desirable for efficiency, economy and

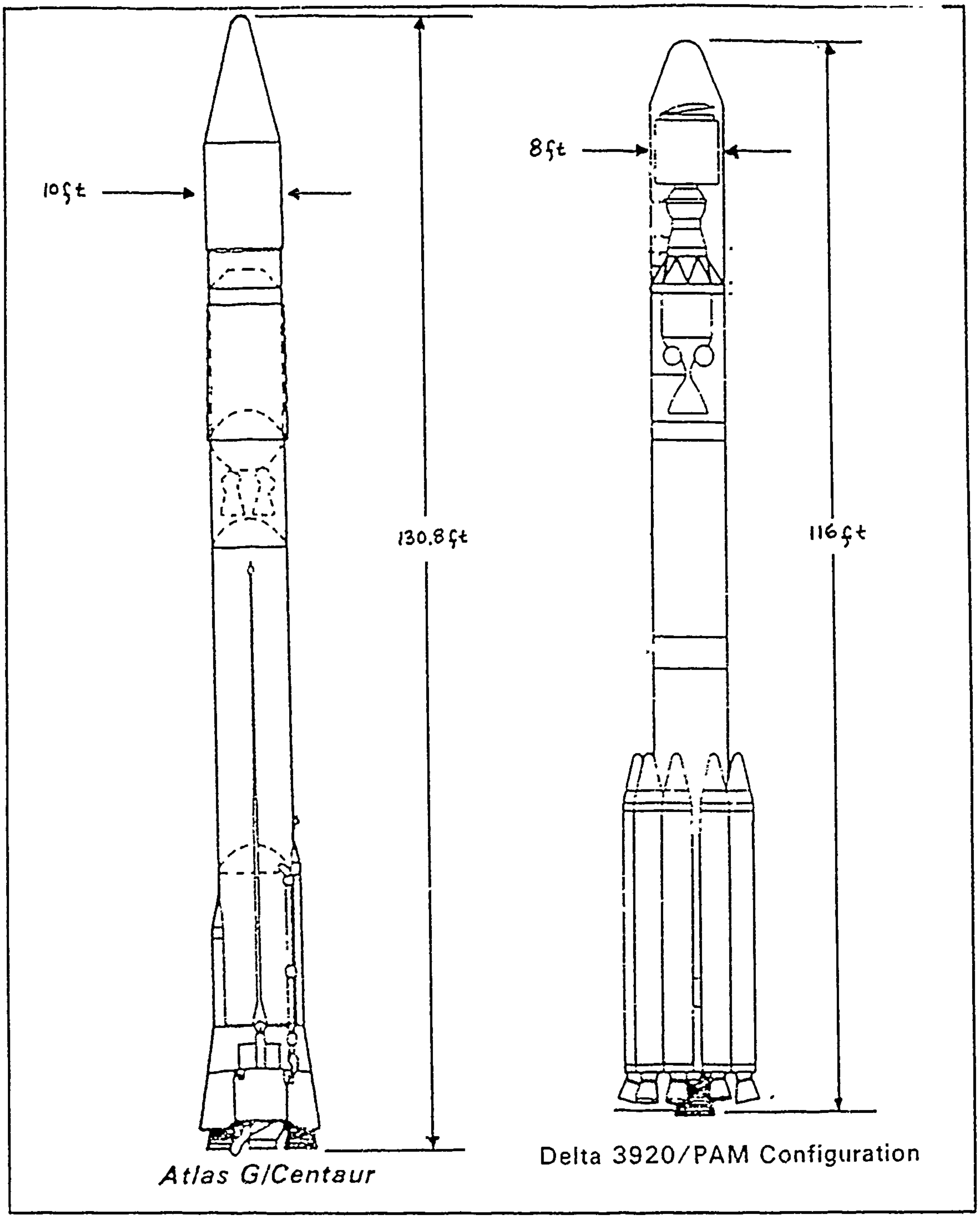

Figure 5. Atlas and Delta Launch Vehicles

reliability. Since the operational Shuttle would be able to accommodate requests for launch services by all who requested, the maintenance and operation of the NASA ELVs (Delta and Atlas/Centaur) by the government solely as a backup to the Shuttle was considered too costly and not justifiable. [Ref. 23: p. 1267]

NASA planned for the utilization of the Space Shuttle and phaseout of the U.S. Governments' use of expendable launch vehicles upon the completion of the final Delta and Atlas-Centaur launches. [Ref. 23: p. 40]

With NASA using up their remaining ELVs by 1987 and no plans, short or long-range, to produce any more ELVs, the Shuttle was rapidly becoming the U.S.'s sole source to space. [Ref. 23: p. 55]

In July 1982, President Reagan announced the expanding of the private sector investment and involvement in civil space and space related activities as a basic goal of U.S. space policy. With respect to ELVs, the announcement was more specific, stating that ELV operations should be continued by the U.S. Government until the capabilities of the STS are sufficient to meet its needs. Beyond this time frame (early 1987) the policy did not endorse or prohibit the turnover of ELV production to the private sector. [Ref. 23: p. 1267]

Since the administration considered the Space Shuttle as the primary access to space, every step was taken to ensure the Shuttle was fully utilized. Operating the Shuttle in a robust manner was the goal of NASA, and in doing so NASA believed robust operations would bolster the confidence of potential customers in the long-term viability of the Shuttle. [Ref. 23: p. 1268]

2. Department of Defense and Assured Access to Space

The DOD was trying to maintain an assured access to space through maintaining ELV capability. As Secretary of the Air Force Edward Aldridge stated before Congress during the NASA 1985 Authorization Hearings:

The DOD has a valid requirement for an assured launch capability which is a function of satisfying two specific requirements: The need for complementary launch systems to hedge against unforseen technical and operational problems and the need for a launch system suited for operations and conflict situations.

Existing defense space launch planning specifies that DOD will rely on four unique, manned orbiters for primary access to space for all national security space systems. DOD is concerned that this may not represent an assured, flexible and responsive access to space.

While the DOD is fully committed to the STS, total reliance upon the STS for sole access to space in view of the technical and operational uncertainties could represent an unacceptable national security risk. DOD believes that a complementary system is necessary to provide high confidence of access to space. [Ref. 25: pp. 663-664]

3. Titan IV, the Dedicated DOD Launch Vehicle

Consistent with DOD's position as well as the Presidents space policy speech endorsing a flexible and robust U.S. launch posture, DOD started studying the use of commercially procured ELVs to meet its requirements for improving its assured launch capabilities. [Ref. 25: p. 665]

Because of the Air Force's concern with assured access to space, the administration proposed and the Congress approved new capacity for space transportation in a 1986 supplemental appropriation. The Titan IV ELV became the dedicated DOD launch vehicle. (See Figure 6 for the Titan IV configuration.) The procurement of Titan IV expendable launch vehicles was increased from 10 vehicles to 23 over the 1986 to 1991 time period. In addition, a new ELV program, the Medium Launch Vehicle (MLV) (the Delta II), was approved to launch the DOD Global Positioning Satellite (GPS) constellation. [Ref. 26: pp. xi-xii]

G. THE PRICING PROBLEM

From the beginning, NASA proposed low user prices for the Space Shuttle. For example, NASA's pricing policy for 1986 through 1988 was not based on full cost recovery, on average annual cost recovery, on average per launch recovery, or on any other methodology comparable to a business-like process. [Ref. 25: p. 826]

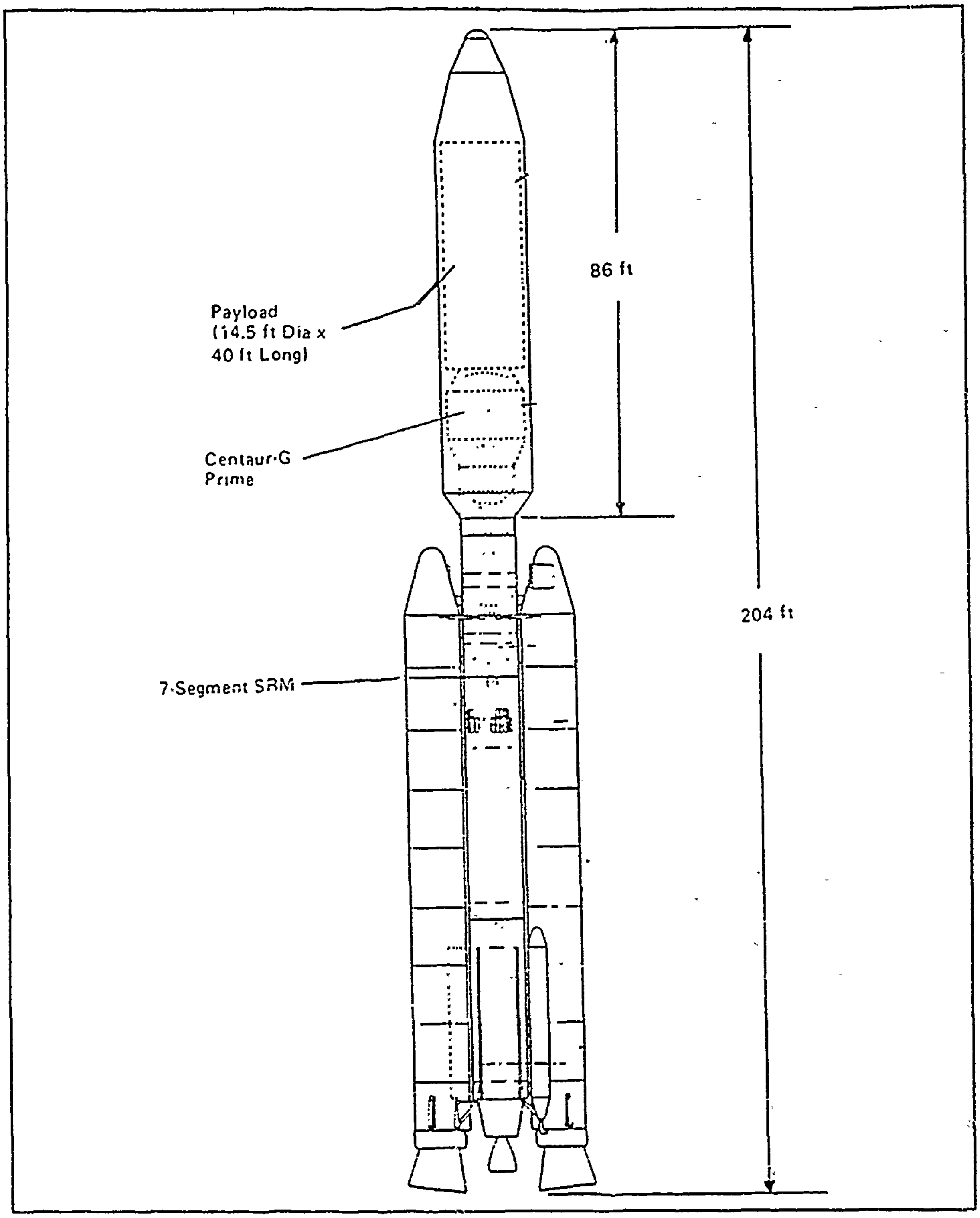

Figure 6. The Titan IV DOD Launch Vehicle

According to NASA's internal analyses, the projected "out-of-pocket" costs for a full Shuttle launch in 1986-88 would be on average $71 million in 1982 dollars. NASA charged as its launch price this $71 million with DOD charged slightly less. [Ref. 24: p. 827]

But, as economist P. K. Salin stated before the Congress during the 1985 authorization hearings, NASA's process was questionable:

> NASA attempted to exclude many types of Shuttle-related costs from its pricing calculations. NASA also attempted to exclude large parts of the total annual cost for even the 'included' cost categories. For what small costs were left, NASA applied analytic methods almost guaranteed to result in cost underestimation. It averaged cost estimates from later years with cost estimates from earlier years, and then based its prices on the calculated average. Since NASA's analysts are hoping Shuttle costs will drop dramatically during the 1980's the resulting average cost estimate used as the basis of NASA's proposed pricing policy is very low. [Ref. 24: p. 841]

In 1984 the Space Shuttle was already being regarded as much more expensive to operate than originally planned in 1971. The Shuttle was far more expensive for launching communications satellites to geostationary orbits than competing vehicles such as Delta, Atlas Centaur, or Ariane. [Ref. 24: p. 836]

The Shuttle was uncompetitive in the launching business primarily due to the unavoidably heavy costs associated with supporting manned capability, as well as heavy costs associated with integrating multiple payloads on each mission. Because of these unavoidable extra costs, the Space Shuttle was destined to be more costly to operate for launching satellites than a more specialized ELV. [Ref. 24: p. 836]

NASA's data confirmed various economists findings of the Shuttle program. The data indicated that every Shuttle launched during the period 1982 through 1988 would cost NASA more than $200 million dollars but would be priced below $100 million in accordance with Shuttle pricing policy. [Ref. 24: pp. 850-852]

1. Pricing Policy

NASA's pricing policy for the Shuttle was controversial, and the agency was criticized for trying to run the Shuttle program as a business. As NASA's quest for increased launch frequency continued, disagreement arose on how much of the operational costs NASA should be allowed to recover and what was a reasonable goal for the number of flights per year, since more flights meant a larger base over which fixed costs could be spread.

Over the years, the goals of reducing prices and recovering costs came increasingly into conflict. NASA increased the base price charged to Shuttle users, but never enough to fully recover its increasing operational costs. By 1986 the user price was $71 million per flight (1982 dollars) for launches, a figure meant to recover average operating costs if 24 flights per year could be achieved. [Ref. 28: p. 2]

As a result, every Shuttle launched prior to 1989, carrying mainly commercial communications satellites, resulted in an excess operational cost of around $100 million subsidized by the U.S. Government. By contrast, the equivalent payload could be launched on existing Deltas or Atlas.Centaurs for a cost of around $100 million with no subsidies. [Ref. 24: p. 836]

Critics pointed out that as a result of NASA's pricing policy the more cost effective ELV's were being subjected to unfair competition by a taxpayer-subsidized Shuttle. [Ref. 24: p. 836]

However, the majority of space users enjoyed the Space Shuttle's lower prices and did not want to see NASA raise the price of a Shuttle launch. During the 1986 NASA Authorization hearings before the Congress, Robert K. Roney, Vice President of Hughes Aircraft Company voiced the communication satellite manufacturer's concerns with Space Shuttle prices. Mr. Roney felt that Shuttle pricing should be kept reasonable and NASA should only seek to recover the costs associated with that mission only:

> Much of the cost of operating the Shuttle stems from its status as a manned flight vehicle. I have detected no perception among communications operators of any operational advantage from the special characteristics of the Shuttle. In fact, on the whole, the operational problems of using the Shuttle have a negative appeal relative to the convenience of a dedicated expendable vehicle. So it is unfair to charge any of the cost of maintaining the manned space flight program for the service of simply transporting a payload to orbit. [Ref. 19: p. 395]

Another advocate of the "out-of-pocket" Shuttle pricing approach was Charles A. Ordahl, Vice President of the McDonnell Douglas Astronautics Company. In a statement for the 1986 NASA Authorization Hearings he said:

> The Shuttle ... should be used to foster and encourage space commercial investments. This can be achieved through a policy of additive cost pricing in which commercial customers are charged all out of pocket costs incurred on their behalf but no allocated share of the fixed or capacity costs of the Shuttle system. This could provide a Shuttle price of less than the current $71 million FY 1986 - 1988 price. Such pricing will place Shuttle in a position to win competitions with Ariane, and with each win, achievement of the economic benefit of increased shuttle launches and more Shuttle related commercial business retained in the United States. [Ref. 19: p. 411]

Many commercial users of the Shuttle were frightened by the trend to raise Shuttle launch prices. They feared the following scenario:

- The Shuttle launch price is raised to obtain total operational cost recovery and to be a fair competitor for commercial ELVs.
- The commercial ELV industry is born.
- The European Space Agency's Ariane, with subsidies, keeps its prices below that of the U.S. Shuttle and ELVs.
- The U.S. ELV market share is not sufficient to provide a return on investment and within a year or two commercial companies abandon their effort.
- The commercial payloads are committed to Ariane at a lower price than Shuttle.
- The Shuttle is maintained as a national asset and is more expensive to maintain due to lack of satellite payloads and the withdrawal of potential new space applications.

But some observers felt no remorse for the taxpayers subsidizing access to space by the Shuttle. They felt that the government had many times throughout history subsidized profit making ventures especially in opening new frontiers such as the transcontinental railroad or civilian airport and air traffic control system. [Ref. 19: p. 418]

2. Operational Shuttle in Question

In 1984, the Aerospace Safety Advisory Panel expressed concern and made recommendations concerning NASA's "operational" Space Shuttle program. For example, the panel warned against the heavy launch processing burden associated with each mission. They cautioned NASA management to avoid advertising the Shuttle as being "operational" in the airline sense "when it clearly wasn't." In the panel's opinion such routine operations would not be achieved for 5 to 10 years and NASA should focus on improving the Shuttle's reliability, maintainability, and safety. [Ref. 29: p. 219]

The panel expressed the view that NASA's goal of 18 to 24 flights per year was not within reach and that 12 to 15 per year was the most NASA could hope to achieve. The panel believed that an "operational" Space Shuttle program was still many years in the future. [Ref. 29: p. 219]

Additionally, the panel noted that "... continuing use of the term 'operational' simply compounds the unique management challenge of guiding the STS through this period of 'developmental evolution.'" The panel stressed the importance of upgrading the safety and reliability of many of the Space Shuttle's critical systems and of recognizing that the continuing process of change and improvement would require the discipline and caution of a developmental, as opposed to a "operational," program. [Ref. 29: p. 223]

V. TRANSITIONAL PERIOD

In 1986 the United States was plagued by a series of launch disasters:

- the *Challenger* exploded shortly after lift-off killing its crew of seven and destroying its cargo;
- a Titan 34-D accident in April destroyed a military satellite, following an accident the preceding August involving an identical launcher and similar satellite;
- a Delta rocket, with a NOAA weather satellite aboard, was destroyed following launch failure.

The *Challenger* accident in January 1986 had an enormous effect on the U.S. access to space.

A. THE CHALLENGER ACCIDENT

Flight of the Space Shuttle *Challenger* on mission 51-L began at 11:38 a.m. Eastern Standard Time on January 28, 1986. It ended 73 seconds later in an explosive burn of hydrogen and oxygen propellants that destroyed the External Tank and exposed the Orbiter to severe aerodynamic loads that caused complete structural breakup. All seven crew members perished. The two Solid Rocket Boosters flew out of the fireball and were destroyed by the Air Force Range Safety Officer 110 seconds after launch. [Ref. 11 p. 19]

Just after liftoff, photographic data showed a strong puff of grey smoke spurting from the vicinity of the aft field joint on the right SRB. Computer graphic analysis of the film indicated the smoke came from the aft field joint of the right SRB. This portion of the SRB faced the External Tank. Smoke streaming from the joint indicated there was not complete sealing action within the joint. [Ref. 11: p. 19] (See Figure 7 for the location of the leak.)

More distinctive puffs of increasingly blacker smoke were recorded seconds after liftoff. The black color and dense composition of the smoke puffs suggested that the grease, joint insulation, and rubber O-rings in the joint seal were being burned and eroded by the hot propellant gases. [Ref. 11: pp. 19-20]

Both the Shuttle Main Engines and the Solid Rocket Boosters operated at reduced thrust approaching and passing through the area of maximum dynamic pressure. Main engines were throttled up to 104 percent thrust and the SRBs were increasing their thrust when the first flickering flame appeared on the right SRB in the area of the aft field joint. At about the same time, telemetry data showed a pressure differential between the chamber pressures of the right and left SRB. The right SRB chamber pressure was lower, confirming the growing leak in the area of the field joint. [Ref. 11: p. 20]

A swirling flame from the right SRB breached the External Tank was 65 seconds into the flight, apparent by an abrupt change in the shape and color of the right SRB plume. This indicated mixing with the leaking hydrogen of the External Tank and the SRB plume. Telemetry also indicated a leak in the ET. Within milliseconds of breaching the ET, a bright sustained glow developed on the black-tiled underside of the Orbiter between it and the ET. [Ref. 11: p. 20]

Beginning at about 72 seconds, a series of rapidly occurring events terminated the flight:

- At about 72.22 seconds, the lower strut linking the SRB and the ET was severed from the weakened ET permitting the right SRB to rotate around the upper attachment strut.
- At 73.124 seconds structural failure of the ET was signified by the white vapor blooming from the side of the ET bottom dome.
- When the entire aft portion of the ET dropped away, massive amounts of liquid hydrogen caused a sudden forward thrust of 2.8 million pounds.
- At about the same time the rotating right SRB impacted the remaining ET structure. [Ref. 11: pp. 20-21]

At this point of the trajectory, traveling almost mach 2 at an altitude of 46,000 feet, the *Challenger* was totally enveloped in the explosive burn. The Orbiter, under severe

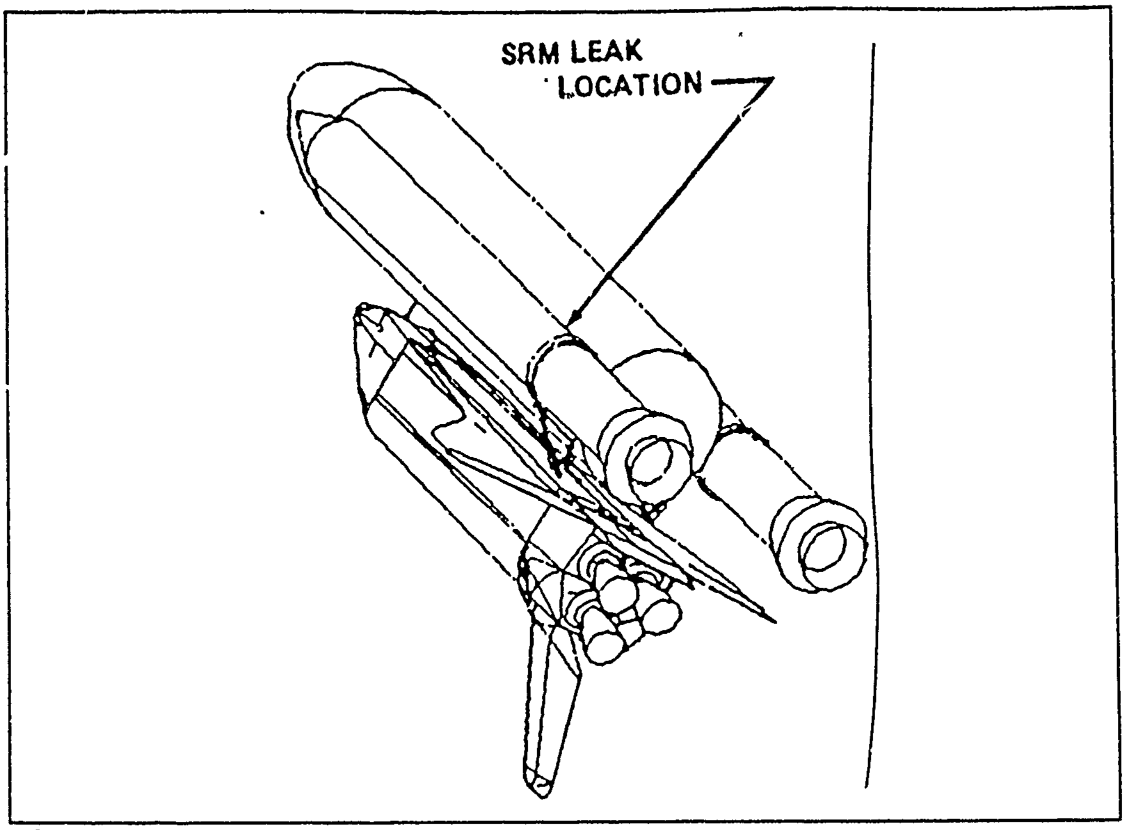

Figure 7. The Leak Location in the Solid Rocket Booster

aerodynamic loads, broke into several large sections which emerged from the fireball. [Ref. 11: p. 21]

B. CAUSES OF THE ACCIDENT

The consensus of the Presidentially appointed Rogers Commission, tasked with investigating the accident, was the loss of the Space Shuttle *Challenger* was caused by a failure in the joint between the two lower segments of the right Solid Rocket Booster. Specifically, the failure was the destruction of the seals intended to prevent hot gases from leaking through the joint during the propellant burn of the rocket motor. The evidence assembled by the Rogers Commission indicated no other element of the Space Shuttle system contributed to the failure. [Ref. 30: p. 6]

In addition to the failure of the aft field joint of the right Solid Rocket Motor, the Commission found other contributing factors to the Shuttle *Challenger* accident.

1. O-ring Temperature

Within the joint, there are various components that collectively contribute to the sealing process and keep hot combustion gases from escaping. A major component is the O-ring, and O-ring performance is directly related to its temperature. On previous Shuttle flights with ambient temperatures lower than 61 degrees fahrenheit, the O-rings showed greater than normal erosion. The ambient temperature on the day of the *Challenger* launch was 36 degrees fahrenheit. Because of this cold temperature (coldest Shuttle launch ever attempted) the O-rings lost their resiliency and were unable to seal the joint properly. [Ref. 30: p. 33, Ref. 11: pp. 70-71]

2. "Flawed Decision Process"

In addition to the technical problems, the Commission also found a "flawed decision process" within NASA, as well as between NASA and its contractors. That is, the decision to launch the *Challenger* was wrong. Those who made the decision to launch were unaware of the recent history of problems concerning the O-rings in the joint and were unaware of the written recommendation of the SRB contractor (Morton Thiokol) advising against a launch at temperatures below 53 degrees fahrenheit. [Ref. 30: p. 35]

Also discovered during the investigation was that the design of the SRB field joint was faulty from its inception. The problem increased as both NASA and Morton Thiokol management failed to recognize the problem; once recognized, they failed to fix the problem; and finally they treated the problem as an acceptable flight risk. [Ref. 30: pp. 36-37]

3. Pressures on the System

With the 1982 completion of the orbital test flight series, NASA began a planned acceleration of the Space Shuttle launch schedule. In 1985, NASA published a projection calling for an annual rate of 24 flights by 1990. Long before the *Challenger* accident, however, it was clear that even two flights per month was overly ambitious. [Ref. 11: p. 164]

In establishing the schedule, NASA did not provide adequate resources for attainment. As a result, the capabilities of the system were strained even by the modest nine mission rate of 1985. The Commission found that NASA would not have accomplished the 15 scheduled flights for 1986. [Ref. 30: p. 39]

The Rogers Commission found that with respect to flight rate pressures:

- The capabilities of the Shuttle System were stretched to the limit to support the flight rate.
- The Shuttle program made a conscious decision to postpone spare parts procurements in favor of budget items of perceived higher priority. Lack of spare parts would have limited flight operations in 1986.
- Stated cargo manifest policies were not enforced. Numerous late manifest changes were made to both major payloads and minor payloads, throughout the Shuttle program. [Ref. 30: pp. 39-40]

Flight rate pressures developed because of the need to meet customer commitments, which translated into a requirement to launch at a high rate and to launch them on time. NASA managers had forgotten that even though the Shuttle system flew 24 times prior to the accident, the program could still be considered to be in a research and development phase. [Ref. 11: p. 165]

4. Rogers Commission Recommendations

The Presidential Commission on the Space Shuttle *Challenger* accident made recommendations to return the Shuttle System to a safe flight status. They included:

- redesigning the Solid Rocket Motor joint,
- restructuring NASA management,
- holding critical flight readiness reviews,

- establishing an effective safety organization,
- improving communications,
- improving landing safety,
- designing a launch abort/crew escape capability,
- and incorporating maintenance safeguards. [Ref. 11: pp. 198-201]

Also the commission recommended establishing a more realistic flight schedule for the Shuttle System to meet as well as establishing other launch capabilities:

> The nation's reliance on the Shuttle as its principal space launch capability created relentless pressure on NASA to increase the flight rate. Such reliance on a single launch capability should be avoided in the future. NASA must establish a flight rate that is consistent with its resources. A firm payload assignment policy should be established. [Ref. 11: p. 201]

C. RAMIFICATIONS OF CHALLENGER ACCIDENT

Before the *Challenger* accident, NASA thought the late 1980's would see the realization of the Shuttle's promise. NASA felt the anticipated capacity of 24 flights per year was attainable. The Shuttle system was declared operational and considered the U.S. workhorse in deploying satellites.

NASA officials anticipated the realization of cost-effective Shuttle operations rewarding the entire space program. From a budgetary standpoint, commercial launches provided NASA revenues, as would servicing DOD launch requirements. These revenues would not only enable NASA to offset some of the high fixed costs of operating the Shuttle, but also would allow NASA to conduct a vigorous space science program as well as proceed with the space station. [Ref. 27: p. 3]

1. President Reagan Restructures Space Policy

Following the Space Shuttle *Challenger* accident, President Reagan restructured the United States space policy primarily in two areas. First, the Space Shuttle would no longer carry commercial communications satellites to space. Secondly, NASA was given permission to procure a fourth Space Shuttle Orbiter vehicle. [Ref. 29: p. 323]

The administration's decision to remove commercial communication satellite traffic from the Shuttle had immediate budgetary ramifications to NASA. The user fees generated by commercial Shuttle launches were intended to create a source of revenue for NASA in the future. [Ref. 27: p. 3]

In 1986, the future NASA budget outlook was uncertain. Reduced DOD transfers through reduced DOD Shuttle use, lower commercial revenues through elimination of commercial communication satellite traffic, and new costs to improve Shuttle safety all contributed to the Shuttle no longer being considered the "routine access to space." [Ref. 27: p. 3]

NASA is presently building a new replacement Orbiter for the *Challenger*. At President Reagan's request, Congress has fully funded the project based on the belief that the new Orbiter is essential to the planned shuttle flight buildup for the space station. [Ref. 31]

Designated the *Endeavor* (OV-105), the Orbiter is scheduled to be delivered in May 1991 with the initial launch targeted for early 1992. The *Endeavor* will incorporate improvements such as:

- A drag chute that will allow for contingency abort landings on relatively short runways, also reducing rollout and brake/tire loads.
- A redesigned disconnect between the External Tank and the Main Engines.
- A new APU controller.
- A solid state star tracker navigation system.
- Improved nose wheel steering. [Ref. 31]

2. Shuttle to ELV Transfer

By the Summer of 1986, NASA estimated that through FY 1992 approximately 43 percent of scheduled payloads could be transferred from the Shuttle and flown on ELVs, if ELVs were available. NASA recognized there would be some additional costs in spacecraft modification and possible significant cost to modify the current ELV systems to accommodate these spacecraft. Additionally, at this time NASA's Delta and Atlas/Centaur vehicles, which would accommodate most of the payloads, were out of production. New production of the Delta and Atlas/Centaur vehicles would require 24 to 36 months from contract go-ahead before new delivery could begin. NASA approximated 57 percent of Shuttle payloads were Shuttle dependent or would be too expensive to transfer to ELVs. [Ref. 31: p. 669]

If Expendable Launch Vehicles had been available after the accident, the 1986 estimated prices of ELVs are in Table 7.

Table 7. 1986 ELV COSTS

Vehicle	Estimated Cost, 1986
Titan I	$50.0 Million
Titan III	$142.0 Million
Titan IV	$171.0 Million
Delta	$38.0 Million
Delta II	$38.0 Million
Atlas-F	$15.0 Million
Atlas-H	$40.0 Million

3. Vandenburg Shuttle Launch Complex

Vandenburg Air Force Base in California is the West Coast equivalent of the Kennedy Space Center, with numerous launch pads available. Though Vandenburg is run by the Air Force, both military and civilian payloads are launched from it.

After investing approximately seven years and $3.3 billion on research, development, construction, and testing, the Air Force announced on 31 July 1986, that it was placing the Vandenburg Shuttle Complex in "caretaker" status (maintaining the equipment but closing the complex) until 1992. The decision was preceded by several years of concern with facility cost over-runs, safety issues, and delays in commencing operations at the site. Following the loss of the *Challenger*, both NASA and DOD questioned the cost-effectiveness of operating two launch sites with only three Orbiters. The Air Force commander in charge of the Shuttle test facility at Vandenburg commented that launch of the Shuttle from Vandenburg is now being considered as backup to ELVs. Though no Shuttle flights are planned from the Vandenburg facility, the Air Force will "protect the capability" for a Shuttle Launch in 1992. [Ref. 32: p. 16]

D. EXPENDABLE LAUNCH VEHICLE/MIXED FLEET

The National Space Policy that resulted from President Reagan's speech in July of 1982 directed that U.S. government payloads, including DOD payloads, would be transitioned from ELVs to the Space Shuttle. By the *Challenger* accident in January 1986, this transition was nearly complete. Most payloads were configured for the Space Shuttle only and no new U.S. government ELVs were being built. [Ref. 33]

The projected increase of Shuttle flights and the associated decrease in ELV launches prior to the *Challenger* accident is evident in Table 8 and Table 9.

Table 8. SHUTTLE MANIFEST PRIOR TO CHALLENGER ACCIDENT

	FY 86	FY 87	FY 88	FY 89	FY 90
Commercial	4.8	1.9	2.6	5.3	5.2
DOD	3.0	5.7	9.3	9.8	8.4
NASA	6.2	8.7	6.1	7.3	9.5
Opportunity	--	0.7	--	1.6	0.9
Total Flights	14	17	18	24	24

Table 9. ELV SCHEDULE PRIOR TO CHALLENGER ACCIDENT

	FY 86	FY 87	FY 88	FY 89	FY 90
Scout	2	4	2	2	2
Delta	2	2	0	0	0
Atlas/Centaur	1	2	0	0	0
Atlas E/F	1	1	1	1	1
Total Flights	6	9	3	3	3

After the accident, NASA felt the United States should re-examine its policy on space transportation and move toward a mixed fleet concept versus the 1982 policy of having the Shuttle as the sole source to space. Although NASA feels the Shuttle, with its redundancy and unique man rated capability, is a valuable national resource that can be used for practically all space transportation needs, NASA admitted a reassessment of policy is required. [Ref. 35: p. 632]

A major NASA study in December 1986 advocated a mixed fleet of launch vehicles. The study covered a period from 1988 to 1995 and concluded that a mixed fleet composed of the Shuttle and ELVs is necessary to assure access to space. [Ref. 36: p. 18] NASA believes a mixed fleet approach will provide the flexibility and options in effectively executing space transportation operations. [Ref. 35: p. 632]

The mixed fleet program was initiated in fiscal year 1987. The study recommended that U.S. civil government's spacecraft be launched using a balance of ELVs and STS to provide increased access to space, to assure continuity of space operations, and to enhance mission flexibility. [Ref. 37: p. 91]

In December of 1986, the U.S. Space Launch Strategy (NSDD 254) mandated the reconstitution of launch assets using a mixed fleet of ELVs and the Space Shuttle. The strategy included a balanced mix of the Space Shuttle and ELVs, utilization of the Space Shuttle principally for missions requiring its unique capabilities, and maintain a dual compatibility for critical launches. [Ref. 34]

NASA revised its space flight manifest plans for civil government payloads based on the mixed fleet concept. [Ref. 37: p. 91]

NASA believes the ELV family of vehicles (Titan, Atlas, and Delta) along with the Shuttle will satisfy the needs of the nation's civil space program in the near future. These ELV launch services are procured competitively from the private sector. [Ref. 36: p. 21]

Since NASA is no longer responsible for the production and maintenance of ELVs, the National Space Policy of 1988 specified directives on ELV commercialization:

- NASA is to procure ELV launch services directly from the private sector or from the Department of Defense.
- The U.S. government is to facilitate private sector access to U.S. launch facilities and services. [Ref. 34]

1. Criteria for a Shuttle Launch

In response to the mixed fleet study, NASA established a flight assignment board in 1989 to manifest payloads on the Shuttle or ELVs. The criteria now established for a Space Shuttle launch are:

- The mission or payload requires a manned presence.
- The mission or payload requires the unique capabilities of the Space Shuttle.
- Other compelling circumstances for the Shuttle exist (e.g., foreign policy or national security). [Ref. 34]

E. LAUNCH DEMAND

The *Challenger* accident catalyzed reconsideration of U.S. space transportation policy. The policy debate focused on underlying questions concerning the capacity of the Shuttle System, the nation's future demand for launch services, and the roles of the public and private sectors in meeting launch demand. [Ref. 27: p. xii]

According to NASA, the market traditionally served by U.S. launch capability is projected to require the equivalent of 30 Shuttle flights annually in the early 1990s -- roughly four times the level of actual average launch activity experienced from 1970 to 1985. [Ref. 26: p. 2]

Using the historical record as a guide, NASA, DOD, and government contractors have consistently over-estimated launch demand.

Since the *Challenger* accident, estimated flight rates became increasingly conservative. With a four Orbiter fleet NASA is projecting a flight rate of 16 flights per year while the National Research Council (NRC) is projecting 12 flights per year. NASA and the NRC agree that four flights per year per Orbiter is achievable. The NRC, however, states that with a four Orbiter fleet only three of the four Orbiters will be "manifestable." This judgment is based upon unpredictable occurrences that in effect would remove one of the four Orbiters from use. On the other hand, the NASA projection is based on analysis and experience that NASA feels supports the view that each of the orbiters may fly four times a year. [Ref. 37: p. 15, Ref. 35: p. 18]

1. Shuttle Flight Equivalent

The *Shuttle Flight Equivalent* is now used as the unit of measure for launch demand. While the shuttle flight equivalent is precise enough to provide a reasonably accurate representation of the level of launch activity, it is defined with reference to a specific set of parameters that all Shuttle launches, past or projected, conform to:

Shuttle Flight Equivalent: An orbiter capable of carrying 65,000 pounds, launched with a 50,000 pound load from Kennedy Space Center to a low earth orbit of 28.5 degrees, 160 nautical miles above the earth. [Ref. 26: p. 6]

Table 10 is a comparison of historic launch vehicles and their corresponding Shuttle Equivalent.

Table 10. HISTORIC ELVS AND SHUTTLE EQUIVALENT

Launch Vehicle	Shuttle Equivalent
Saturn I	0.6
Titan III	0.5 to 0.7
Titan Agena	0.33
Atlas E/F	0.25
Delta	0.15 to 0.21
Atlas Centaur	0.33
Scout	0.125

2. Official Forecasted Launch Demand

The Congressional Budget Office defines space launch demand as:

Space Launch Demand: Payloads that are ready to be integrated with launch vehicles and that have enough financing, public or private, to cover launch costs. The unit of measurement of space launch demand is Shuttle Equivalents. [Ref. 26]

Before the *Challenger* accident, NASA officials anticipated impressive growth in traditional satellite deployment and also in new kinds of activity, such as space construction, servicing orbital spacecraft, and round-trip scientific experimentation. According to this "official view," the group of users traditionally served by U.S. space transportation would rapidly expand their requirements from about 7.5 Shuttle flight equivalents annually in the first half of the 1980s to almost 30 equivalents annually throughout the 1990s. [Ref. 26: p. 7]

According to DOD and NASA projections, all types of space users will increase their launch demands. DOD is projected to increase three times over the shuttle equivalents they required in the early 1980s. This increase will stem from the deployment of the Global Positioning System (GPS) and MILSTAR, an advanced communication system, as well as SDI tests and existing system upgrades.

Additionally, NASA's support of the Space Station will increase their share of shuttle equivalent flights dramatically, as much as 10 flights per year by the first half of the 1990s while sustaining a rate of 11 shuttle equivalents per year by the end of the 1990s. [Ref. 26: p. 9]

Table 11. U.S. SPACE LAUNCHES 1970 TO 1985

Year	Flights (in Shuttle Equivalents)
1970	6.1
1971	7.0
1972	6.9
1973	7.1
1974	5.0
1975	6.6
1976	7.2
1977	7.3
1978	9.3
1979	4.5
1980	4.2
1981	5.7
1982	5.5
1983	8.4
1984	12.2
1985	12.4

3. Launch Activity: 1970-1985

An examination of historic U.S. launches indicates a gradual increase in launch demand. (See Table 11.) From 1970 through 1985, the launch market traditionally served by the United States averaged 7.5 equivalent Shuttle flights per year. From 1970 to 1985, DOD launches alone accounted for an average of 45 percent of the payloads flown on U.S. systems. During the same period, NASA and NOAA accounted for another 25 percent of the spacecraft launched by the United States. [Ref. 26: pp. 12-13]

4. Over-Estimation of Launch Demand

Previous projections of launch demand have over-estimated actual demand in both the immediate future (one to three years), and the longer term (beyond three years). The NASA launch forecast for 1985 is an example of this:

- In 1979, 44 Shuttle equivalents were projected by NASA for 1985, but this estimate dropped to only 39 flights in the 1980 projection for 1985, and 22 flights in the 1983 projection. [Ref. 26: p. 10]
- The majority of the decline in the projections between 1979 and 1983 for 1985 resulted from over-estimation of demand.
- An early 1985 projection of flights for that same year was 14 Shuttle flight equivalents, much closer to the actual 12 shuttle equivalents of 1985 (including ELVs). [Ref. 26: p. 10]

There are three reasons that drive the consistent over-estimation of launch demand:

- In responding to projection surveys, potential launch service users systematically under-estimate the technical, market, and budgetary constraints that tend to force actual space transportation demand below planned demand.
- Military launch requirements are over-estimated because DOD assumes that satellite life times will be far shorter than actual experience indicates.
- NASA's projections of its own needs, particularly when the Shuttle system is concerned, are often overstated because NASA is assumes that planned capacity will be filled by budget-supported demand when, in fact, the Congress regularly approves lower appropriations than requested by NASA. [Ref. 26: p. 11]

F. SPACE SHUTTLE RETURNS TO FLIGHT

In September of 1988, the Space Shuttle *Discovery* was launched, returning the Space Shuttle fleet back to space. NASA conducted thorough reviews of the Shuttle program and essentially met all the recommendations of the Rogers Commission. The Space Shuttle has new, redesigned, and safer solid rocket boosters that have been extensively tested. But NASA points out that the return-to-flight effort will not be fully complete until a sustained flight rate is achieved. [Ref. 30]

The Shuttle will now undergo continuous improvements. The reasons for continued change is that NASA wants a safer, higher performing Shuttle that is less expensive to operate through cost reductions. Additionally, the Shuttle is built around early 1970 technology which is largely obsolete. NASA intends to upgrade the flight computers by increasing processing speed, doubling the memory, and reducing the size and weight. The projected first flight of a Shuttle with the upgraded computer is planned for early 1991. [Ref. 30]

Additional improvements to the Shuttle will include a new auxiliary power unit (APU) with increased life and reduced turnaround time. Also a new carbon brake was developed to increase performance and safety margins and was flown on STS-31 in April 1990. [Ref. 30]

1. Post Challenger Accident Shuttle Flight Record

The flights per vehicle since the Shuttle's return to flight is in Table 12.

Table 12. FLIGHTS PER SHUTTLE VEHICLE SINCE ACCIDENT

Vehicle	Number of Flights
Columbia OV-102	2
Discovery OV-103	4
Atlantis OV-104	4

The number of Shuttle flights by year since the return of the Shuttle fleet to flight in September 1988 were one flight in FY 1988, four flights in FY 1989, and five flights in FY 1990.

Since the Vandenburg Launch Facility is in a "mothball" status, NASA revised the Shuttle flight numbering system to the original method of indicating only the numerical sequence of flights. The Shuttle mission history since the *Challenger* accident is in Table 13.

Table 13. SPACE SHUTTLE MISSIG HISTORY (POST CHALLENGER ACCIDENT)

Flight Number	Date Launched	Vehicle	Payload
STS-26	9 Sep 88	*Discovery*	NASA Relay satellite
STS-27	2 Jan 88	*Atlantis*	DOD mission
STS-28	8 Aug 89	*Columbia*	DOD mission
STS-29	13 Mar 89	*Discovery*	NASA relay satellite
STS-30	4 May 89	*Atlantis*	Magellan space probe
STS-31	18 Apr 90	*Discovery*	Hubble Space Telescope
STS-32	9 Jan 90	*Columbia*	Space science payloads
STS-33	22 Nov 89	*Discovery*	DOD mission
STS-34	18 Oct 89	*Atlantis*	Galileo space probe

2. Projected Space Shuttle Flights

In January 1990, NASA provided a schedule for future Space Shuttle flights of which a portion is presented in Table 14.

Table 14. PROJECTED SPACE SHUTTLE FLIGHTS (AS OF JAN. 1990)

Flight Number	Date	Vehicle	Primary Payload
STS-35	9 May 90	*Columbia*	Astronomy and X-Ray Telescope
STS-36	22 Feb. 90	*Atlantis*	DOD Mission
STS-37	1 Nov 90	*Atlantis*	Gamma Ray Observatory
STS-38	9 Jul 90	*Atlantis*	DOD Mission
STS-40	29 Aug 90	*Columbia*	Space Life Sciences
STS-41	5 Oct 90	*Discovery*	International Solar Polar Mission
STS-42	12 Dec 90	*Columbia*	International Microgravity Lab
STS-43	31 Jan 91	*Discovery*	Tracking and Data Relay Sat.
STS-44	4 Mar 91	*Atlantis*	DOD Mission
STS-45	4 Apr 91	*Columbia*	Atmospheric Lab for Applications and Science
STS-46	16 May 91	*Discovery*	European Retrievable Carrier
STS-47	17 Jun 91	*Atlantis*	Spacelab
STS-48	22 Aug 91	*Discovery*	Upper Atmospheric Research Sat.
STS-49	30 Sep 91	*Atlantis*	Starlab
STS-50	5 Dec 91	*Discovery*	Laser Geodynamics Sat.
STS-51	23 Jan 92	*Atlantis*	Infrared Background Signature Survey
STS-52	13 Feb 92	*Endeavor*	Geostar

VI. PROPOSED HEAVY LAUNCH SYSTEMS

A. NATIONAL SECURITY LAUNCH STRATEGY (NSDD-144)

On 25 February 1985, President Reagan signed the National Security Decision Directive (NSDD-144) entitled "National Security Launch Strategy," which initiated a study to look at the future development of a second-generation space transportation system. The National Security Launch Strategy reaffirmed that the Space Shuttle would continue to be the primary space launch system for the United States. [Ref. 1: p. 1]

Additionally, with regard to the future, the Directive specified:

> DOD and NASA will jointly study the development of a second-generation space transportation system -- making use of manned and unmanned systems to meet the requirements of all users. A full range of options will be studied, including shuttle-derived technologies and others. [Ref. 1: p. 1]

B. FINDINGS OF THE JOINT DOD/NASA NATIONAL SPACE TRANSPORTATION STUDY

The Joint DOD / NASA team queried both government and industry personnel involved in the acquisition and operation of current launch systems. The information gathered will aid in the definition and evaluation of future space transportation systems and policies. Table 15 summarizes what the joint DOD / NASA team found concerning current launch systems as well as the considerations for future space transportation systems. [Ref. 38, Ref. 1]

Table 15. FINDINGS OF THE JOINT DOD/NASA TASK TEAM

Current Launch Systems
The current systems were originally designed to meet space mission planning models which have never fully materialized.
Funding limitations during the development phases forced compromises which inhibited existing national launch systems from realizing the full potential for cost-effective operations.
The U.S. has neither funded nor maintained a robust space launch system that allows for improvement of the operational effectiveness of the existing national launch systems.
The U.S. launch industrial base cannot rapidly react to changing space mission requirements and or adversity.
A complementary launch strategy must be inherent in the national space policy to increase the probability of continuous access to space.
Space transportation costs are substantially driven by both launch systems and spacecraft designs which require man-power intensive, technically complex, and high-cost integration efforts.
The existing Space Shuttle and ELVs have relatively high operating costs when compared to that achievable in the 1995 to 2010 time period. Although continued use would require no significant development investments, anticipated traffic growth would necessitate high Shuttle and ELV flight rates and sizeable investments in additional orbiters, expendables, ground processing and launch facilities, and operations support.
Current funding levels inhibit the timely development of a majority of necessary key technologies.
Future Launch Systems
Future U.S. launch systems must be driven by operations and support as well as assured access considerations, in order to achieve operational flexibility and cost effectiveness. A substantial reduction in recurring operations cost is achievable if launch vehicles are designed for operational efficiency rather than maximum performance.
Preferred systems will employ new launch vehicles, such as an unmanned cargo vehicle (with supplementary use of ELVs for specific missions): and new launch and flight operations approaches. This approach is cost-effective across a wide range of mission scenarios and would improve assured access capabilities.
Integration of payloads with the launch vehicle is a significant operational cost. New processing and integration methods approaching those applied to cargo aircraft and other truly "operational" transportation systems must be developed.

C. OPTIONS FOR SPACE TRANSPORTATION

Preliminary analysis by the Joint DOD / NASA Task Team indicated severe shortfalls for space policies that utilize only one launch system due to high launch rates, lack of flexibility, and assured access. [Ref. 1: p. 19]

New launch vehicle focus is on candidate launch vehicle systems composed of two or more new primary vehicle types which could be supplemented by current launch vehicles. According to the Joint Task Team, three general categories of candidate launch vehicles can be established:

- Type A A new unmanned cargo vehicle in the mid-1990's with a new manned vehicle around 2002 and a partially or fully reusable new orbit transfer system (OTS) in the intervening years.
- Type B The same as Type A with the exception of the additional capability of down payload associated with the unmanned cargo vehicle. This could be attainable through the use of recoverable payload canisters, a fully reusable flyback second-stage and cargo bay, or other configurations.
- Type C Fundamentally the same as A and B above with an additional cargo vehicle(s). [Ref. 1: p. 21]

An early introduction of a vehicle type described above could keep Shuttle flight rates nominal, while increasing assured access reliability. The new vehicle could also relieve dependence on more costly ELVs, while accommodating increasing launch demand according to the Joint Task Team. The new vehicle could exhibit cost reduction through containerization of small payloads and minimal or no payload support services (e.g., power and environmental conditioning) aboard the launch vehicle. [Ref. 1: p. 21]

Even with a new unmanned vehicle to reduce late-1990s Shuttle utilization, the Joint Task Team recognizes a new manned vehicle is necessary for a more cost-effective, robust system capable of maintaining the United States' world leadership in space transportation. The Shuttle fleet will be reaching service limits sometime in the 2000 to 2005 time frame and represents early 1970's technology. Rather than replenishing the Shuttle fleet, the Joint Task Team feels it would be advantageous to introduce a new manned vehicle with a lower operating cost. [Ref. 1: p. 21]

According to the Joint Task Team, expendable launch vehicles require the least technology development and allow the earliest available launch capability with low development cost and risk. Also, new expendable vehicles would most likely use low-cost current engines or derivatives of current technology engines. However, the study indicates that high-technology based new expendable launch vehicles are competitive in terms of total life-cycle costs. [Ref. 1: pp. 26-27]

The Joint Task Team admits that partially reusable systems offer lower initial development costs but higher operating costs than fully reusable concepts. The main technological challenges for fully reusable vehicles are the recovery module, aerothermodynamics and control, as well as a new hydrocarbon booster engine. [Ref. 1: p. 27]

Fully reusable launch systems generally require advanced technologies. The single-stage-to-orbit (SSTO) vehicles like the proposed aero-space plane require high performance liquid oxygen / liquid hydrogen and/or liquid oxygen / hydrocarbon rocket engines. Additionally, new light weight structures, long-life thermal protection systems, and autonomous avionics are needed because of performance and weight sensitivity. [Ref. 1: p. 27]

In addition to the performance technologies needed, investments in additional technologies and new developments are required to achieve major reductions in operations costs (e.g., automation of manufacturing, checkout, etc.). New vehicles incorporating these technologies can achieve a ten-fold reduction compared to the present costs of $1800 to $3000 per pound to orbit, according to the Joint Task Team. [Ref. 1: pp. 27-28]

D. THE RECOMMENDATIONS OF THE JOINT DOD / NASA TASK TEAM

The Joint Task Team recommended the following:

- If new manned and unmanned launch systems and lower costs for space transportation are to be attained, the U.S. must commit to implementing a plan that is complementary to other planned technology activities (e.g., the National Aero-Space Plane, ongoing DOD/NASA programs, and industry programs). The plan must be focused to provide a base for new systems which can achieve the objective of substantially reduced operating costs. The plan must support the development of both evolutionary and revolutionary technology alternatives necessary to assure continued U.S. world leadership in space transportation.
- Conduct studies to refine and confirm the cost beneficial investments which will provide the most efficient operations and vehicle systems for the future.
- Reassess the transition to the next generation launch vehicles while considering all elements of the proposed system as well as the current Space Shuttle and Titan systems. [Ref. 38: pp. 23-24]

E. THE NATION'S DIRECTION

In 1988, the Congressional Office of Technology Assessment published *Launch Options for the Future: A Buyers Guide*, which clearly defines options the United States could pursue with new launch systems. To determine which of the new space transportation alternatives is most appropriate and most cost-effective, the United States must first make some broad decisions about the future. Some of the fundamental questions are presented in Table 16. [Ref. 39]

Table 16. DECISIONS TO BE MADE

If the U.S. wishes to:	Then it should:
Maintain U.S. leadership in launch system technology	Increase funding for space transportation basic research, technology development, and applications. Maintaining leadership will require a NASA/DOD technology development program across a range of technologies.
Improve resilience (ability to recover quickly from failure) of U.S. launch systems	Fund the development of a new high capacity, high reliability launch vehicle *or* expand current ground facilities *or* reduce downtime after failures *or* improve the reliability of current launch vehicles. At high launch rates, developing a new launch vehicle is probably most economical.
Increase launch vehicle reliability and safety	Aggressively fund technologies to provide: (1) improved subsystem reliability; (2) on-pad abort and in-flight engine shutdown for escape from piloted vehicles; and (3) redundancy and fault tolerance for critical systems.
Limit the future growth of NASA and DOD space programs	Maintain existing launch systems and limit expenditures on future development options. Current capabilities are adequate to supply both NASA and DOD if the present level of U.S. space activities is maintained or reduced.
Deploy the Space Station by the mid-1990's while maintaining an aggressive NASA science program	Continue funding improvements to the Space Shuttle *and/or* begin developing Shuttle-C. The current Space Shuttle can launch the Space Station, but will do so more effectively with improvements or the assistance of a Shuttle-C. Although Shuttle-C may not be as economical as other new cargo vehicles at high launch rates, it is competitive if only a few heavy lift missions are required each year.
Continue trend of launching heavier communications, navigation, and reconnaissance satellites	Commit to the development of a new unmanned cargo vehicle by the mid to late 1990's. In theory, current launch systems could be expanded to meet future needs; however, new systems are likely to be more reliable and more cost effective.
Dramatically increase the number and kind of other military space activities	Commit to the development of a new unmanned cargo vehicle (e.g., Advanced Launch System). Current launch systems are neither sufficiently economical or reliable to support a dramatically increased military space program.

F. NEW LAUNCH CONCEPTS

Although many new launch concepts are currently under investigation and/or development, two concepts, the Advanced Launch System (ALS) and Shuttle-C (for cargo), are systems being endorsed by NASA and DOD.

The Advanced Launch System (ALS) is a totally new launch system under study by the Air Force and NASA that would be designed to launch large cargo payloads economically at high launch rates. The Congressional Office of Technology Assessment assumes a partially reusable vehicle featuring a flyback booster, a core stage with expendable tanks and a payload faring, and a recoverable payload avionics module. [Ref. 41: p. x]

The Shuttle-C is an unmanned cargo vehicle, derived from the Shuttle, with a heavy lift capacity of 100,000 to 150,000 pounds to low earth orbit. Shuttle-C would use the existing expendable external tank and reusable solid rocket boosters of the current Shuttle, but would replace the Orbiter with an expendable cargo carrier. [Ref. 41: p. x]

1. Advanced Launch System (ALS)

On January 5, 1988, President Reagan signed a Report to Congress creating a joint DOD and NASA program for the development of the ALS. The report established a joint program office headed by an Air Force program manager with a NASA deputy program manager. The Department of Defense will lead the systems engineering and integration, vehicle, logistics, and payload module while NASA leads liquid engine systems and the focused technology effort. [Ref. 37: p. 90]

ALS is currently in a 25 month Phase II program that includes a mixture of technology development and system analysis efforts. Full-scale development of the ALS has not been approved. [Ref. 42: p. 440]

The goal of the Advanced Launch System (ALS) program is to design a low cost, heavy lift launch system to serve U.S. needs at the turn of the century. However, because an ALS would require some technologies not fully developed at this time and because NASA and the Air Force would like to prepare to meet any additional demand for launch services in the mid 1990's, they are also considering options for new interim, high capacity launch systems based on current technology. [Ref. 21: p. 24]

The ALS seeks to provide the focused technology which will lead to a heavy-lift launch system which is flexible, robust, reliable, responsive, operationally efficient, while significantly lowering the cost of getting payloads into low earth orbit. The ALS goal is to have an operational capability no later than 1998. [Ref. 36: p. 90]

The ALS development is focusing on both advanced technologies and improvements to current technologies. The focus of the program is on a broad payload range which includes payloads from 1 to 220 thousand pounds. Additionally, managers of current ELVs were asked to assess the application of ALS-developed technologies to current ELVs. [Ref. 40: p. 441]

The ALS goal of a $300 per pound payload launch cost was derived from a 25 per year launch rate by the year 2005. However, reductions in planned flight rates and the broadening payload range have reduced the focus on the $300 per pound cost goal. The Joint Program Office acknowledges that the $300 per pound goal is probably not achievable for current mission models. [Ref. 40: p. 441]

The reference two-stage vehicle (See Figure 8.) has an expendable liquid oxygen / liquid hydrogen propellant core with three low-cost Space Transportation Main Engines (STME). Like most of the proposed ALS, the low-cost STME are yet to be developed. This vehicle concept has a payload delivery capability of approximately 120,000 pounds to low earth orbit. [Ref. 41: p. 3]

Variants of this vehicle will use the same standard core and will deliver more or less payload by varying the arrangement, type, and number of boosters and booster engines. [Ref. 41: p. 3]

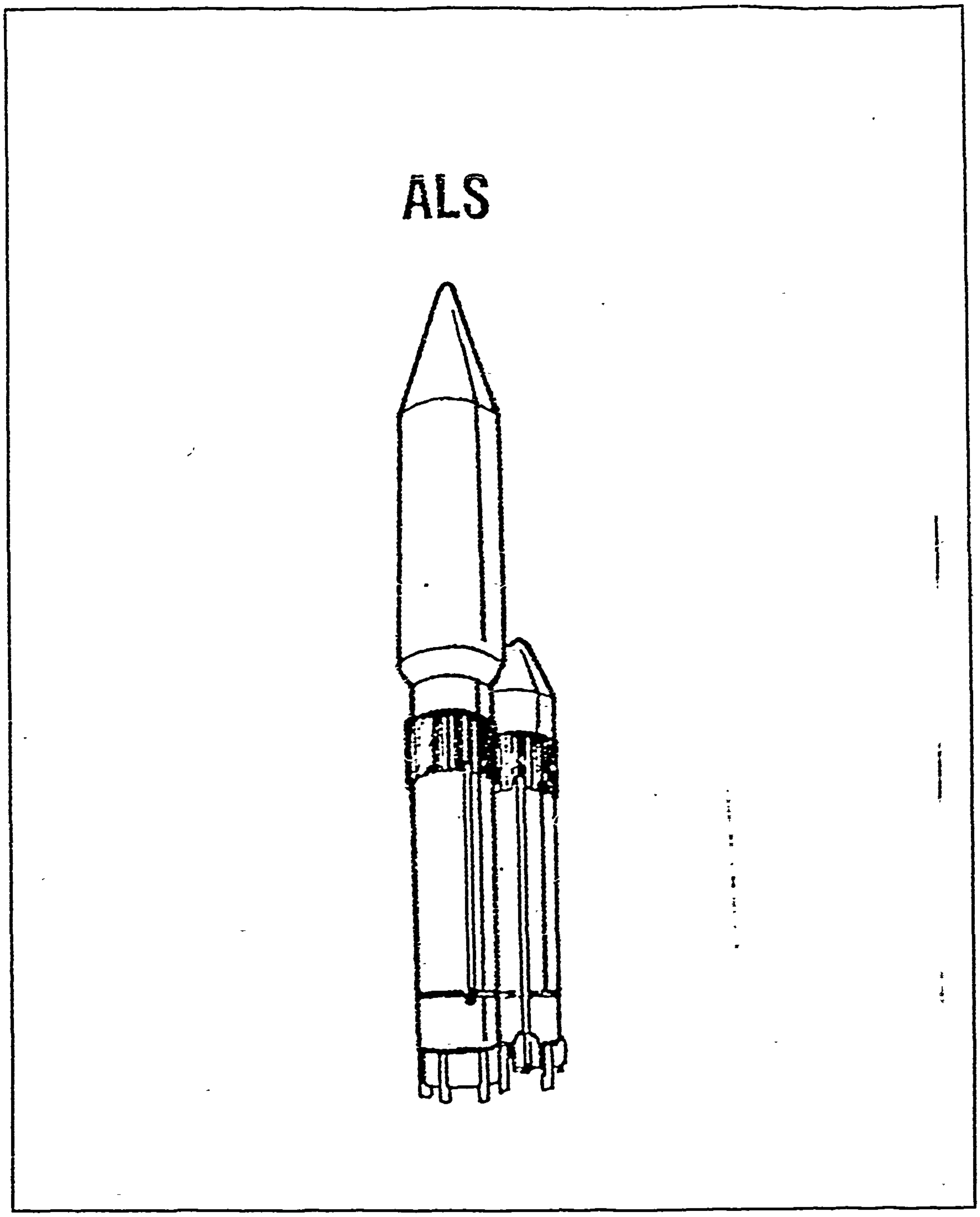

Figure 8. Advanced Launch System Reference Vehicle

The ALS will operate as a bulk cargo transport. To reduce cost, cargo interfaces will be minimized and standardized, ground processing functions will be streamlined and the cargo will be delivered to standard orbits. Payload peculiar services and on orbit propulsion, if required, will be provided by payload owners. [Ref. 44: p. 4]

Although being intensively reviewed, preliminary estimates indicate that the development and first flight cost of the ALS would be in the range of $1.7 to $2.0 billion, in FY 1989 dollars. [Ref. 42: p. 436]

2. Shuttle-C

NASA's version of the heavy lift vehicle is the Shuttle-C, which in several aspects competes with the ALS. The Shuttle-C would be an unmanned cargo vehicle based primarily on Shuttle technology. If Shuttle-C is used to ship major subassemblies of the space station to orbit, one Shuttle-C flight could replace two or three Shuttle missions. Shuttle-C could reduce the need to fly all of NASA's planned Shuttle missions. [Ref. 21: pp. 24-25]

NASA feels that, if approved, the Shuttle-C could deliver approximately 100 to 150 thousands pounds to orbit depending on whether two or three main engines are used. Since the Shuttle-C concept has an unmanned cargo element in place of the Shuttle orbiter, a new processing facility would likely be required for this cargo element. The cargo element design allows for use of existing as well as planned STS payload processing capabilities. The Shuttle-C could use the same production capability for External Tanks and SRB's as the STS. However, NASA envisions flying Shuttle-C on average only three times per year, with an associated reduction in the number of Shuttle flights. Hence, there will be no significant difference in External Tank and SRB production efficiencies. [Ref. 42: pp. 452-453]

The National Space Launch Program submitted to the Congress the following statement on Shuttle-C:

Studies to date have concluded that the Shuttle-C could meet potential near term requirements for heavy-lift with minimum development cost (although without the full long-term operating cost reduction, flexibility, and resiliency desired). Shuttle-C studies are examining the potential for increasing the flexibility, robustness, and cost- effectiveness of the Space Shuttle fleet to meet NASA unmanned launch requirements, including Space Station Freedom assembly and planetary payloads. [Ref. 42: pp. 435-436]

In August 1987, as part of concept and definition study efforts, NASA initiated Shuttle-C studies focusing on maximum utilization of Shuttle hardware, facilities, and operations. NASA projects that the system will offer a near term heavy-lift capability with minimum cost and schedule risk. NASA feels the Shuttle-C could provide a step toward an early robust national launch posture in the mid-1990s. [Ref. 37: p. 88]

In 1989, NASA was assessing Shuttle-C as a possible new start for FY 1991. If proposed, Shuttle-C funding would be a stand-alone new NASA start. In other words, Shuttle-C would not be associated with other on-going activities, an additional orbiter, or the orbiter spares. [Ref. 42: p. 436]

NASA has baselined the current Shuttle for all space station delivery and assembly needs. NASA feels the current Space Shuttle can deliver and support the assembly of all station elements. If Shuttle-C was approved and made an integral part of station planning, it could be used to reduce the number of Space Shuttle launches required to assemble the Space Station. This would be accomplished by placing fully outfitted habitat and experiment laboratories into orbit, eliminating the need to accomplish this task in space. NASA admits the use of an unmanned vehicle must be sensitive to the need for a manned presence to complete the assembly process, and for appropriate services to the unassembled pieces prior to assembly with the growing space station. Studies are continuing to examine the utilization of Shuttle-C for Space Station assembly. [Ref. 42: p. 436]

Three parallel systems definition contracts were begun in FY 1987, to define a shuttle-derived vehicle configuration most appropriate to satisfy the anticipated national needs beginning in the mid-1990's. The current Shuttle-C concept was a result of these studies. (See Figure 9. Source: Ref. 43) These contracts have been extended through the end of FY 1989 and, along with in-house efforts, are further defining the Shuttle-C configuration. FY 1990 funds will be needed to continue the activity to mature the Shuttle-C system design in preparation for a new start proposal in FY 1991. [Ref. 42: p. 453]

Shuttle-C would have the advantage of using much of the same technology and many of the same parts that have already proved successful in Shuttle flights. To keep fixed costs down, it would use the same launch pads, integration facilities, and launch support crews now used for the Shuttle. However, another stand-down like the 1986 to 1988 stand-down of the current shuttle would result in delaying Shuttle-C flights for the same reasons. [Ref. 21: p. 25]

3. Cost Considerations with Shuttle-C

Table 17 (Source: Ref. 21) represents the cost considerations that space planners have with the Shuttle-C as well as the Shuttle-C's relationship with the current Shuttle:

Table 17. SHUTTLE-C COST CONSIDERATIONS

Orbiter Processing	Not having to process a Shuttle orbiter would likely speed up launch operations and therefore reduce costs compared to the current Shuttle. However, the Shuttle-C would still need to be assembled, integrated, and tested prior to each flight. If the Shuttle-C were not specifically designed for simplicity and ease of operation, its operational costs could grow to become a significant fraction of the cost of preparing for launch.
Simultaneous Shuttle-C and Current Shuttle Processing	Shuttle-C will affect the processing flow of the current Shuttle orbiter. Because the Shuttle-C would be similar to the current Shuttle, it would be processed in the same facilities as the current Shuttle.
Shuttle-C Processing Time	Because NASA intends to use the Shuttle-C for transporting major components fo the space station to orbit, which are likely to be of greater value than the vehicle, NASA would have considerable incentive to process the Shuttle-C as carefully as it processes the current Shuttle, and with the same crews and procedures.
Shuttle Facilities	The Shuttle facilities, including the launch pads, may constrain NASA's ability to reach the desired flight rate projected for a four orbiter fleet, and simultaneously launch Shuttle-C two or three times per year. Launching both vehicles will require either shifting some payloads from the current Shuttle to Shuttle-C and flying fewer orbiter missions, or building new facilities to accommodate the Shuttle-C.
Parts	Because Shuttle-C would share many of the same parts as the current Shuttle, delays may occur in one or the other launch system should the parts supply become constrained. On the other hand, because parts become cheaper when purchased in quantity, the existence of a Shuttle-C might reduce the costs of some components.
Mission Operations	Mission operations for the Shuttle-C would be simpler and possibly less costly than the current Shuttle. Because the Shuttle-C would not carry humans, mission operations would consist primarily of control, navigation, guidance, and releasing the payload(s) at proper orbit.

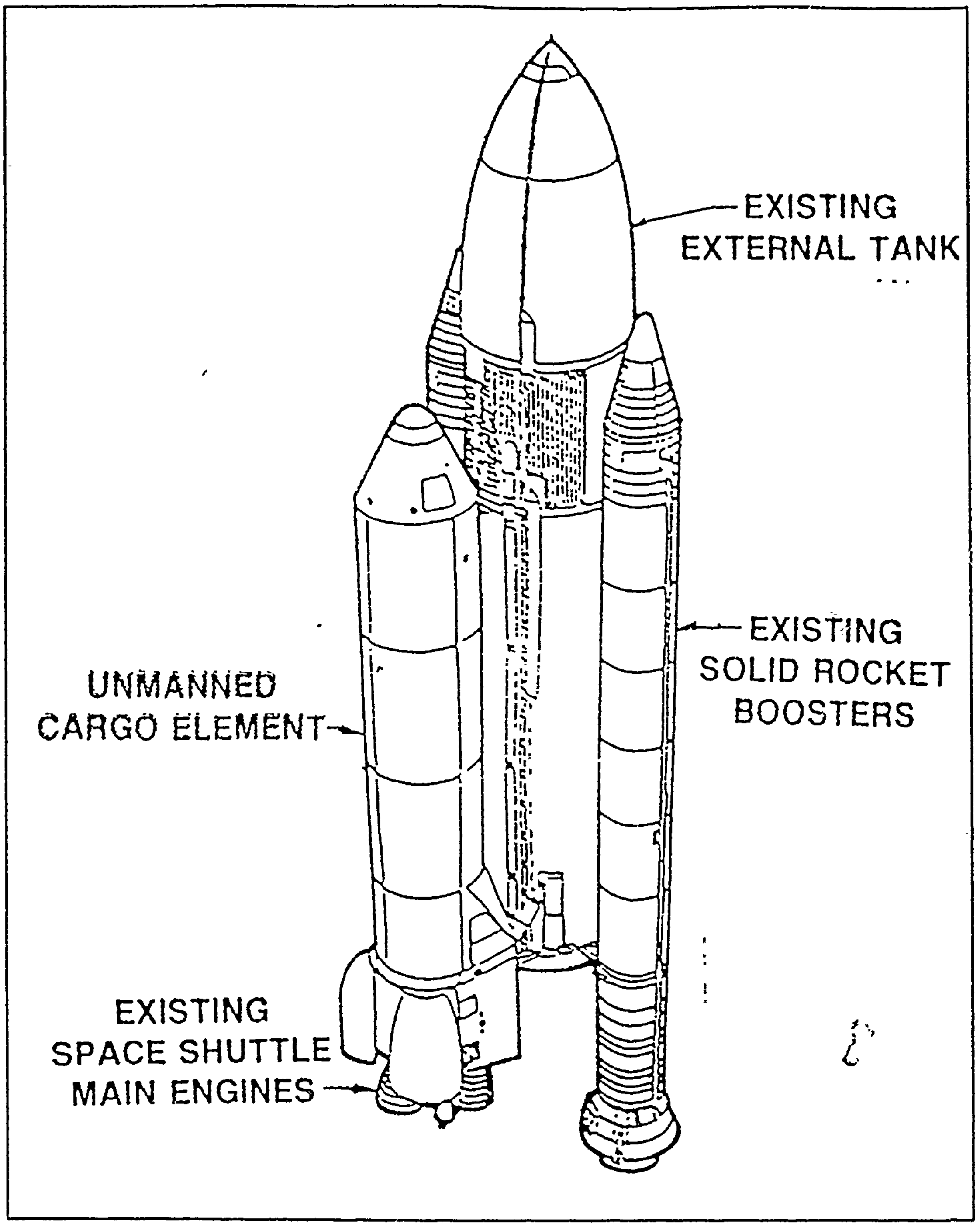

Figure 9. The Shuttle-C Concept

VII. OBSERVATIONS

The Space Shuttle was an attempt at developing a low-cost, routine access to space. But the Space Shuttle has had some unique cost effectiveness difficulties that restrict it from reaching that goal.

A. SPACE POLICY

The Space Shuttle was inhibited by lack of a clear, consistent and concise National space policy.

If the administration and Congress had mandated in the late 1960's that the United States will research, design, and develop a low-cost, routine access to space while investigating all possible technologies in doing so, the resulting launch system would have been much different than the current Space Shuttle.

As originally planned, the Space Shuttle was to be an integral part of an Earth orbiting space station ferrying people and supplies back and forth to earth. When the space station was put on "hold" for budgetary reasons, NASA continued to pursue the Space Shuttle, although now the space shuttle had a new mission - - routine, cost-effective access to space to all potential users of space. However, the Space Shuttle was not originally envisioned for cost-effective space transportation for all potential users; it was to be part of the space station.

If the United States had wanted to invest in developing a cost-effective, routine access to space, it should have issued clear long-term goals as well as a defined plan for developing and incorporating low-cost space transportation systems.

A long-term plan is needed presently as well. Instituting a long-term research, development and technology application plan for cost-effective space transportation would serve as a road map for the future. The current process of the administration setting the space goal while the Congress, who allocates the funds, either supports or does not support the goal, inhibits the production of efficient space transportation systems.

B. SPACE SHUTTLE FUNDING

Budgetary constraints during Space Shuttle development caused schedule slippage, cost overruns, and limited the Space Shuttle in reaching its full potential.

When NASA did not receive the required funds during Space Shuttle development, NASA management had to take the following actions:

- Slip the schedule,
- defer some work,
- delete some work, or
- reprogram funds

which had profound effects on the resulting Space Shuttle. The finished Space Shuttle was not as originally planned, behind in schedule, and over in costs.

Developing new technologies in space transportation will most certainly unveil hidden costs that were not originally seen. This was evident with the Space Shuttle. When an unforeseen cost arose and funds were not available, NASA had to take actions, c those listed above, to solve the problem.

If the United States is to pursue new low-cost space transportation, the necessary funds must be guaranteed to do so. Limiting or constraining funds on developing new space transportation systems will only serve to compromise that system and lessen the system's ability to reach full cost-effective potential.

C. SPACE SHUTTLE COMPLEXITY

The Space Shuttle is the most complex launch system ever built which has restricted its ability to be a routine, low-cost access to space.

The Shuttle was an revolutionary step in launch systems and was not designed for operational simplicity. Many of its systems are highly complex, and made up of a multitude of parts that need to be inspected or repaired.

For example, each of the Solid Rocket Boosters, considered one of the simpler Shuttle elements, contains about 75,000 parts and components. Of these, about 5,000 are removed, inspected, and replaced or refurbished after each Shuttle flight. The Thermal Protection System, composed of over 31,000 tiles, requires careful inspection and repair, an extremely labor intensive operation. In addition, each tile must be tested for adherence to the vehicle.

If the United States wants low-cost access to space, then lower performing, simpler systems must be investigated. The trend to maximize new technologies must be balanced with the desired goal and needs of the space transportation system.

D. SAFETY AND THE MANNED ELEMENT

The human presence in the Space Shuttle Orbiter increases time and complexity of launch operations.

Because the Shuttle carries human crews, and because it is a highly visible symbol of American technology, safety issues receive unusually great attention. As a result of the investigation of Shuttle subsystems following the loss of *Challenger* and its crew, the Shuttle system has undergone many major safety related changes, which have led to considerable system redesign. These changes have also increased the time and complexity of launch operations.

Prior to the loss of *Challenger*, NASA had reduced the turnaround time necessary to prepare the Shuttle orbiter for flight to about 55 workdays. Since the Shuttle has returned to flight, the turnaround times have been on the order of 150 workdays and NASA hopes to decrease this to about 75 days. [Ref. 21: p. 21]

If the United States continues to pursue the space station and desires to maintain world leadership in space, then a manned launch system will be necessary. However, routine launches of satellites can be performed without a manned element. The Shuttle has proven that a manned element drastically increases the costs of space transportation.

E. SHUTTLE STILL IN DEVELOPMENT

The Space Shuttle is not yet a fully operational system and has not proven to be routine access to space.

Although NASA declared the Space Shuttle operational after the fourth flight, it has as yet not achieved true operational status. Because the Shuttle is undergoing major design changes, it requires larger launch operations staff than an operational system. For example, NASA employs about 5000 engineers at KSC, Marshall Flight Center, and JSC who work on Shuttle systems. They have strong incentives to implement changes for increasing safety and performance, many of which increase the time and cost of preparing a shuttle for flight. On the other hand, there are few incentives for increasing operations efficiency and reducing costs. [Ref. 21: p. 21]

If the Space Shuttle is to continue evolving, NASA must control the evolution towards increased efficiency and simplicity. Upgrades to the Space Shuttle must be considered with a cost-effective mind-set; however, because of the manned element, safety must always be paramount.

F. NEW LAUNCH SYSTEMS

Launch demand will determine if developing new low-cost space transportation systems or upgrading and modifying current systems is more cost-effective.

The United States possesses the technology to improve the capabilities of existing launch vehicles and facilities through modifications. Incremental improvements to current systems could reduce their operations cost and increase their lift capacity. If improvements in vehicle reliability can be achieved, then current vehicles could be used with greater confidence at higher flight rates. By improving existing vehicles and ground facilities and buying more launch vehicles, the United States could easily increase its launch capabilities.

The costs of developing improvements to existing launch vehicles must be compared to developing new vehicles.

The demand for launch services in the future will be one of the primary determinants of the value of investing in new launch systems. If future missions are as infrequent and diverse as they have been previously, launch options such as the Shuttle-C and the ALS will not likely reduce average launch costs significantly, although these systems will most likely improve launch reliability, capability, and resiliency. If launch demands continue to increase, it would most likely be more economical to develop and procure new launch vehicles that could be processed and launched efficiently at high launch rates.

New launch vehicles could lift heavier payloads but would require more investment than improving current vehicles. Upgrading existing vehicles would have low development costs but would save less on operational costs. Additionally, launching current vehicles at high rates would require improvements in reliability, back-up launch vehicles and facilities, or reductions in "downtime" following failures. If such changes could not be achieved economically with current vehicles, then it would appear pursuing new cargo vehicles is a better course of action.

VIII. LESSONS LEARNED

If the United States is to pursue new heavy-lift space transportation, the Space Shuttle program and the lessons learned from it must be considered so the most efficient and cost-effective systems can be built. The following are areas in which new heavy-lift launch systems must be fully supported for low-cost access to space to be achieved:

- A clear, concise, and consistent national space transportation policy must be articulated and instituted.
- Manned launch vehicles must be utilized primarily when a human presence is necessary. Use manned vehicles sparingly.
- If the Space Shuttle is to continue to evolve, the evolution must be towards efficiency and simplicity. The desire to upgrade and increase performance must be weighed against cost benefits.
- Realistic and honest evaluation of future launch demand must be addressed. Launch demand is the key element in determining the cost-effectiveness of new launch systems like ALS and Shuttle-C.
- New launch initiatives must have stable funding and support.
- Complementary, simple, lower performing systems must also be considered for routine, unmanned launches. Modifying current ELVs may be an attractive approach for the near term.

APPENDIX A. ACRONYMS

ALS	Advanced Launch System
APU	Automatic Positioning Unit
CBO	Congressional Budget Office
DDT&E	Design, Development, Test and Evaluation
DOD	Department of Defense
ELV	Expendable Launch Vehicle
ESA	European Space Agency
ET	External Tank
EVA	Extra Vehicular Activity
FFP	Firm Fixed Price
FMOF	First Manned Orbital Flight
FY	Fiscal Year
GPS	Global Positioning System
IOC	Initial Operating Capability
JSC	Johnson Space Center
KSC	Kennedy Space Center
LEASAT	Leased Satellite
LEO	Low Earth Orbit
LSA	Launch Service Agreement
MLV	Medium Launch Vehicle
MPT	Main Propulsion Test
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSDD	National Security Decision Directive
OMB	Office of Budget and Management
OMS	Orbiter Maneuvering System
OTA	Office Of Technology Assessment

OTS	Orbital Transfer System
OV	Orbiter Vehicle
PIP	Payload Integration Plan
PSAC	President's Science Advisory Committee
RFP	Request for Proposal
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SSME	Space Shuttle Main Engine
SSTO	Single Stage to Orbit
STME	Space Transportation Main Engine
STG	Space Task Group
STS	Space Transportation System
TPS	Thermal Protection System
TRS	Teleoperator Retrieval System
VAFB	Vandenburg Air Force Base

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