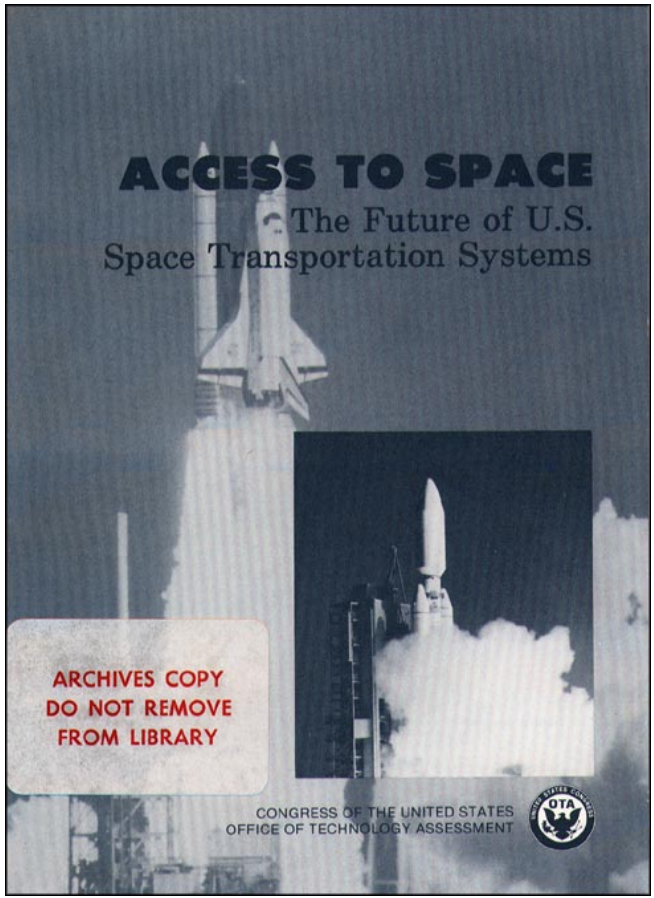
Access to Space: The Future of U.S. Space Transportation Systems

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Foreword

The United States today possesses a capable fleet of cargo and crew-carrying launch systems, managed by the National Aeronautics and Space Administration, the Department of Defense, and the private sector. Emerging technologies offer the promise, by the turn of the century, of new launch systems that may reduce cost while increasing performance, reliability, and operability.

Continued exploration and exploitation of space will depend on a fleet of versatile and reliable launch vehicles. Yet, uncertainty about the nature of U.S. space program goals and the schedule for achieving them, as well as the stubbornly high cost of space transportation, makes choosing among the many space transportation alternatives extremely difficult. Can existing and potential future systems meet the demand for launching payloads in a timely, reliable, and cost-effective manner? What investments should the Government make in future launch systems and when? What new crew-carrying and cargo launchers are needed? Can the Nation afford them?

This special report explores these and many other questions. It is the final, summarizing report in a series of products from a broad assessment of space transportation technologies undertaken by OTA for the Senate Committee on Commerce, Science, and Transportation, and the House Committee on Science, Space, and Technology. In the course of the assessment, OTA has published the special reports, *Launch Options for the Future: A Buyer's Guide* and *Round Trip to Orbit: Human Spaceflight Alternatives;* the technical memorandum, *Reducing Launch Operations Costs: New Technologies and Practices;* and the background papers, *Big Dumb Boosters: A Low-Cost Space Transportation Option?* and *Affordable Spacecraft: Design and Launch Alternatives.*

In undertaking this effort, OTA sought the contributions of a wide spectrum of knowledgeable individuals and organizations. Some provided information, others reviewed drafts. OTA gratefully acknowledges their contributions of time and intellectual effort. OTA also appreciates the help and cooperation of NASA and the Air Force. As with all OTA reports, the content of this special report is the sole responsibility of the Office of Technology Assessment and does not necessarily represent the views of our advisors or reviewers.



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NOTE: OTA appreciates the valuable assistance and thoughtful critiques provided by the advisory panel members. The views expressed in this OTA report, however, are the sole responsibility of the Office of Technology Assessment. Participation on the advisory panel does not imply endorsement of the report.

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Related OTA Reports

Civilian Space

Advanced Space Transportation Technologies Assessment

- *Affordable Spacecraft: Design and Launch Alternatives. OTA-BP-ISC-60,* January 1990. GPO stock #052-003-01 174-3 ; $2.25 .
- *Round Trip to Orbit: Human Spaceflight Alternatives. OTA-ISC-419,* August 1989, GPO stock #052-003-01 155-7; $5.50.
- *Launch Options for the Future: A Buyer's Guide. OTA-ISC-383,* July 1988. NTIS order #PB 89-1 142681AS.
- *Reducing Launch Operations Costs: New Technologies and Practices. OTA-TM-EC-28,* September *1988. GPO* stock #052-003-01 118-2; $4.50.
- *Big Dumb Boosters: A Low-Cost Space Transportation Option?* OTA Background Paper, February 1989. (available from OTA's International Security-and Commerce Program)

Other Reports

- *Commercial Newsgathering From Space. OTA-TM-ISC-40,* May *1987.* NTIS order #PB 87-235 396/XAB.
- *Space Stations and the Law: Selected Legal issues. OTA-BP-ISC-41,* September 1986. NTIS order #PB 87-118 220/AS.
- *International Cooperation and Competition in Civilian Space Activities. OTA-ISC-239,* July 1985. NTIS order #PB 87-136 842/AS.
- *U.S.-Soviet Cooperation in Space. OTA-TM-STI-27,* July 1985. NTIS order #PB 86-114 758/AS.
- *Civilian Space Stations and the U.S. Future in Space.* OTA-STI-241, November 1984. GPO stock #052-003-00969-2; $7.50.
- *Remote Sensing and the Private Sector: Issues for Discussion. OTA-TM-ISC-20,* March 1984. NTIS order #PB 84-180 '777.
- *Salyut: Soviet Steps Toward Permanent Human Presence in Space.* OTA-TM-STI- 14, December 1983. NTIS order #PB 84-181 437/AS.
- *UNISPACE '82: A Context for International Cooperation and Competition. OTA-TM-MC-26,* March 1983. NTIS order #PB 83-201848.
- *Space Science Research in the United States. OTA-TM-STI-19,* September 1982. NTIS order #PB 83-166512.
- *Civilian Space Policy and Applications. OTA-STI-177,* June 1982. NTIS order #PB 82-234444.
- *Radio frequency Use and Management: Impacts From the World Administrative Radio Conference of 1979. OTA-CIT-163,* January 1982. NTIS order #PB 82-177536.
- *Solar Power Satellite Systems and Issues.* OTA-E-144, August 1981. NTIS order #PB 82-108846.

Military Space

- *SDI: Technology, Survivability, and Softwre. OTA-ISC-353,* May 1988. GPO stock #052-003-01084-4; $12.00.
- *Anti-Satellite Weapons, Countermeasures, and Arms Control. OTA-ISC-281,* September 1985. NTIS order #PB 86-182 953/AS.
- *Ballistic Missile Defense Technologies. OTA-ISC-254,* September, 1985. NTIS order #PB 86-182 961/AS.
- *Arms Control in Space. OTA-BP-ISC-28,* May 1984. NTIS order #PB 84-198 209/AS.
- *Directed Energy Missile Defense in Space. OTA-BP-ISC-26,* April 1984. NTIS order #PB 84-21011 I/AS.

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Legislative Options for Space Transportation

Space Program Futures

Congress could choose to support the development of one or more of many different types of space transportation systems. To determine which of these alternatives is most appropriate, Congress must first make some broad decisions about the future of the United States in space. A commitment to key space program goals will entail a similar commitment to one or more launch systems.

If Congress wishes to:	*Then it should:*
Limit the expansion 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.**
Develop the capability to launch small- and intermediate-size payloads quickly and efficiently to support DoD and civilian needs:	*Continue to support the development of small and intermediate capacity launch systems.* **The U.S. private sector has the financial and technical capacity to develop such systems on its own if a market for launching small payloads exists.**
Deploy Space Station Free*dom* by the end of the century, while maintaining an aggressive NASA science program:	*Continue funding improvements to the Space Shuttle and other existing space transportation systems and/or begin developing Shuttle-C:* **The existing 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 might not be as economical as other new cargo vehicles at high launch rates, it would be competitive if only a few heavy-lift missions are required each year.**
Continue trend of launching heavier communications, navigation, and surveillance satellites and/or pursue an aggressive Strategic Defensive Initiative test program:	*Commit to the development of a new cargo vehicle for use early in the 21st century.* **Although existing launch systems could be expanded to meet such growth in payload weight, if demand is high, new, advanced systems would be more reliable and cost-effective.**
Deploy a full-scale space-based ballistic missile defense system and/or dramatically increase the number and kind of other military space activities:	*Commit to the development of a new cargo vehicle such as the Advanced Launch System.* **Current launch systems are neither sufficiently economical to support full-scale space-based ballistic missile defense deployment, nor reliable enough to support a dramatically increased military space program.**
Establish a permanent base on the Moon or send humans to Mars:	*Commit to the development of a new cargo vehicle(s) (Shuttle-C, Advanced Launch System, or other system) and continue funding advanced, crew-carrying launch systems.* **Any major initiative beyond the Space Station involving humans in space will require new launch systems.**

Improving U.S. Space Transportation Systems

Whichever broad program goals are selected, if Congress wishes to continue to improve the safety, reliability, performance, and/or economy of U.S. launch systems, it has a number of possibilities from which to choose. Several are listed below; they are not mutually exclusive, nor is the list exhaustive. Congress could decide to proceed with one or more from each list of options. Because of the long lead times for the development of space transportation systems, some decisions will have to be made in the next year or two. Others can wait until the middle of this decade or later.

Near-Term Decisions

If Congress wishes to:	*Then it could:*
Improve cargo launch system reliability or performance:	• *Fund development of technologies in the Advanced Launch System and other programs.*
Improve Space Shuttle system safety, reliability:	. *Fund development of Liquid-fueled Rocket Boosters (LRBs).* . *Fund continued development and improvement of Advanced Solid Rocket Motors (ASRMs) and alternate turbopumps for the Space Shuttle Main Engines.* . *Fund installation of built-in test equipment in the Shuttle and more automated test equipment in launch facilities.*
Maintain a sustainable Shuttle launch rate of 9 to 11 launches per year:	• *Fund the purchase of at least one additional orbiter to be delivered as soon as possible (1996), and direct NASA to reduce the number of Shuttle flights planned per year. NASA could reduce Shuttle flights by:* *a. postponing or canceling some planned Shuttle launches; or* *b. relying more on cargo-only launch vehicles, such as Titan IVs.*
Reduce risks to successful Space Station assembly:	. *Direct NASA to develop and use Shuttle-C to carry some Space Station elements to orbit. (This would reduce the total number of flights required.)*
Develop the technology base and plan for building new crew-carrying launch systems:	• *Continue to fund planning and technology development and test efforts such as:* *a. the Advanced Manned Launch System studies;* *b. the National Aero-Space Plane program (NASP); or* *c. the Advanced Launch System (ALS) program.*
Provide for emergency crew return from the Space Station:	• *Fund a program to develop a U.S. crew emergency return vehicle.* • *Support joint development with Space Station partners of vehicle for emergency return.*

Far-Term Decisions

If Congress wishes to:	*Then it could:*
Build safer, more reliable crew-carrying launch systems:	• *Fund development of safer, more reliable launch systems to augment or succeed the Shuttle. These might include:* *a. a Personnel Launch System (PLS), or* *b. an Advanced Manned Launch System (AMLS), or* *c. vehicles derived from the National Aero-Space Plane (NASP) program.*
Improve cargo launch system reliability and reduce costs:	. *Fund development of launch vehicles or systems (e.g., ALS engines) that could be manufactured, integrated, and launched by highly automated methods with improved process control.*
Increase operability:	• *Fund development of vehicles designed for quick turnaround, such as those considered for an Advanced Manned Launch System or possible successors to the proposed National Aero-Space Plane test vehicle (X-30).*

Major Launch Systems Discussed in This Report:

Existing Systems



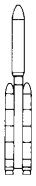
Delta II Expendable Launch Vehicle **(ELV)—manufactured by McDonnell** Douglas, it is capable of lifting over 11,000 pounds to low Earth orbit (LEO). Developed for the U.S. Air Force from earlier Delta versions, the Delta II is also available commercially from McDonnell Douglas. Its first launch took place in August, 1989.



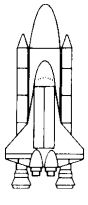
Atlas II ELV---capable of lifting about 14,500 pounds to LEO. Manufactured by General Dynamics under contract to the Air Force, the Atlas is also available in a commercial version from General Dynamics. Its first commercial launch is scheduled for summer, 1990.



Titan III ELV—a commercial launch vehicle capable of lifting up to 32,500 pounds to LEO, manufactured by Martin Marietta. Its first commercial launch occurred on December 31, 1989.



Titan IV ELV—manufactured by Martin Marietta under contract to the U.S. Air Force, it is capable of lifting about 39,000 pounds to LEO. It was first launched on June 14, 1989, and carried a military payload.

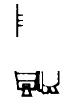


Space Shuttle—a piloted, partially reusable launch vehicle capable of lifting about 52,000 pounds to LEO. The Shuttle fleet now consists of three orbiters; a fourth is being completed.

Potential Future Launch Systems



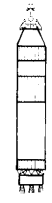
Shuttle-C-an unpiloted cargo vehicle, derived from Shuttle systems, with a heavy-lift capacity of up to 150,000 pounds to LEO. It would use the existing expendable external tank and reusable solid rocket boosters of the Shuttle, but replace the orbiter with an expendable cargo carrier.



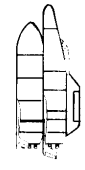
Advanced Launch System (ALS)--a totally new modular launch system under study by the Air Force and NASA. ALS would be capable of launching a range of cargos at high launch rates and reduced costs.



Crew Emergency Return Vehicle-a vehicle that would provide for crew escape and return from the Space Station, independent of the Shuttle, in case of crew medical emergencies or major Space Station failures.



Personnel Launch System (PLS)--a new concept for a crew-carrying vehicle launched atop expendable launch vehicles. It would be less complex and less expensive than the Shuttle. A PLS could transport crew to and from space, and might also serve as an emergency return vehicle.



Advanced Manned Launch System (AMLS)—an advanced successor to the Shuttle, available after the year 2005. System concepts vary from partially reusable through fully reusable vehicles.

National Aero-Space Plane (NASP)



—a proposed reusable vehicle that could be operated like an airplane from conventional runways, but fly to Earth orbit powered by air-breathing, or air-breathing/ rocket engines. The Air Force and NASA are working on designs for an experimental version of this vehicle, the X-30.

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Chapter 1

Executive Summary

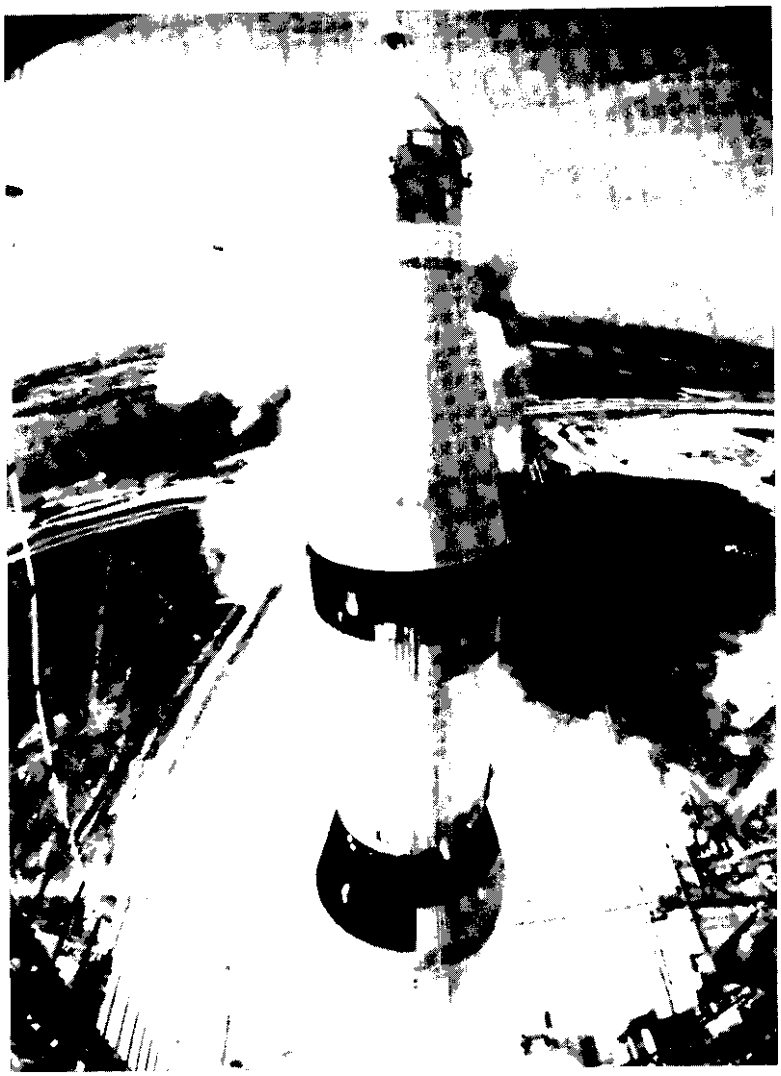


Photo credit: National Aeronautics and Space Administration

The Apollo 11 spacecraft lifts off from Kennedy Space Center atop the Saturn 5 launcher, July 16, 1969, on its way to the Moon. Four days later the United States landed two men on the Moon. The Saturn 5 launch vehicle was capable of lifting more than 200,000 pounds to low-Earth orbit.

Chapter 1
Executive Summary

INTRODUCTION

The Nation's recovery from the space transportation crisis of 1986, which brought the U.S. launch fleet to a standstill, is well under way. The United States now has an operating, mixed fleet (figure l-l) comprised of reusable Space Shuttle orbiters and expendable launch vehicles (ELVs). The government and the private sector have invested in new launch technologies and established a fledgling private launch services industry. Yet concerns over launch system reliability, operability,[1] capacity, and cost remain. Over the next few years, Congress will be faced with making critical decisions affecting the **future** of U.S. space transportation systems.[2] Congress' decisions will depend directly on:

- what future course the Nation wants to follow in space; and
- understanding whether existing and planned launch systems, and their component technologies, are adequate to support the chosen direction.

This report summarizes OTA's assessment of advanced space transportation technologies; it was requested by the Senate Committee on Commerce, Science, and Transportation and the House Committee on Science, Space, and Technology. Previous publications from this assessment (box l-A) have examined a range of U.S. launch options, ways of reducing launch operations costs, the "Big Dumb Booster" concept, crew-carrying launch systems, and spacecraft design.

The report examines the space transportation needs of publicly supported space programs, as executed by the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD). However, private sector space activities are slowly growing in importance. Hence, the report also explores aspects of the private sector's role in space transportation, both as contractor for the government's needs and as commercial supplier of launch services.

Box 1-A—OTA Space Transportation Publications

- *Launch Options for the Future: A Buyer's Guide*
- *Reducing Launch Operations Costs: New Technologies and Practices*
- *Big Dumb Boosters: A Low-Cost Transportation Option?*
- *Round Trip to Orbit: Human Spaceflight Alternatives*
- *Affordable Spacecraft: Design and Launch Alternatives*

THE U.S. FUTURE IN SPACE

Except for the field of satellite communications, essentially all U.S. space activities continue to be characterized and managed by the Federal Government and supported with public funds. The Federal Government invests in space activities in the expectation that they will serve U.S. interests by:

- demonstrating international leadership in space science, technology, and engineering;
- contributing to economic growth;
- enhancing national security;
- supporting the pursuit of knowledge; and
- promoting international cooperation in science.[3]

Over the years, the United States has pursued a set of goals for its civilian and military space programs that derive from these broad policy principles. It has established systems in space for worldwide communications, global Earth observation, and scientific activities, including solar system exploration probes and landers. It has also sent men and women to work in space. Space transportation systems are critical elements in realizing these missions.

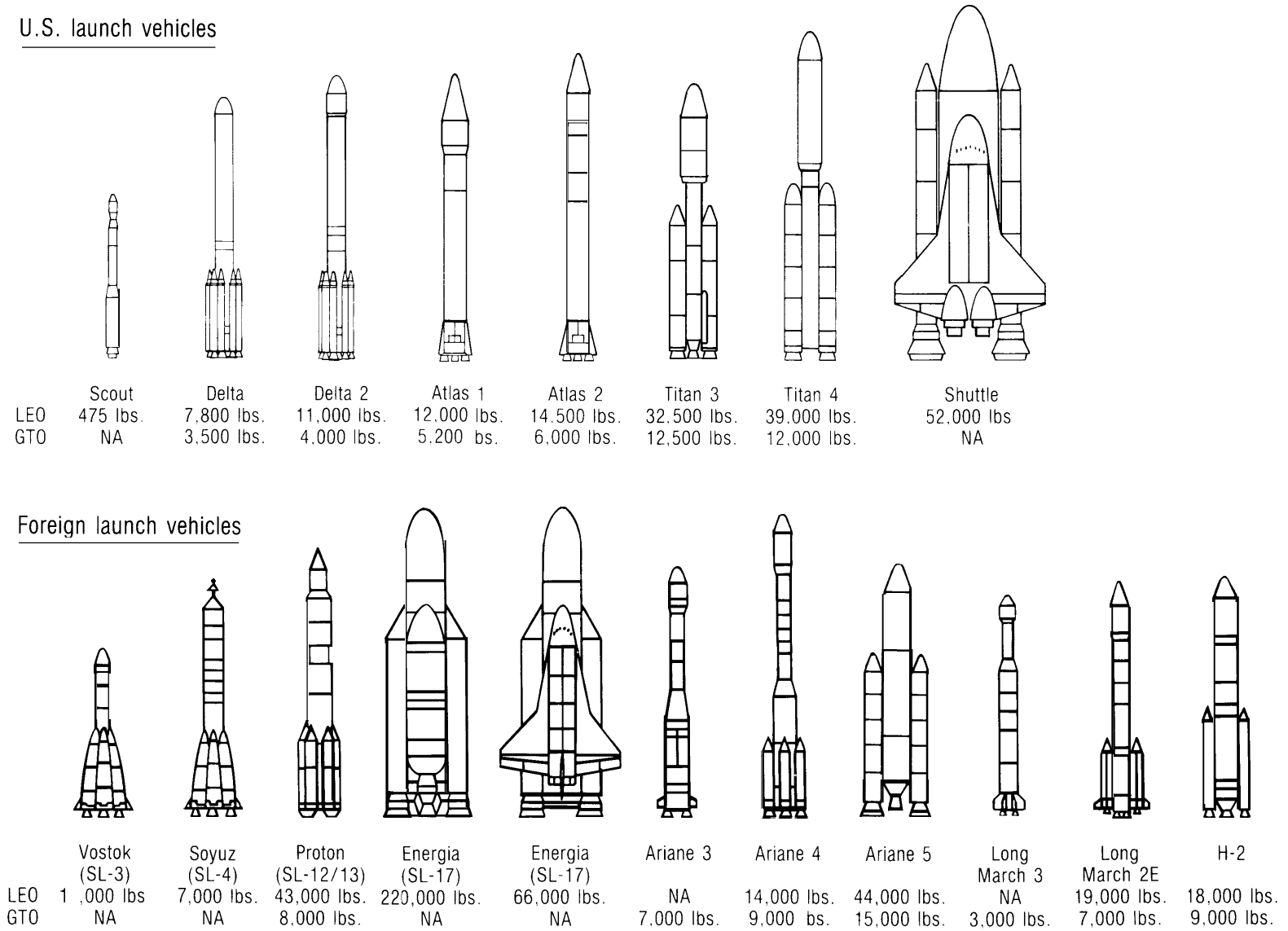
The U.S. future course in space is uncertain, especially in light of the tremendous political and economic changes in progress around the world and the strong pressures to reduce Federal spending. Will the Government cut back on civilian and/or

[1] I.e., flexibility and ability to meet a schedule.

[2] A space transportation or launch system includes the launch vehicle, the buildings, launch pad, and other launch facilities, and the technologies and methods used for launch.

[3] National Aeronautics and Space Act of 1958, sec. i; U.S. Congress, Office of Technology Assessment, *Civilian Space Policy and Applications*, OTA-STI-177 (Washington, DC: U.S. Government Printing Office, 1982), pp. 35-38.

Figure 1-1—Primary Launch Vehicles of the World



KEY: GTO = Geostationary Transfer Orbit; LEO = Low Earth Orbit
SOURCE: Office of Technology Assessment, 1990.

Box 1-B—The Costs of Humans in Space

As experience with the Space Shuttle demonstrates, routinely placing humans in space is especially costly as well as risky. Since 1%1, when President Kennedy called for a program to send men to the Moon and back, NASA's "manned"[1] space efforts have determined much of the direction and spending of the Government's civilian space program. In fiscal year 1990, NASA's projects involving humans in space, primarily the existing Space Shuttle and the planned Space Station, will consume about 70 percent of NASA's budget for space activities.[2]

From the early days of the U.S. space program, experts have argued over the appropriate mix of crew and automated civilian space activities. Although employing people in space to conduct most science research and exploration dramatically raises the costs compared to automated approaches, the perceived national and international benefits of having U.S. and foreign citizens live and work in space have nevertheless sustained the human component of the civilian space program.

Existing U.S. policy calls for expanding "human presence and activity beyond Earth orbit into the solar system."[3] Pursuing this policy in earnest would eventually require markedly increased funding of the Government% civilian activities involving people in space, and therefore additional space transportation capability. Building a permanent base on the Moon and sending explorers to Mars, as suggested by President Bush, would lead to substantial in-orbit infrastructure, such as a space station, orbital maneuvering vehicles, crew modules for orbit transfer, and fuel storage depots. The pace and timing of such expansion would depend on the willingness of Congress, on behalf of U.S. taxpayers, to support such activities in competition with other uses of public monies.

[1]The terms crew-carrying or piloted are used in this report in lieu of "manned."

[2]Of the $11.92 billion appropriated for NASA's space activities, prior to sequestration, which excludes $463 million of NASA's 1990 budget for aeronautics, approximately $8.4 billion will be spent on projects involving human crews.

[3]"The White House, National Space Policy," Nov. 2, 1989, p.1.

SOURCE: Office of Technology Assessmen t, 1990.

military space programs, or will it continue to build steadily on our previous accomplishments? Alternatively, will the United States embark on sharply expanded programs of human exploration (box l-B) or space-based defense? This report provides a guide to the opportunities for, and impediments to, supporting a range of goals with existing and future launch systems. Because the lack of a clear future course for U.S. space activities makes the scale and character of future demand for space transportation highly uncertain, it is not sensible to choose among space transportation options without first selecting the specific goals to be served. **OTA concludes that a national dialog is urgently needed to establish the future course of the publicly supported space program and to outline the preferred means of accomplishing program goals.**

If Congress and the Executive decide to follow the current course of steady growth in civilian and military space activities, no *new* launch systems[4] would be needed before the first decade of the next century to meet demand for launch of cargo and peoples Taken together, the existing launch fleet is capable of launching at least 900,000 pounds[6] to low Earth orbit (LEO) per year, which is about 37 percent more payload than the United States expects to launch in 1990,[7] the first year that all of its major launch systems will be fully operational.[8] Nevertheless, new systems may be desirable to meet specific needs, such as crew rescue, or to reduce the dependence of the Space Station project on the Shuttle. **Even if the steady growth in payload demand is limited to a few percent per year, the Nation's space transportation systems could be managed to reduce average launch costs. The Government spends at least $5 billion per year on space transportation for civilian needs alone. [t would be prudent to place greater**

[4]However, additional Shuttle orbiters or new facilities to launch existing systems may be needed, as explained later.

[5]For a 3 percent per year growth rate or less.

[6]In 1992—based on 9 Shuttle, 18 Delta II, 4 Atlas II, 4 Titan III, and 6 Titan IV launches per year, at a 90-percent manifesting efficiency.

[7]OTA assumed 8 Shuttle, 12 Delta II, 2 Atlas H, 1 Titan HI, and 2 Titan IV flights.

[8]The years of 1984 and 1985 were the last two in which U.S. launch systems were fully operational. It appears that 1990 will mark the first year since 1985 that all major U.S. launch systems can be expected to operate on a sustained schedule, In addition, new private launch systems will be tested in 1990.

emphasis on improving the reliability, operability, and payload capacity of existing launch systems, for example, by incorporating new technologies into launch vehicles and launch operations procedures.

If, on the other hand, the Nation decides to invest in a permanent lunar base, exploratory missions to Mars, or a large-scale, space-based ballistic missile defense, new cargo launch systems would be necessary, including a heavy-lift launcher.[9] Either a lunar base or a mission to Mars could also require new crew-carrying launch vehicles, and would necessitate systems capable of transferring payloads and people between orbits. New, advanced launch systems could add $10 billion to $20 billion in development costs alone to the price tag for any major space program initiative.[10] The timing and scale of government investments in new space transportation systems will depend directly on the commitment to the goals being defined for public space programs.

Because the Nation cannot afford to invest in all the good ideas proposed for improved or new launch systems, Congress and the Administration will have to choose from among a wide range of options. Some choices must be made in the next 2 to 3 years. Others can wait longer. However, as argued earlier, **all space transportation decisions will depend directly on the Nation% vision for its future in space. The** following sections present options to meet a range of near-term and far-term space futures.

Near-Term Space Transportation Options

For the coming decade, the primary space transportation issue is how to enhance U.S. access to space by improving the reliability and operability of existing systems—the Shuttle and ELVs. Whether the future launch rate is high or low, higher reliability for all launch systems (box l-C) and improved safety and operability for the Shuttle would increase the ability of current systems to meet program needs. **Reducing launch costs would also reduce the impact of space transportation on the Federal budget (for equivalent demand levels) and might lead to more effective use of space. To be most useful to the Nation, decisions about the following options should be made within the next** 2 **to** 3 **years.**

- *Fund improvements in expendable launch vehicles (ELVs).* Improved assurance against program cost overruns and delays can be gained by improving the reliability and operability of existing ELVs, which are based on designs originally developed in the 1950s and 1960s. The Advanced Launch System (ALS) Program has been studying technologies and methods to enhance launch system operability, reliability, and payload capacity. **Incorporating the most promising of these technologies and methods in existing ELV systems,[11] if feasible, would improve the ELV fleet and give launch manufacturers and operators valuable experience in using them.**
- *Limit the Shuttle's launch rate to a regular, sustainable rate.* Attempting to meet NASA's goal of 14 Shuttle launches per year[12] would increase the cumulative risk to orbiter crews, and to space program costs and schedules. **Furthermore, because it is reusable and carries a crew, the Shuttle is not necessarily the most appropriate choice for launching satellites and space probes, and for doing many space science observations and experiments. The presence of a crew necessarily shifts NASA's primary concern from the mission's scientific objectives to the safe launch and return** of its crew. Hence, additional, costly requirements are added to the payload, and to the mission as a whole. The Shuttle launch schedule could be limited to a regular, sustainable rate of 8 to 10 launches per year[13] by restricting Shuttle flights to payloads requiring human crews. NASA is already pursuing a strategy of restricting Shuttle payloads to those

[9] NASA's recent *Report of the 90-Day Study on Human Exploration of the Moon* and *Mars* (Washington, DC: National Aeronautics and Space Administration, November 1989) states that supporting the development and operation of a lunar base and the exploration of Mars would require a space transportation capacity of two to four times the mass that can now be delivered to orbit per year.

[10] As noted later in this report, these new launch systems might nevertheless make it possible to achieve sharply reduced operating costs.

[11] Some of these improvements, such as fault-tolerant subsystems and artificial intelligence process controls, may also be appropriate for inclusion in the Shuttle system.

[12] After Orbiter *Endeavour* (OV-105) enters service in 1992.

[13] OTA's estimate is based on the need to maintain a rate high enough to maintain flight-ready launch operation crews but low enough to avoid stressing those same crews. Such a rate should also allow for occasional surge to meet civilian or military needs and provide sufficent down-time to make major changes to the orbiters as required.

Box I-C-Coping With Launch Risks

Launching payloads to orbit has always carried a high degree of risk--to people, cargo, and financiers. One of the critical near-term needs for spare transportation will be to reduce these risks. As demonstrated by the long **standdown** following the losses of *Challenger* and the Titan and Delta expendable launch vehicles in 1985 and 1986, major launch failures will have a significant negative impact on public and private space activities, causing loss of income for private companies that depend on space assets for their business, reduced effectiveness of national security programs, and erosion of public confidence in U.S. space efforts. OTA estimates that the standdown and recovery from *Challenger alone* cost U.S. taxpayers more than $15 billion.

Demonstrated success rates for U.S. launch systems, including the Shuttle, range between 85 and 97 percent, yet U.S. plans, in both NASA and DoD, are optimistic and make little allowance for launch failures. **In particular, the heavy U.S. dependence on the Space Shuttle[1] raises questions concerning the ability of the existing Shuttle fleet to meet its allocated share of the demand for space transportation services. The Shuttle fleet has never met projected flight rates and the existing fleet is unlikely to meet NASA% goal of 14 flights per year in the 1990s, as a result either of launch operations delays, or orbiter attrition as a result of Shuttle failures.** Attempting to meet such a high rate increases the risk to human lives, to NASA's budget, and to other NASA programs, especially Space Station.

The United States should expect the partial or total loss of one or more Shuttle orbiters some time in the next decade. Public reaction to the loss of *Challenger* demonstrated again that there are qualitative differences between public attitudes toward launching people and launching cargo into space. If the United States wishes to send people into space on a routine basis, the Nation will have to come to grips with the risks of human spaceflight, Airliners occasionally fail catastrophically but people continue to fly. The United States should exert its best efforts to ensure flight safety and prepare itself for handling further losses that will likely occur. If the Nation perceives that the risks are too high, it may decide to reduce the current emphasis on placing humans in space until more reliable launchers are available.

[1]The Shuttle accounts for more than half of the Nation's existing payload capacity.

SOURCE: Office of Technology Assessment, 1990.

requiring the Shuttles' unique capabilities. However, this curtailment will take several years to execute because payloads already designed for Shuttle launch cannot, without excessive modification and reintegration costs, be launched on an ELV.[14] The restriction will also cost more in the short run than launching on the Shuttle because the Government will have to purchase ELV launch services[15] entailing substantial redesign and re-integration costs.[16] However, if NASA can establish a Shuttle launch rate that improves the probability of recovering the orbiter after each launch, in the long run the Government could save money and also reduce the risk to Shuttle crews.[17]

- *Fund additional orbiters.* Even if NASA sustains a Shuttle rate of 8 to 10 launches per year, because of the risk of Shuttle attrition, additional orbiters may be needed just to carry out current plans, including construction of the planned Space Station (box l-D). **The actual reliability of the Shuttle system is unknown, but may lie between 97 percent and 99 percent. If reliability is 98 percent, the Nation faces a 50-50 chance of losing an**

[14]The size and/m weight of some payloads require them to be launched on the Shuttle. Opportunities for Titan IV to carry civilian payloads appear to be severely limited, the result, in part, of limited production and launch facilities. Planned DoD payloads currently fill the Titan IV manifest through the year 2000.

[15]Note that flying payloads on ELVS would not necessarily reduce the risk of losing the payload. Demonstrated launch success rates for ELVs are slightly lower than for the Shuttle. Launch services on the commercial launchers, Delta, Atlas Centaur, and Titan III, are available for NASA's purchase.

[16]For example, the Cosmic Background Explorer (COBE) Satellite, which was originally scheduled for launch on the Shuttle, w&s redesigned to fit on an ELV at a cost of $30 million to 40 million. COBE was launched into a 900-kilometer polar orbit on Nov. 18, 1989, on a Delta ELV. Among other astrophysical observations, COBE will make two total surveys of the sky of the faint background radiation that scientists believe is a remnant of the original Big Bang, some 15 billion years ago.

[17]Developing a Shuttle-C cargo vehicle based on the Shuttle system would also m&c ıı possible to off-load certain payloads from the Shuttle (see Shuttle-C option below).

additional orbiter in the next 34 flights (3 to 4 years). To reduce the risk of attempting to carry out the Nation's goals with only a 3-orbiter fleet, Congress may wish to purchase one or more additional orbiters. A new orbiter would cost between $2 billion and $2.5 billion, and if ordered in fiscal year 1991, could be ready no earlier than 1996 or 1997.

- *Fund a program to improve the safety and reliability of the Shuttle.* **In many respects, the Shuttle is not yet operational and can still be improved in a variety of ways.** Much like the B-52 bomber, which has steadily grown more capable and remained operational for over 30 years, the ability of the Shuttle orbiters to stay in service can theoretically be extended for another two decades. NASA is working on technologies that could enhance Shuttle safety and reliability as well as longevity. For example, NASA is improving the construction of the Shuttle main engines, has begun a program to build more reliable, higher capacity, Advanced Solid Rocket Motors, and is installing new, more fault-tolerant computers. A long-term, integrated program of improvements to the orbiter and other subsystems would be more effective in fostering Shuttle reliability and safety than a piecemeal program. An integrated improvement program should also devote resources to enhancing the management of launch operations, which would increase Shuttle's operability and might reduce operations costs. Congress may wish to require NASA to prepare an integrated plan for accomplishing these objectives.
- *Fund development of the Shuttle-C.* For launching payloads that exceed the payload capacity of the Shuttle and the Titan IV, the Nation will eventually need a heavy-lift launch system. It could build a heavy-lift cargo system in the near term by developing a cargo launcher based on Shuttle technology (Shuttle-C). **Shuttle-C would generally reduce the risk to the orbiter fleet of flying large payloads. Because it would be capable of lifting heavy payloads, Shuttle-C could also reduce the total number of flights required to construct the Space Station.** In the far term, a Shuttle-C could carry a variety of large payloads for building a lunar base or supporting an exploratory mission to Mars. NASA asserts that developing a Shuttle-C would cost about $1.1 billion[18] and could be completed by 1995, if started in 1991.[19] Infrastructure costs, which are included in this figure, would be minimal because Shuttle-C would use the same launch pads and many of the same facilities as the Shuttle.[20] However, launch costs would be

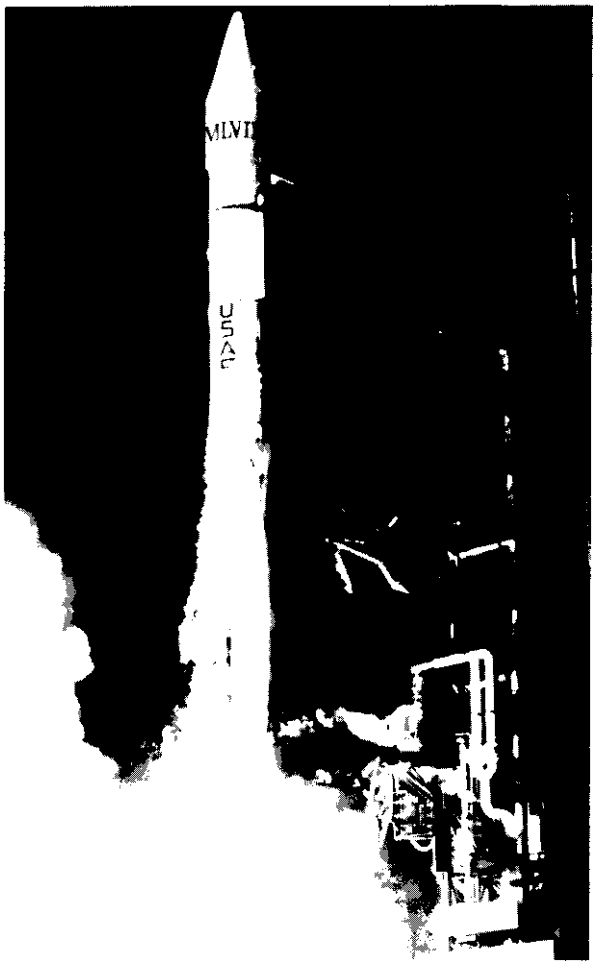


Photo credit: General Dynamics Corp.

An Air Force Atlas lifting off from the launch pad.

[18] In 1991 dollars. This figure does not include the estimated $480 million for the first Shuttle-C launch.

[19] NASA officials appear to be divided over the advisability of pursuing Shuttle-C, some believing that the Shuttle will be adequate, others concerned that new systems, including Shuttle-C, should be developed.

[20] If the Shuttle launch rate were kept at about 8 to 10 launches per year, 2 to 3 Shuttle-C launches per year could be accommodated if improvements to existing facilities, costing about $300 million, were made.

Box I-D-Space Transportation and the Space Station

The planned international Space Station is the largest single space project that will be undertaken in the decade of the '90s. It will have to be launched in pieces and assembled in space. Current plans call for 29 Shuttle flights to construct the station (including several logistic flights) and 5.5 flights per year to operate it. To **reduce the risks of costly delay in constructing or operating the Space Station, or concurrently meeting other NASA and DoD missions, Congress could:**

1. Fund the purchase of one or more additional orbiters for the existing Shuttle fleet, and restrict the use of Shuttle to payloads that cannot fly on other launch vehicles.
2. Direct NASA to use ELVs or develop Shuttle-C's for constructing and/or operating the Space Station.
3. Delay construction of the Space Station for several years and fund NASA to develop an alternative launch system for taking crews to and from orbit. Such a spacecraft could be as simple as an Apollo-type capsule mounted atop an expendable launch vehicle, or as complicated as an aerospace plane. If Space Station were delayed, it would be possible to redesign the current configuration to make the best use of existing and new transportation systems. However, as recent reactions to changes in the Space Station configuration and schedule from our foreign partners and Congress have shown, significant additional delay in deployment of the Space Station might cause them to withdraw their participation and Congress to curtail funding. Such actions would significantly affect other areas.
4. Increase NASA's budget to accommodate development of anew, more reliable crew-carrying launch system to replace Shuttle early in the next century.

[1]A heavy-lift cargo system based on shuttle technology.

SOURCE: Office of Technology Assessment, 1990.

relatively high, so the Shuttle-C would be most cost effective at relatively low launch rates (2-3 per year). NASA estimates each launch of a Shuttle-C would cost over $400 million.

. *Develop a crew rescue vehicle for Space Station.* Crews living and working in the planned Space Station could be exposed to substantial risk from major failures of the Station. Because the Shuttle cannot respond in a timely manner to emergencies, the United States may need a means independent of the Shuttle to rescue crews from the Space Station. A rescue vehicle would add $1 billion to $2 billion in development and procurement costs to the Space Station. Additional costs would be incurred in developing the necessary support infrastructure, which might include ground operations hardware and personnel at the mission control site, landing site crews, and the necessary subsystems and logistics support to resupply, replenish, and repair a rescue vehicle on orbit. **To decide whether a risk-reducing effort is worth the investment required, Congress must be advised about how much the investment would reduce the risk. Even if an alternate crew return vehicle were built, and worked as planned, it would not eliminate all risks to station crewmembers. To assist in making such a decision, the risks and costs of building a rescue vehicle should be weighed against the risks and costs of other hazardous duty in the national interest.** To reduce costs that would accrue to Space Station development, it may be prudent to cooperate with one or more of our Space Station partners in jointly developing a crew rescue vehicle, or adapting one of theti crew-carrying vehicles, now under development, for the purpose.

Far-Term Space Transportation Options

Although upgrading the current fleet of ELVs and the Shuttle would improve their operability and might even reduce space transportation costs, new systems will ultimately be needed if the Nation wishes to improve the U.S. capacity to launch payloads and crews. **Emerging technologies offer the promise of new launch systems and of significant evolutionary improvements in existing systems during the early decades of the 21st century.** These improvements could reduce the costs of manufacturing, logistics, and operations while increasing reliability, operability, and performance. Developing new systems that use advanced technology would entail high cost risk and



Photo credit: National Aeronautics and Space Administration

The orbiter *Atlantis* lifts off from Kennedy Space Center carrying the Galileo spacecraft on the first stage of its journey toward Jupiter.

technical risk and would require a sustained technology development program. Yet new systems could also bring substantial benefits to U.S. launch capabilities. **The appropriate time to start development of any new system will depend on the perceived future demand for space transportation services, the readiness of the technology, and the system% cost in competition with alternative means of performing comparable missions--including existing launch systems. The long lead times necessary to develop a new system and construct necessary supporting facilities require** beginning development some 5 to 10 years before a system is needed.[21]

Congress could fund the development of:

- *Advanced Launch Systems (ALS).* Through the ALS program, the Air Force and NASA seek to develop a reliable, flexible family of medium- and high-capacity, low-cost launch vehicles to serve government needs. They expect to capitalize on advanced materials and manufacturing and launch processing technologies, to increase launch rate and reduce acquisition, maintenance, and operational costs. They also

[21]For example, the decision to begin development of the Space Shuttle was made in 1972, and the orbiter Columbia made its first flight in April 1981.

plan to include the ability to launch vehicles at a higher than average rate for a short time (i.e., surge). **A decision to proceed with ALS development would depend on whether there will be sufficient anticipated demand to justify development and procurement of a new, high capacity launcher, or whether the value of improved efficiency in launching currently planned payloads would justify investing in new systems.** Because it would be significantly different in design and operation than current launch systems, and would use a wide variety of new technologies, development of an operational ALS carries a significant cost and schedule risk.[22]

The ALS program has been funded almost entirely by DoD, which has decided not to pursue development of the ALS at this time; DoD plans to continue technology development of propulsion and other crucial enabling technologies. If ALS technology development continues to be funded by Congress and the Executive, the DoD could be in a position to start full development of the ALS in the mid or late 1990s, if necessary.

- *A Personnel Launch System (PLS) or Advanced Manned Launch System (AMLS).* **Even if NASA makes substantial improvements to the Shuttle, eventually a replacement will be needed if the United States decides to continue its commitment to maintaining crews in space. A decision to replace the Shuttle should be based on the age and condition of the Shuttle fleet and the estimated benefits to be gained from developing a new crew-carrying launch** system. NASA is exploring the technologies, systems, and costs required for development of two new launch systems. Although concepts for the two proposed systems overlap, their general focus is different. PLS designers are considering several concepts, ranging from ballistic entry vehicles to a small "spaceplane. " A PLS vehicle would carry very little cargo and could be launched atop a large expendable booster. AMLS designs favor a reusable vehicle larger than the PLS, but smaller and easier to refurbish and launch than the Shuttle, and capable of carrying both crew and cargo (about 20,000 pounds). An AMLS might be launched by a reusable booster.

  A PLS could be developed and tested sooner than an AMLS and might be needed to backup or replace the Shuttle. Developing and operating a PLS would likely costless than an AMLS. If it entered the fleet before the Shuttle is retired, a PLS could assist in providing more reliable access to space for humans. In addition, a version of the PLS vehicle might serve as a Space Station crew escape vehicle. The choice between an AMLS and a PLS will depend on cost and the need for an alternative to the Shuttle.
- *An Aerospace Plane.* Developing a fully reusable piloted vehicle that could be operated like an airplane from conventional runways, but fly to Earth orbit powered by a single propulsion stage, as envisaged for the National Aero-Space Plane (NASP), would provide a radically different approach to space launch and a major step in U.S. launch capability. If successful, an aerospace plane could provide increased flexibility and reduced launch costs. NASA and the Air Force are jointly developing the technology base that could lead to an X-30 experimental aerospace plane, which would incorporate advanced air-breathing propulsion as well as rocket propulsion. Developing a successful X-30 test vehicle may cost more than $5 billion.[23] Proponents argue that benefits to U.S. industry and U.S. competitiveness may more than repay that investment.

  Until an X-30 flies successfully to orbit and back, estimated costs for building an operational vehicle based on technology demonstrated in the X-30 will remain highly uncertain. At the present time, the Air Force has shown the greatest interest in an operational aerospace plane, primarily because it would provide quick response to emergencies and fast turnaround in preparation for reflight. **While very attractive from an operational point of view, building such a vehicle poses large technological and cost risks. Either a PLS or AMLS could be developed sooner than an aerospace plane based on X-30 technology. Other proposed launch systems, including**

[22] As noted earlier, reducing launch costs by means of ALS or any other new launch system may require increased payload demand.

[23] The NASP Program Office estimates X-30 costs for two test vehicles and supportive infrastructure at $3 billion to $5 billion. OTA regards these estimates as a lower limit.

small launch systems and the ALS, may provide stiff economic competition to an aerospace plane, because they may also serve DoD needs for launching most payloads quickly at much lower investment cost.

- *Other Advanced Concepts.* NASA and DoD are funding studies of a variety of highly advanced launch concepts, including all-rocket, single-stage-to-orbit vehicles, laser propulsion, and chemical ram accelerator techniques. Although each of these concepts has strong proponents, each will also need considerable additional study before its costs and benefits will be sufficiently understood to determine whether or not it is an appropriate candidate for development. Nevertheless, research on advanced concepts and related technologies could eventually lead to a cost-effective future launch system and will be of broad importance in maintaining U.S. innovation in launch technologies. For example, previous studies of single-stage-to-orbit vehicles have cast doubt on their ability to perform efficiently because the necessary lightweight, high-strength materials were not available. However, recent advances in the development of the necessary advanced materials in the NASP program suggest that single-stage-to-orbit rocket-propelled vehicles may yet prove feasible.

REDUCING SPACE TRANSPORTATION COSTS

Reducing launch costs and improving operability are the two most important issues to address as the Nation considers the development of any new launch systems. Launching payloads to low Earth orbit on existing launch systems costs from $3,000 to $10,000 per pound. Placing them in geosynchronous orbit can cost up to $20,000 per pound. Thus, reducing launch costs will play a critical role in making space activities more affordable and productive. It is especially important in this era when there are strong pressures to reduce Federal budget deficits. Making launch systems more flexible and more capable of meeting a schedule could also contribute to reduced operating costs. However, the costs of designing and procuring spacecraft are often much higher, per pound, than launch costs. Attention should also be given to decreasing spacecraft costs (box l-E).

NASA, the Air Force, and the private sector have been working on methods of reducing both nonrecurring and recurring launch costs. For example, new manufacturing and construction methods could lower the cost of building new launch vehicles. Yet, **because launch and mission operations may constitute a sizable fraction of the cost of launching payloads into orbit,[24] system designers and policy makers must give greater attention to launch operations and support and to how launch vehicle and payload designs interact. For many aspects of launch operations, the broad operational experience of the airlines and some of the** methods they employ to maintain efficiency may provide a useful model for space operations (box 1-F). However, even if the launch systems are designed for reduced operational costs, it will be difficult to improve operations and support without making significant changes to the institutions currently responsible for those operations.[25]

Harnessing industry's innovative power in a more competitive environment could lead to reduced launch costs and more effective use of U.S. resources for outer space. By promoting private sector innovation toward improvements in the design, manufacture, and operations of launch systems, the Government could reduce the cost of Government launches, yet relatively few incentives to involve private firms exist today. Current U.S. space policy, which directs NASA, and encourages DoD, to purchase launch services rather than launch vehicles from private firms is a promising first step.[26] Yet, despite the fact that both agencies are moving toward purchasing launch services, change

[24] The cost of operations range from 15 to 45 percent of launch costs, depending on the complexity of operations. For example, operations costs for the Atlas or Delta ELV are about 15 percent of launch costs; operations costs of the Space Shuttle, which also include costs of flight operations as well as launch operations, because the orbiter is reusable and piloted, reach at least 45 percent of the total. See U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: Nm Technologies and Practices, OTA-TM-KC-28* (Washington, DC: U.S. Government Printing Office, September 1988), p. 13.

[25] *Reducing Launch Operations Costs: New Technologies and Practices,* op. cit., footnote21. Adapting airline practices, which have been developed over several decades of experience, and based on millions of hours of flight time, will take considerable imagination and innovation.

[26] When the Government purchases launch systems, it must maintain a large staff to operate the launchers, or to oversee contractors who do so. By purchasing launch services, the Government gives up most of the responsibility (and therefore cost) for overseeing details of launch manufacture and operation.

Box 1-E—Reducing Spacecraft Costs

Although reducing the costs of space transportation is extremely important in bringing down the costs of exploring and exploiting outer space, reducing payload costs, especially for DoD satellites, is also vitally important. For these payloads, launch costs are typically only a small percentage of the total costs of a program, because the costs of designing and building spacecraft are extremely high. NASA and DoD spacecraft typically cost between $160,000 and $650,000 per pound.[1] For commercial satellite launches to geosynchronous orbit, where spacecraft costs and launch costs are comparable, reducing both is important. Price competition between fiber optics cable systems and satellite communications systems for the highly competitive Atlantic and Pacific routes make the reduction of overall program costs especially important to communications satellite companies.

Spacecraft costs can be reduced by innovative design:

- allowing them to be much heavier so expensive weight reduction techniques are not needed (fatsats);[2]
- making them very light and limiting them to fewer tasks (lightsats);
- building very small spacecraft (microspacecraft) that could be launched like cannon shells for specialized tasks.

Each of these approaches would impose different requirements on launch systems. **Congress may wish to order a comprehensive study of these and other innovative approaches to spacecraft design.**

[1]These estimates include amortized spacecraft program costs.

[2]The gains achieved here appear t. be relatively small compared to the overall cost of the payload and launch service, U.S. Congress, Office of Technology Assessment, *Affordable Spacecraft: Design and Launch Alternatives,* OTA-BP-ISC-60 (Washington, DC: U.S. Government Riming Office, January 1990), pp. 12-16.

SOURCE: Office of Technology Assessment, 1990.

Box 1-F—Airlines operational Precepts

- Involve operations personnel in design changes.
- Develop detailed operations cost estimation models.
- Stand down to trace and repair failures only when the evidence points to a major generic failure.
- Design for fault tolerance.
- Design for maintainability.
- Encourage competitive pricing.
- Maintain strong training programs.
- Use automatic built-in checkout of subsystems between flights.

SOURCE: office of Technology Assessment, 1990.

is relatively slow, in part because NASA and DoD managers are reluctant to cede greater control over the fate of extremely expensive payloads to the private sector.[27]

Low-cost space transportation options that are designed to achieve minimum cost rather than maximum performance[28] may merit further study, particularly if their development meshes with other space transportation efforts such as those to develop a liquid rocket booster for the Shuttle, or new engines for the ALS.

One way to stimulate the private sector's innovative creativity would be to issue a request for proposal for ALS-type launch services and have industry bid for providing them. Such an approach assumes minimum government oversight over the design and manufacturing processes. It would also require the aerospace community to assume much greater financial risk than it has taken on in the past.

Another option that might lead to lower launch costs would be for the government to issue space transportation vouchers to space scientists whose experiments are being supported by the government.[29] These vouchers could be redeemed for transportation on any appropriate U.S. launch vehicle, and would free scientists to choose the vehicle they thought most suitable to the needs of the

[27]Bruce D. Berkowitz, "Energizing the Space Launch Industry," Issues *in Science & Technology*, Winter 1989-90, pp. 77-83.

[28]U.S. Congress, Office of Technology Assessment, *Big Dumb* Boosters *A Low-Cost, Space Transportation Option?—Background paper* (Washington, DC: International Security and Commerce Program, 1989).

[29]Molly Macauley, "Launch Vouchers for Space Science Research," *Space Policy*, *vol.* 5, No. 4, Pp. 311-320.

spacecraft. This policy would free space scientists from dependence on the Shuttle, and might increase opportunities for researchers to reach space.

The small launch vehicle concepts being developed by the private sector in response to the Defense Advanced Research Projects Agency's Advanced Satellite Technology Program ("lightsats") promise another avenue for cost reductions. They provide the means for small payloads to reach orbit for a relatively low cost per launch.[30] In this case, the Government provided a market sufficiently large to induce private firms to develop the vehicles using private funding.[31]

LIFE-CYCLE COSTS OF SPACE TRANSPORTATION OPTIONS

Estimates of life-cycle costs, which include the nonrecurring costs required to develop and build a new launch system as well as future recurring procurement and operating costs, provide the best *economic* measure of the worth of a new investment compared to other possible options. The overall cost of Earth-to-orbit transportation over the next three decades will include, at minimum, the costs of launching vehicles of existing types, at least until they are superseded. Almost certainly, some vehicles will fail catastrophically, leading to direct, indirect, and intangible costs. If the Government elects to launch at higher rates, additional facilities will be needed to prepare and launch vehicles.

If the Government elects to develop and use new types of launch vehicles, U.S. taxpayers must fund their development, production, and operation, as well as construction or modification of the facilities that would be needed to launch them. Next-generation vehicles will also incur some risk of failure, although how much cannot now be estimated with confidence. Nevertheless, investment in developing new types of vehicles could yield later payoffs in performance, operability, and safety, as well as lower cost of operation and risk of failure, compared to current vehicles.

To decide whether proposed investments in improving the Nation's Earth-to-orbit transportation system could be justified on economic grounds by predicted savings in the out-years, OTA estimated the life-cycle cost of each of several alternatives.[32] The life-cycle cost includes costs of developing new types of launch vehicles (if any), purchasing reusable elements of launch vehicles, building any additional launch facilities required, launch operations (including purchase of expendable launch vehicle elements), expected costs of launch vehicle failures, and the risk of cost overrun ("cost risk"). OTA considered only expenditures that would be incurred between 1989 and 2020.[33] OTA calculated the present value of the estimated life-cycle cost by discounting future expenditures to reflect the lower opportunity cost of obligating a future dollar, relative to spending a dollar now.

Figure 1-2 presents OTA's estimates of the present value of life-cycle cost of each of six alternative vehicle mixes for each of three space transportation demand scenarios. The ranking of alternatives according to present value of life-cycle cost, and the net benefit of each alternative relative to continued use of current vehicles, depends on the demand for space transportation. The differences in life-cycle cost are small in the low-growth demand scenario, especially when compared to the uncertainty represented by cost risk. However, the cost estimates clearly favor the Advanced Launch System in the expanded demand scenario, which includes low-growth demand plus rapidly increasing demand for launches of heavy cargo, such as formerly contemplated for deployment of a Phase 1 Strategic Defense System (SDS). Options for a lunar base or a Mars expedition could result in demand analogous to the expanded demand scenario. Alternatives for a lunar base and Mars expedition are currently being weighed by the National Space Council, NASA, and others. The DoD continues to assess options for development and deployment of SDS.

[30] For many small launch systems, the cost to launch a pound of payload is relatively high. Nevertheless, small systems may provide a cost-effective launch for owners of small payloads who would otherwise have to launch their payload as a secondary payload on a multiple-payload launch into a less optimum orbit.

[31] Initial flights of Orbital Sciences Corp. Pegasus, an air-launched vehicle capable of carrying 600 to 900 pounds into low Earth orbit, are scheduled for spring 1990.

[32] For additional details on space transportation costs, see box 1-G.

[33] OTA has little confidence in projections of demand to or beyond 2020, but chose 2020 as an accounting horizon to capture most of the discounted out-year savings (5 percent real discount rate) from vehicles that would not be operational until about 2005,

Box 1-G--Additional Information on Costs in Other OTA Reports

- *Launch Options for the Future describes in* greater detail the mission models and launch system options OTA considered and the methods OTA used to estimate the life-cycle costs quoted in this report.
- Reducing Launch *Operation Costs discusses* criteria used for comparing space transportation options, and confidence bounds on launch vehicle reliabilities.
- *Big Dumb Boosters* assesses proposals for designing unmanned, expendable launch vehicles to minimize cost.
- *Round Trip to Orbit* discusses additional options for piloted launch vehicles, and uncertainties in estimates of Shuttle reliability, on which expected Shuttle failure costs depend sensitively.
- *Affordable Spacecraft* **discusses** payload costs, assesses proposals for reducing them, and discusses their effects on demand for space transportation.

SOURCE: Office of Technology Assessment, 1990.

INTERNATIONAL COMPETITION AND COOPERATION

This decade has seen the rise of intergovernmental competition in space transportation (figure 1-1). The Soviet Union, Europe, Japan, and China operate launch systems capable of reaching space with sizable payloads. A number of experts have raised doubts about the capability of the U.S. private sector to compete for launch services in the world market, especially in the face of a relatively small market for commercial launch services and competition from some foreign companies, which receive greater government subsidy than do U.S. firms. **The U.S. Government could assist the U.S. private sector by negotiating with the governments of other nations to ensure a competitive environment for launch services in which prices and other economic factors reflect the true costs of providing those services.** Alternatively, the U.S. Government **could assist U.S. industry to the same degree and in a similar manner as other nations assist their own launch services industry. The U.S. Government also has a stake in reducing its own costs for space transportation.** It **could therefore provide modest finding to encourage private sector innovation for streamlining the manufacturing and launch operations** processes and improving productivity.

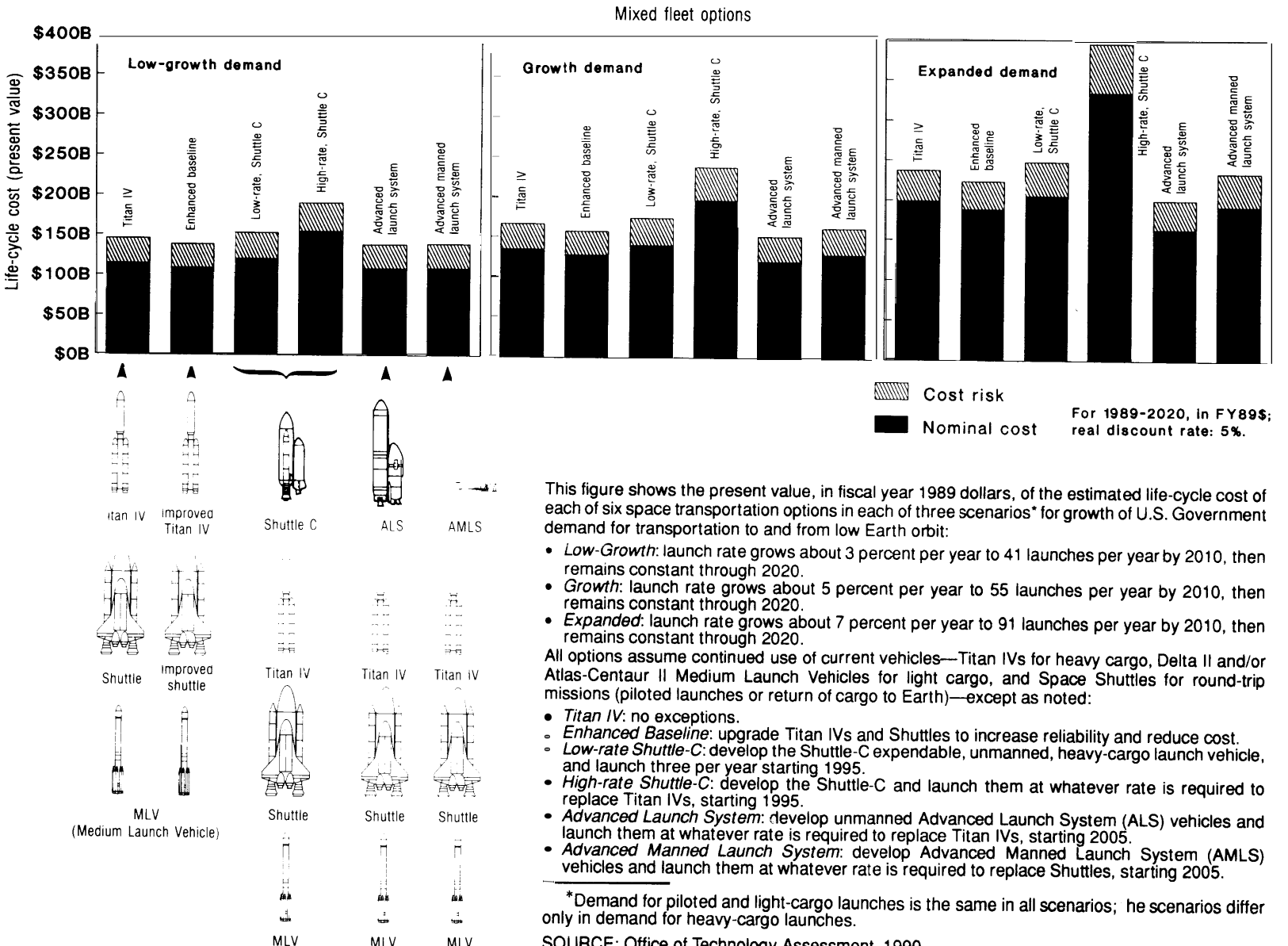
Although the United States has always maintained a vigorous program of international cooperation in space in order to support U.S. political and **economic goals, it has cooperated very little with** other countries in space transportation, in large part because most launch technology has direct military applications. In addition, before other countries had developed indigenous capabilities, the United States was pleased to have them depend on us for launch services. If launch demand does not increase markedly by the turn of the century, and the U.S. supply of launch vehicles remains sufficient, there may be little reason to change the U.S. stance toward cooperation in space transportation. However, if the Nation wishes to expand its activities in space, the costs of space endeavors would quickly reach the level where a much greater degree of international cooperation, including cooperation in space transportation, could be highly desirable.

As it debates the direction and magnitude of the space program, Congress will have to decide, as a matter of policy, how much of our publicly supported space program we want to pursue alone and how much we wish to involve foreign partners. International cooperation lessens our ability to use space to demonstrate national technological prowess, but can place the United States in a position to help guide the direction of global space development. Cooperation could also reduce the cost to the United States of a particular project, though it would generally increase the project's total cost. **However, for potential foreign partners to join with the United States in such projects, the United States will have to demonstrate that it not only has the willingness to cooperate on major projects but the institutional mechanisms to follow through.** Our partners' recent experience with the United States on Space Station[34] and on

[34]Some European and Japanese delegates to the 40th Congress of the International Astronautical Federation, October 1989, expressed considerable dissatisfaction with U.S. actions in Space Station development and worried that the United States was becoming an unreliable partner.

[35]Jeffrey M. Lenorovitz, "Europe Delays Soho Spacecraft Work Until U.S. Approves Joint Project MOU," *Aviation Week and Space Technology*, Nov. 13, 1989. See U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities* (Washington, DC: U.S. Government Printing Office, 1985), for a general discussion of U.S. cooperative agreements, mechanisms, and problems.

Figure 1-2—Discounted Life-Cycle Costs of Space Transportation Options



This figure shows the present value, in fiscal year 1989 dollars, of the estimated life-cycle cost of each of six space transportation options in each of three scenarios* for growth of U.S. Government demand for transportation to and from low Earth orbit:

- *Low-Growth*: launch rate grows about 3 percent per year to 41 launches per year by 2010, then remains constant through 2020.
- *Growth*: launch rate grows about 5 percent per year to 55 launches per year by 2010, then remains constant through 2020.
- *Expanded*: launch rate grows about 7 percent per year to 91 launches per year by 2010, then remains constant through 2020.

All options assume continued use of current vehicles—Titan IVs for heavy cargo, Delta II and/or Atlas-Centaur II Medium Launch Vehicles for light cargo, and Space Shuttles for round-trip missions (piloted launches or return of cargo to Earth)—except as noted:

- *Titan IV*: no exceptions.
- *Enhanced Baseline*: upgrade Titan IVs and Shuttles to increase reliability and reduce cost.
- *Low-rate Shuttle-C*: develop the Shuttle-C expendable, unmanned, heavy-cargo launch vehicle, and launch three per year starting 1995.
- *High-rate Shuttle-C*: develop the Shuttle-C and launch them at whatever rate is required to replace Titan IVs, starting 1995.
- *Advanced Launch System*: develop unmanned Advanced Launch System (ALS) vehicles and launch them at whatever rate is required to replace Titan IVs, starting 2005.
- *Advanced Manned Launch System*: develop Advanced Manned Launch System (AMLS) vehicles and launch them at whatever rate is required to replace Shuttles, starting 2005.

*Demand for piloted and light-cargo launches is the same in all scenarios; he scenarios differ only in demand for heavy-cargo launches.

SOURCE: Office of Technology Assessment, 1990.

science missions[35] may diminish their interest in pursuing cooperative projects with the United States.

Potential areas for cooperation in space transportation include:

- *The use of European and Japanese vehicles to supply Space Station. The* European Space Agency has developed a capable launch system (Ariane IV) and is now developing a much more powerful Ariane V. Either vehicle could be used to supply the Space Station. Japan is developing its H 11 launch system, which will be roughly comparable to the existing Ariane IV. **The United States could benefit by sharing responsibility for resupply of the Space Station with its international partners.**
- *Cooperation with the Soviet Union, Europe, and Japan in space rescue. The* Soviet Union is presently the only country beyond the United States with the capability to launch people into space. However, as noted, Europe and Japan are working on crew-carrying systems. Agreements on docking standards, and procedures for space rescue, could increase astronaut safety for all nations and lead to more extensive cooperative activities in the future. Initial meetings have been scheduled to discuss the nature and extent of such cooperation. Both this cooperative project and the use of foreign vehicles to supply the Space Station have the advantage that they risk transferring very little U.S. technology to other participants.
- *Joint development of a crew rescue vehicle for the Space Station. The* United States could be even more innovative in cooperating with other countries. For instance, as noted earlier, it may decide to provide an emergency crew escape or return vehicle for the Space Station. If properly redesigned and outfitted, the European spaceplane, Hermes, might be used as an emergency return vehicle late in this century. Early in the next century, the planned Japanese HOPE spaceplane might also serve that same purpose.[36] However, such international cooperation would also require a degree of international coordination and technology sharing for which the United States has little precedent.

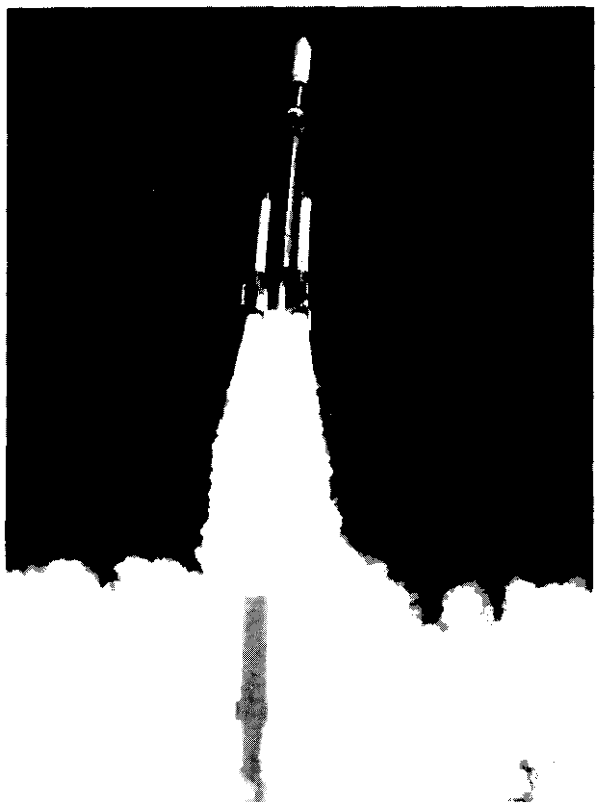


Photo** credit: Japanese **National Space Develepment Agency

A Japanese Mu-3S-3 solid rocket launches the interplanetary probe SUISEI toward Halley's comet in 1985.

- *Joint development of an aerospace plane.* With strong encouragement from their private sectors, Germany, Japan, and the United Kingdom are working separately toward development of aerospace planes. The level of foreign sophistication in certain areas of advanced materials, advanced propulsion, and aerodynamic computation is on a par with U.S. work. A joint development program with one or more of these partners might allow the United States to achieve an aerospace plane faster and with lower cost to the United States than the United States could on its own. Although a joint

[35]Jeffrey M. Lenorovitz, "Europe Delays Soho Spacecraft Work Until U.S. Approves Joint Project MOU," *Aviation Week and Space Technology,* Nov. 13, 1989. See U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities* (Washington, DC: U.S. Government Printing Office, 1985), for a general discussion of U.S. cooperative agreements, mechanisms, and problems.

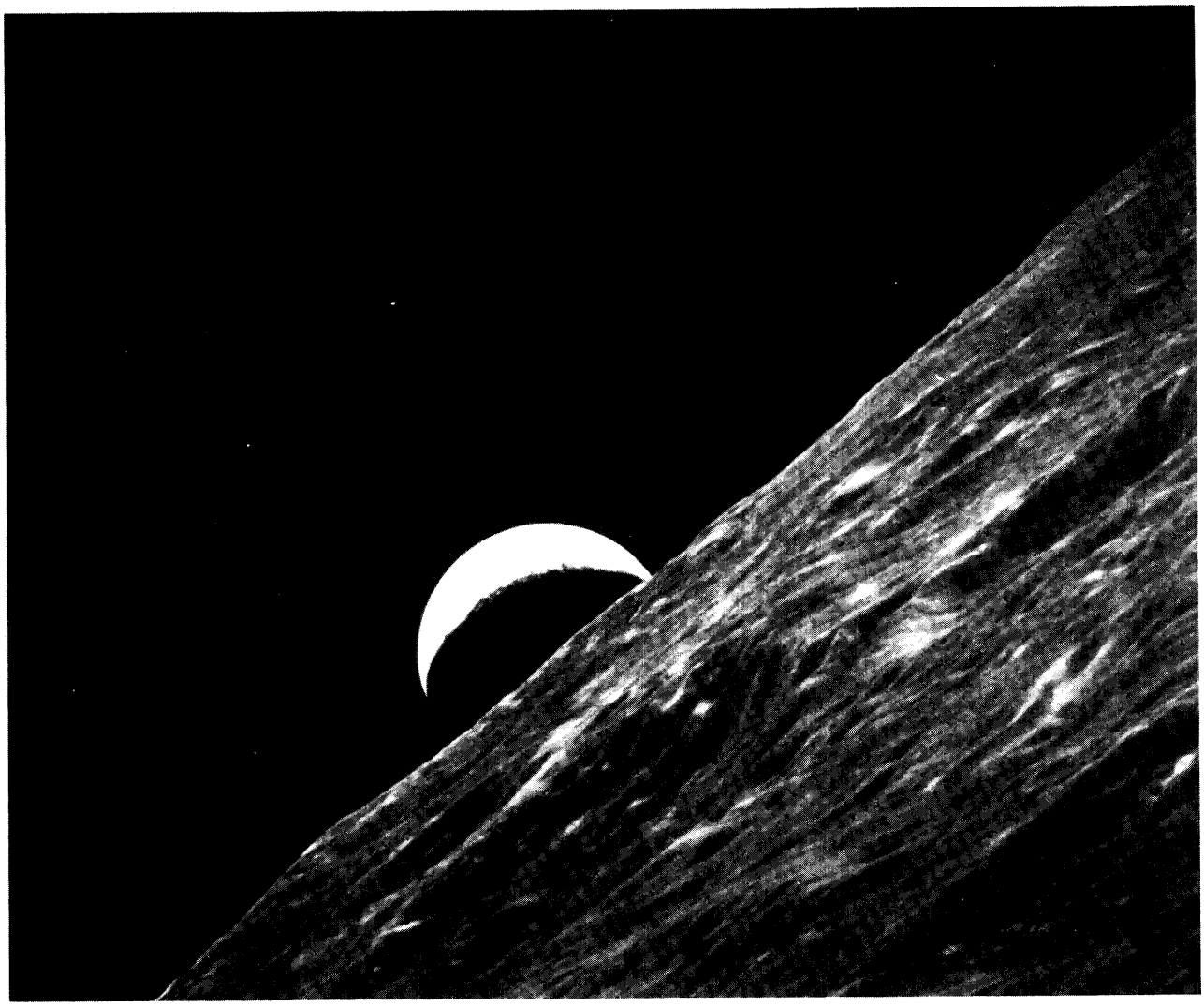
[36]HOPE is not currently being designed to carry crew. If the Japanese were interested in cooperating with the United s@@ in this area, it may be feasible to redesign HOPE for the purpose.

project would risk some technology transfer, if properly structured, such a joint project could be to the mutual benefit of all countries involved.

- *U.S. use of the U.S.S.R. Energia heavy-lift launch vehicle. The* U.S.S.R. has offered informally to make its *Energia* heavy-lift launch vehicle available to the United States for launching large payloads. As noted throughout this report, the United States has no existing heavy-lift capability. Thus, the Soviet offer could assist in developing U.S. plans to launch large, heavy payloads, such as fuel or or other non-critical components of a Moon or Mars expedition. Concerns about the transfer of militarily useful technology to the Soviet Union would inhibit U.S. use of *Energia* for high-technology payloads. As well, NASA would be understandably reluctant to propose use of a Soviet launcher because such use might be seen as sufficient reason for the United States to defer development of its own heavy-lift vehicle.

Chapter 2

Space Program Futures



Na *tics* *ace*

E as m M Ap as cr w ca g g S b se
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Chapter 2
Space Program Futures

INTRODUCTION

As the result of long-term constraints on the Federal budget, the Nation can pursue only a few of the many good space transportation concepts that are proposed today. **Until the Nation chooses what it wants to accomplish in space, and what the U.S. taxpayer is willing to pay for, neither the type nor number of necessary launchers and facilities can be estimated with accuracy. Possible driving forces behind additional space transportation capabilities to support publicly funded space activities include the Space Station, space-based ballistic missile defense, a permanent lunar base, and landing people** on Mars. Some have suggested that more modest Government expenditures are appropriate, especially in the face of pressing domestic needs, until we have reduced our current budget deficit and reversed our foreign trade imbalance. Congress, the Administration, and the American people as a whole are faced today with making choices among these or other, alternative options for the U.S. future in space.

The tremendous economic and political changes now taking place in the Soviet Union, Eastern and Western Europe, the Pacific Rim nations, indeed in the entire world, suggest that charting a course will be fraught with considerable uncertainty about the future, and the United States' place in the world economy. It will be important to weigh the future course of our Government's space activities in the context of these uncertainties. A failure to debate these choices vigorously and to select among them decisively will nevertheless result in some sort of national space program, but one that may not serve the long-term political and economic interests of the United States as well as a carefully considered policy.

This chapter focuses on the broad implications for space transportation of following specific space program futures; they were chosen by OTA to span the range of policy options open to the United States. Later chapters present launch technologies and systems and assess their economic and technological implications for the future of U.S. space activities.

SPACE PROGRAM OPTIONS

The choice among policy options such as those summarized below will determine the demand, and hence costs, for U.S. space transportation. The options are not necessarily exclusive; for example, Options 2 and 4 could be pursued at the same time.

Option 1: Continue Existing NASA and DoD Space Programs.

This option assumes that NASA would continue with its current plans to build the planned Space Station and launch several large space-based observatories and robotic planetary spacecraft by the end of the century. It also assumes that no DoD or NASA spacecraft would weigh more than current launch vehicles could lift.

The United States possesses a capable fleet of launch vehicles and the facilities necessary to meet current launch demands and provide for limited near-term growth. By 1992, the year the Shuttle orbiter *Endeavour* comes on line, planned space transportation capability (table 2-1) would be sufficient to lift about 900,000 pounds of payload into low Earth orbit (LEO)[1] per year, assuming there are no major delays or failures.[2] By comparison, in 1984 and 1985, the last years all U.S. launch systems were full y operational, the United States launched an average of about 600,000 pounds into orbit.

Launching 900,000 pounds to LEO each year would cost the Nation about $7 billion per year for transportation alone, assuming no major failures occur.[3] However, as the launch failures of 1985, 1986, and 1987 illustrate,[4] space transportation is risky. No **launch vehicle is 100 percent reliable; launch success rate, which is an indicator of reliability, varies from 85 to 97 percent (table 2-2). If space transportation capacity is limited to**

[1] To a reference orbit 110 nautical miles high, inclined to 28.5" from the equitorial plane.

[2] To reach 890,000 pounds per year the United States would have to launch payloads equivalent to 9 Space Shuttle flights, 6 Titan IVs, 4 Titan IIIs, 5 Titan IIs, 4 Atlas IIs, 12 Delta IIs, and 12 Scouts.

[3] This estimate, in fiscal year 1989 dollars, includes the expected costs of operations and failures, but no amortized nonrecurring costs or cost risk.

[4] Between November 1985 and *Mm,h* 1987, the *United* States had lost two Titan IIIs, one Delta, one Atlas *Centaur,* the orbiter *Challenger*, and their payloads as a result of technical or human failures. Loss of *Challenger* also resulted m a loss of seven crewmembers. These failures, and the recovery from them, cost the United States an estimated $16 to $18 billion. Arianespace, the French launch company, also sustained a launch failure of an Ariane 3 in May 1986, which cost insurers, Arianespace, and the European Space Agency well over $100 million.

Table 2-l-Maximum Lift Capability of U.S. Launch Vehicles Using Existing Manufacturing and Launch Facilities

Launch vehicle	Mass delivered	Production rate[b]	Launch rate[c]	Capability[d]
scout	570	12	18	6,840
Titan II	5,500	5	5	27,500
Delta H (3920)	7,600	12	18	91,200
Atlas/Centaur	13,500	5	4	54,000
Titan III	27,600	10	4	110,400
Titan IV	39,000	6	6	234,000
Space Shuttle	52,000"	n.a.[f]	9	486,460
Total				992,400 pounds
	x90 percent manifesting efficiency[g] =890,000 pounds			

[a]Pounds delivered to a 110 nm circular orbit at 28.5° inclination, unless otherwise noted.
[b]Maximum sustainable production rate with current facilities, in vehicles per year.
[c]Maximum Sustainable launch rate with current facilities, in vehicles per year.
[d]Mass delivered X the lessor of the maximum production rate or the maximum launch rate
[e]This figure is an average of the three existing orbiters' performance to a 110 nm circular orbit (OV102: 45,600 pounds; OV103 and OV1 04:49,100 pounds).
[f]Not applicable since the orbiter is reusable. No orbiter production is currently planned beyond the *Challenger* replacement.
[g]Vehicles often fly carrying less than their full capacity. Manifesting efficiency is the amount of lift capability that is actually used by payloads or upper stages. Volume constraints, scheduling incompatibilities, or security considerations often account for payload bays being less than full by weight.

SOURCE: Office of Technology Assessment, 1990.

Table 2-2-Launch Vehicle Success Rate

Launch vehicle	Total launches	Percentage successful	
		Overall	Last 20 attempts
Scout	112	88	95
Delta*	182	93	95
Atlas Centaur**	66	85	85
Titan	145	95	85
Shuttle	33	97	95

*Does not include flights of Delta II.
**Does not Include flights of Atlas II.

SOURCE: National Aeronautics and Space Administration & U.S. Air Force.

Lower Confidence Bounds on Reliability for 95 Percent Confidence (in percentage)*

Launch vehicle	Based on all launches	Based on last 20 launches
Scout	82	78
Delta	89	78
Atlas Centaur	76	66
Titan	91	66
Shuttle	86	78

*Exact, nonrandomized, one-sided lower confidence bounds.

SOURCE: Office of Technology Assessment, 1990.

vehicles currently in the fleet and on order, the United States runs a significant risk that some planned missions—most notably the Space Station-could be delayed, disrupted, or lost because of technical difficulties or accidents. If such risks are deemed too high, additional space transportation capacity may be needed before the end of the century just to carry out current plans.[5] Near-term additional capacity could be provided by one or more additional Shuttle orbiters or a Shuttle-C.

Even if growth of the Nation's space programs is moderate (less than 3 percent per year in terms of total mass lifted to low Earth orbit), it would be prudent to continue to improve the reliability and capacity of current systems by incorporating new technologies into launch vehicles and launch operations. A continuing program to make such improvements to systems and facilities could cost a billion dollars per year. In addition, the United States may need a means independent of the Shuttle for returning crews from the Space Station in case of

[5]Note, however, that purchasing extra space transportation capacity carries a certain cost risk If the extra Capacity were not needed, the expenditures would have been wasted.

emergency. A crew emergency return vehicle and the facilities to support it would add between $1 billion and $2 billion in development costs to NASA's space transportation budget over the next decade, plus an unknown amount of operating costs.

Option 2: Limit growth of NASA's activities for humans in space.

This option would defer beginning construction of the Space Station until the early part of the 21st century and place greater near-term emphasis on space science and robotic planetary exploration. It **would require only six to eight Shuttle flights per year and reduce NASA's need for a heavy-lift launch vehicle such as Shuttle-C.**

Limiting Space Shuttle flights to eight per year would reduce space transportation costs for 1989-2010 by about $10 billion, compared to space transportation costs for OTA's Option 1, in which the Shuttle flight rate would increase to 12 per year by 2005.[6] Probably, even more would be saved on other NASA accounts, because 65 to 70 percent of NASA's budget goes to support space activities involving people in space—a fraction that will increase as Space Station funding grows.

The United States possesses the technology to improve the capabilities of existing launch vehicles and facilities through evolutionary modifications. Even if overall space transportation demand fell well below U.S. capability, **the incremental improvement of current vehicles and facilities could provide a low-cost means to enhance U.S. launch capabilities. Evolutionary improvements will be most effective if they are guided by a long-term plan that includes both a concrete goal and the steps to reach it.**

Option 3: Establish a lunar base or send crews to Mars.

On the 20th anniversary of the Apollo Moon landing, President Bush announced his intention to support "a sustained program of manned exploration of the solar system and the permanent settlement of space."[7] His vision includes the construction of the Space Station during the 1990s and the establishment of a permanent lunar base, as well as human exploration of Mars sometime in the next century (box 2-A).

A long-term program of this magnitude would require building new heavy-lift cargo systems, such as the Shuttle-C or the Advanced Launch System now under study, or even larger ones,[8] and would require new crew-carrying systems. It would also need orbital maneuvering vehicles and reusable orbital transfer vehicles.[9] In addition to scientific instrumentation, crew accommodations, and propulsion units, cargo would consist of large amounts of fuel and supplies to support both Moon or Mars crews and the necessary Earth-orbit infrastructure.[10] Such a program would continue the strong dominance of government in the development and deployment of space infrastructure and require considerable growth in the U.S. budget for the civilian space program.

Option 4: Continue the trends of launching increasingly heavier payloads and/or pursue an aggressive Strategic Defense Initiative (SDI) test program.

The size and weight of spacecraft for communications, navigation, reconnaissance, and weather observations have been increasing slowly and have been forcing the lift capacity of launch systems up with them. An aggressive SDI test program would also require vehicles of greater weight capacity than we now possess.

Although it would be feasible to expand the lift capacity of current launch systems to meet such growth in payload weight, if demand is high, new, advanced systems may be more reliable and cost-effective. This option would require moderate growth in the Nation's capacity to launch payloads.

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[6] U.S. Congress, Office of Technology Assessment, *Launch Options for the Future A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988). However, the average cost per launch would increase somewhat.

[7] President George Bush, Speech at the Smithsonian Institution's National Air and Space Museum, July 20, 1989.

[8] National Aeronautics and Space Administration, *Report of the 90-Day Study on Human Exploration of the Moon and Mars* (Washington, DC: November 1989), sec. 5.

[9] An orbital maneuvering vehicle is designed t. move payloads around in space Within a single orbit. An orbital transfer vehicle would transfer payloads from one orbit to another, e.g., from low-Earth transfer orbit to geosynchronous orbit.

[10] I.e., orbital maneuvering and orbital transfer vehicles, and other supporting elements

Box 2-A--Space Transportation and the Human Exploration Initiative

On July 20, 1989, 20 years after man first set foot on the Moon, President Bush announced his intention to support "a sustained program of manned exploration of the solar system and the permenent settlement of Space."[1] In particular, the President suggested establishing a permanent base on the Moon after the turn of the century and exploring Mars sometime later. The President's initiative follows through on a recommendation first made to President Nixon by the Space Task Group in 1969,[2] and reexamined in the 1986 report of the National Commission on space,[3] and in NASA's "Ride" report of 1987.[4]

Shortly afterward, NASA began a 90-day study to frame alternative strategies for accomplishing these goals. NASA's report starts with the assumption that "reliable access to space will be provided through a mixed fleet of launch vehicles that includes the Space Shuttle, existing expendable launch vehicles, and planned heavy-lift launch vehicles."[5] It also assumes that the Space Station will serve as an orbital space transportation node.

The transportation needs of the Human Exploration Initiative would be substantial. NASA estimates that in order to establish the lunar outpost, it would need a vehicle having a lift capacity of about 60 metric tons (132,000 pounds), capable of launching a payload 7.6 meters in diameter and 27.4 meters long. With three Space Shuttle Main Engines, the proposed Shuttle-C could carry such a payload. NASA estimates total payload mass per year necessary to support contstruction and operation of the lunar outpost would equal 110 to 200 metric tons, depending on whether or not the lunar transfer vehicle is reusable, and whether those missions carry cargo and crews, or cargo only. About three Shuttle-C flights would be sufficient to accomplish this task.

For the Mars mission, NASA estimates it would need a vehicle capable of lifting 140 metric tons (308,000 pounds). This large heavy lift vehicle is about 50 percent larger than any vehicle yet proposed for the ALS program and about twice as large as the largest Shuttle-C NASA has contemplated. Building such a vehicle would require a new development effort, including development of high-thrust liquid engines. Yearly masses delivered to orbit to support the Mars mission are estimated to range between 550 and 850 metric tons (1,210,000 to l,870,000 pounds) depending on mission type and the place in the overall mission schedule.

According to NASA, the existing ELV fleet, with a few enhancements, could support "all the robotic lunar and Mars missions that are required before the human missions begin."[6] However, some of these missions might be made cheaper or simpler if a heavy-lift vehicle were already available. For heavy-lift capacity prior to the end of the century, NASA expects to use its planned Shuttle-C. After that, larger, cheaper vehicles would be required to carry out the Human Exploration Initiative.

Other groups, including the Aerospace Industries Association, and the American Institute of Aeronautics and Astronautics, are exploring space transportation and other requirements for the initiative. For example, a group working at Lawrence Livermore National Laboratory has suggested that the mass requirements for a Mars mission might be vastly smaller than NASA has proposed.[7] As these and other interested groups develop their proposals, space transportation requirements will be an essential part of planning for a return to the Moon or the exploration of Mars.

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[1] President George Bush, Speech at the Smithsonian Institution's National Air and Space Museum, July 20, 1989.

[2] Space Task Group, *The Post-Apollo Space Program: Directions for the Future*, September 1969.

[3] National Commission on Space, *pioneering the Space Frontier* (New York, NY: Bantam Books, May 1986).

[4] Sally K. Ride, Leadership *and* America's *Future in Space*, a report to the Administrator {Washington, DC: National Aeronautics and Space Administration, August 1987).

[5] National Aeronautics and Space Administration, *Report of the 90-Day Study on Human Exploration of the Moon and Mars*, p. 5-1.

[6] Ibid., p. 5-4.

[7] Lowell Wood, "The Great Exploration: Assuring American Leaderhsip in Manned Exploration of the Solar System," briefing presented to the National Space Council, Nov. 29, 1989.

Option 5: Develop the capability to launch small-and intermediate-size payloads quickly and efficiently to support DoD needs.

DoD space policy calls for the development of a launch system, or systems, to launch satellites at substantially reduced costs with increased responsiveness, capability, reliability, availability, maintainability, and flexibility, plus the ability to operate in peace, crisis, and war. The Air Force Space Command (AFSPACECOM) has stated that to perform its mission, primarily the operation of satellites, it would need the ability to schedule a launch within 30 days, change out payloads on 5 days' notice, and launch 7 satellites in 5 days. AFSPACECOM noted that "the DoD's inability to provide launch support at heightened conflict levels has been highlighted by both policy emphasis on warfighting capability and by the constriction of DoD's launch capability caused by recent Space Shuttle and expendable launch vehicle groundings."11 The proposed Advanced Launch System (ALS), with its family of launch vehicles, could help meet the requirement for responsiveness—at least in peacetime. ALS is also being designed for a' 'surge' rate higher than average in order to recover from a backlog or to respond in crisis.

It may be impractical to assure launch support in wartime,[12] but if such support proves practical, it would probably require additional launch systems to complement the ALS. For example, the National Aero-Space Plane (NASP) Program is examining the potential for building a highly responsive launch system that could fly to orbit with a single propulsion stage from a conventional runway. If the experimental X-30 that would be built in this program proves successful, it might lead to operational vehicles that are more responsive than an ALS and potentially as survivable as, say, SR-71 aircraft.

Small, transportable rockets, such as the Pegasus or Taurus, *3 could provide a survivable, responsive capability to launch payloads, such as "lightsats"[14] much sooner, but neither they nor operational aerospace planes could launch the largest satellites that have been proposed. U.S. Space Command is currently conducting an Assured Mission Support Space Architecture study to evaluate the potential role of lightsats and survivable launch.

Option 6: Deploy a full-scale space-based ballistic missile defense system and/or dramatically increase the number and kind of other military space activities.

Deployment of a full-scale, space-based missile defense[15] would require large cargo vehicles that are relatively inexpensive to launch. In 1988, the Air Force Space Command stated that:

> . . . deployment of a [SDI] Strategic Defense System. . will require payload capability and launch rates beyond the capacity of present systems.
> . . . even if available, such lift capability and launch rates would not be affordable at today's launch cost .16

This remains true in 1990. The Administration has not yet decided on the form a Strategic Defense System would take, but AFSPACECOM established its requirements for ALS payload capability per launch (220,000 pounds[17]) and per year (over 5 million pounds) to accommodate the numerous payloads that a Phase I Strategic Defense System might require and the very heavy payloads that a Phase II Strategic Defense System might require.[18] A Phase I Strategic Defense System, by itself, might

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11 Air *Force* Space Command, *AFSPACECOM Statement of Operational Need (SON) 003-88 for an Advanced Launch System (ALS)*, Aug. 12, 1988.

12 The Air Force Space Command recognizes that a wartime launch capability is not the only means of providing wartime mission capability; alternatives include proliferation, hardening, or defense of satellites, or reliance on terrestrial systems. None of these, including wartime launch, can assure capability to perform all missions in wartime; see U.S. Congress, Office of Technology Assessment, *Anti-Satellite Weapons, Countermeasures, and Arms Control*, OTA-ISC-281 (Washington, DC: U.S. Government Printing Office, 1985).

13 See later section (ch. 4) entitled *Small Launch Systems*. Pegasus is being designed to launch up to 900 pounds to a 110 nautical mile orbit inclined to 28". Taurus should carry up to 3,000 pounds to a similar orbit.

14 See U.S. Congress, Office of Technology Assessment, *Affordable Spacecraft—Design and Launch Alternatives*, OTA-BP-ISC-60 (Washington, *DC:* U.S. Government Printing Office, January 1990), ch. 4.

15 Under current plans, the full-scale, space-based ballistic missile defense structure would only be undertaken in Phase II of deployment.

16 Air Force Space Command, Op. cit., footnote 11.

17 $ pecifically, AFSPACECOM requires launch of 160,000-pound payloads to polar orbit; a rocket that could do that could &o launch 200,000 &O 220,000 pounds to a low-inclination, low-attitude orbit.

18 For examples, see U.S. Congress, Office of Technology Assessment, *SDI: Technology, Survivability, and Software*, OTA-ISC-353 (Washington, *DC:* U.S. Government Printing Office, June 1988), pp. 148-153.

require much less capacity,[19] especially if a limited system intended primarily for protection from a few accidental launches is deployed. Current U.S. launch systems can launch only about 52,000 pounds per launch and 890,000 pounds per year.[20]

In some form or another, each of these alternatives has been championed by one or more advocates. Choosing among them and following through with the necessary funding will require political and economic consensus on the part of the American people and continued, focused attention from Congress and the Administration.

Meeting the space transportation needs of specific programs is only part of the reason for making changes to the current launch systems. Other, more qualitative, goals serve to guide policy choices, and may be even more important in setting the Nation's agenda in space. For example, Congress may wish to find the development of critical new capabilities or improvements to the quality of space transportation, or Congress may wish to ensure that funding serves abroad national objective of maintaining leadership in space activities.

PEOPLE IN SPACE

One of the distinguishing characteristics of the U.S. civilian space program is its emphasis on activities by people in space, to demonstrate U.S. leadership in the development and application of high technology. Since the early days of the Apollo program, the "manned" space efforts of the National Aeronautics and Space Administration (NASA) have served as a major driver of the direction and spending of its space activities. Today, NASA's projects involving people in space, primarily the Space Shuttle and Space Station programs, consume about 70 percent of NASA's budget.

Critics of NASA's emphasis on humans in space, especially individuals in the space science community, have questioned the wisdom of continuing to emphasize these activities because of the heavy explicit and implicit demands they place on the civilian space budget.[21] In particular, critics note that using the Shuttle to launch the Hubble Space Telescope and large solar system probes, like Galileo and Ulysses, subjects space science to unnecessary reliance on the Shuttle's ability to meet a launch schedule, and exposes the crews to unnecessary danger. Costs for launching such payloads are generally higher on the Shuttle than with ELVs. These critics point out that Europe and Japan, while spending considerably less on space than the United States, have nevertheless achieved noteworthy scientific and technological results. However, supporters of maintaining the human presence in space argue that such activities provide essential visibility for the U.S. space program and underscore America's international technological leadership:

> The [reamed] space[flight] program is a visible symbol of U.S. world leadership; its challenges and accomplishments motivate scientific and technical excellence among U.S. students; and it provides for a diverse American population a sense of common national accomplishment and shared pride in American achievement.[22]

Current administration space policy calls for demonstrating U.S. leadership by expanding "human presence and activity beyond Earth orbit into the solar system, ' and developing "the Space Station to achieve permanently manned operational capability by the mid-1990s."[23] This policy directs NASA to improve the Space Shuttle system and start the Space Station by the mid-1990s. It also directs NASA to establish sustainable Shuttle flight rates for use in planning and budgeting Government space programs, and to pursue appropriate enhancements to Shuttle operational capabilities, upper stages, and systems for deploying, servicing, and retrieving spacecraft as national requirements are defined.[24] Recently, President Bush announced his intentions to complete the Space Station before the end of the century, establish a permanent Lunar base at the

[19] In U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide,* OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988), OTA assumed that 50 Titan IV launches per year, in addition to launches for other missions, would suffice to deploy and maintain a representative Strategic Defense System. This corresponds to 2 million pounds per year.

[20] Ibid., p. 3, table 2-1.

[21] Robert L. Park, ''~efica's $30 Billion Pie in the Sky,'' *Washington Post,* Jan. 21, 1990, p. B3; Robert Bless, "Space Science: What's Wrong at NASA,''lssues *in Science and Technology,* winter 1988-89, pp. 67-73; Bruce Murray, ''Civilian Space: In Search of presidential Goals, ''Issues in Science *and Technology,* spring 1986, pp. 25-37.

[22] John M. Logsdon, "A Sustainable Rationale for Manned Space Flight," *Space Policy,* vol. 5, 1989, pp. 3-6.

[23] The White House, Office of the Press Secretary, "National Space Policy," Nov. 2, 1989.

[24] Ibid.

beginning of the next century, and later send crews to explore Mars.[25]

Achieving each of these goals would be expensive. In the Apollo era, the Nation had the well-defined political goal of landing a man on the Moon within a decade and returning him safely, a goal that carried the rest of the space program and a large budget commitment with it. If the budget for space activities were unlimited and if the needs of the various space interests could all be met equally well, then many space program goals might be usefully pursued at the same time. However, as a result of the current budgetary stringency, and many demands on the Federal budget, Congress must choose among competing ideas for the United States to demonstrate its leadership, rather than attempting to demonstrate leadership across the board as it once did.[26]

In contrast to U.S. civilian activities, the military space program has spent relatively little on crews in space, despite numerous efforts over the years by some to identify military missions that would require crews. Indeed, DoD has recently reaffirmed that it has no requirements for crews in space, although the Air Force has articulated requirements for piloted aerospace vehicles. Production of a piloted aerospace plane for military use, such as is contemplated for a follow-on to the current National Aero-Space Plane Program, would reverse DoD's historical stance.

Expanded commitment to crews in space, as contemplated by NASA and the Air Force, would require increasing budgetary outlays and require the development of new crew-carrying space vehicles. These systems would be costly to develop, but might return their investment over time if operational costs can be kept extremely low.

To illustrate the problem Congress faces, the Space Shuttle system and the Space Station, both of which require crews, dominate NASA's budget for the 1990s.[27] As noted in a 1988 Congressional Budget Office report, simply to maintain NASA's ''core program,' which includes these major programs, but no large additional ones, will require NASA's overall budget to grow from $10.5 billion in fiscal year 1989 to about $14.4 billion in fiscal year 1995.[28] NASA plans to spend about $2.5 billion per year for investment in its space transportation system, including improvements to the Shuttle, an advanced solid rocket motor, and in-orbit transportation vehicles. Operating the Shuttle will cost at least $2.0 billion per year. Anything new, such as an additional orbiter beyond OV-105, major modifications to the Shuttle, a Shuttle-C, a Personnel Launch System, or an emergency crew return vehicle, will add to these costs.

Spaceflight is inherently risky. As noted in a previous section, the exact reliability of the Shuttle system is uncertain, but experts estimate that it lies between 97 and 99 percent. Therefore, the United States may expect to lose or severely damage one or more orbiters within the next decade, perhaps with loss of life. One of the major challenges for the U.S. civilian space program will be to learn how to reconcile America's goals for the expansion of human presence in space with this potential for loss of life. **In particular, if the United States wishes to send people into space on a routine basis, the Nation will have to accept the risks these activities entail. If such risks are perceived to be too high, the Nation may wish to reduce its emphasis on placing humans in space.**

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[25]"Remarks by the president at the Twentieth Anniversary of Apollo Moon Landing," The White House, Office of the Press Secretary, July 20, 1989.

[26]U.S. Congress, Office of Technology Assessment, *Civilian Space Policy and Applications*, OTA-STI-177 (Washington, DC: U.S. Government Printing Office, June 1982), ch. 3.

[27]Most of President Bush 's requested 20 percent budget increase for NASA in fiscal year 1990 derived from increases to build the Space Station, which is now scheduled for completion in 1999.

[28]U.S. Congress, Congressional Budget Office, *The NASA Program in the 1990s and Beyond* (Washington, DC: May 1988), pp. x-xiv.

Chapter 3

Space Transportation Demand and Costs

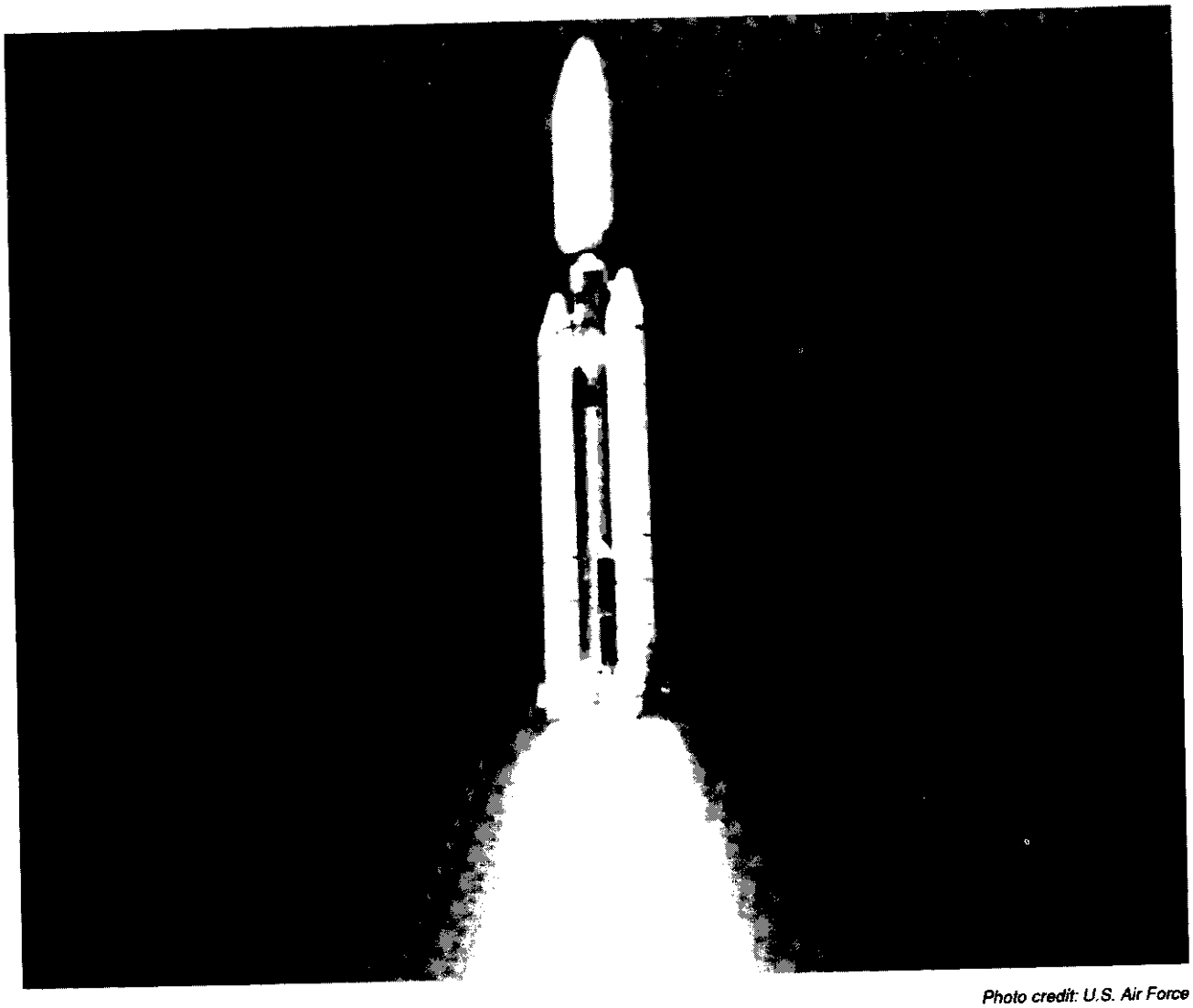


Photo credit: U.S. Air Force

The Titan IV launch vehicle lifts off from Space Launch Complex 41 at Cape Canaveral Air Force Station. This launcher will be the workhorse launcher for the Air Force for at least the next decade.

Projections of demand for U.S. transportation to and from low Earth orbit vary from about 600,000 pounds to more than 4 million pounds of payload per year. The lower projections are based on an assumption that the tonnage launched annually will grow slowly for the next two decades. The higher projections are based on an assumption that the United States will undertake an ambitious space initiative, such as deployment of a space-based missile defense system, establishment of a manned base on the Moon, or a manned expedition to Mars. Because there is no broad consensus on the desirability of these proposals and on the willingness to pay for them (nor even on how much they would cost), post-1995 demand for U.S. space transportation is highly uncertain.[1] This uncertainty makes rational choice among options for improving the Nation's space transportation systems extremely difficult. Nevertheless, failing to choose an alternative now could leave the United States incapable of meeting future needs, or paying for excess capacity.

In the face of such uncertainty, OTA analyzed the space transportation needs for three scenarios (called mission models) for growth of demand:

- *Low-Growth:* launch rate grows about 3 percent per year to 41 launches per year by 2010, then remains constant through 2020.
- *Growth:* launch rate grows about 5 percent per year to 55 launches per year by 2010, then remains constant through 2020.
- *Expanded:* launch rate grows about 7 percent per year to 91 launches per year by 2010, then remains constant through 2020.[2]

These mission models represent, respectively, the approximate demand that would likely result from efforts to:

— maintain the existing course of NASA and DoD space programs (option 1),[3]
— deploy the Space Station in the mid-1990s while expanding the NASA science program and continuing the trend of launching heavier military satellites (options 4 or 5), *or*
— send humans to Mars and establish a base on the Moon, or deploy a layered ballistic-missile-defense system in orbit (options 3 or 6).

The mission models differ only in demand for heavy-cargo launches; they are identical in postulated demand for light-cargo launches and piloted missions. By largely ignoring the weights, sizes, and destinations of individual payloads, these simplified mission models help focus OTA's broad-brush analysis on the sensitivity of costs to gross demand.[4]

OTA calculated the life-cycle cost of servicing the demand postulated by each mission model with each of five different combinations of types ("fleets" of launch vehicles—box 3-A).[5] Although intangible benefits such as "space leadership" may be weighed in comparing the options, the most appropriate *economic* yardstick is life-cycle cost (box 3-B), discounted to reflect the opportunity cost to the Nation of diverting funds from competing demands on the Federal budget.

THE MOST ECONOMICAL OPTIONS

Figure 3-1 shows OTA's estimate of the discounted life-cycle cost of each of five space transportation options in each of the three OTA mission models. Estimated life-cycle costs increase with increasing demand, even though cost per pound of payload (not shown) would decrease with increasing demand.

[1] Estimates of demand through 1995 are relatively accurate, because the lead time for payload development is so long.

[2] Presumably, Government demand for space transportation would depend on space transportation costs, but there have been few efforts to forecast the price elasticity of demand for space transportation. For two examples, see DoD and NASA, *National Space Transportation and Support Study 2995-2010, Annex* B: Civil Needs Data Base, Version 1.1, Volume I-Summary Report, Mar. 16, 1986, pp. 3-31,3-32; and Gordon R. Woodcock, "Economics on the Space Frontier: Can We Afford It?" *SSI Update* (Princeton, NJ: Space Studies Institute, May/June 1987).

[3] Option 2 would fit within this scenario, but would save about $10 billion by reducing the total mass of payload launched to orbit.

[4] A more detailed analysis would examine the sizes and weights of expected payloads and match them Up with expected launch vehicles. However, in most cases, pursuing such a detailed analysis for periods beyond 5 or 10 years would yield no additional insight, as the characteristics of payloads that far in the future are extremely poorly known.

[5] See also U.S. Congress, Office of Technology Assessment, Launch *Options for the Future A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988), table 1-1.

Box 3-A--Mixed Fleet Options

In the future, as in the past, the United States will probably want to perform such a variety of missions in space that a variety of types of launch vehicles—a "mixed fleet' '-will be needed, for operational flexibility if not economy. The current mixed fleet includes the Scout, Delta, Atlas, and Titan launchers (including several versions of each), as well as the Shuttle and a few new, small, privately developed launch vehicles such as the Conestoga and Pegasus. In the near future, most payloads will be carried by the Titan, Shuttle, and Medium Launch Vehicles (the Medium Launch Vehicle is derived from the Delta, and the Medium Launch Vehicle II from the Atlas).

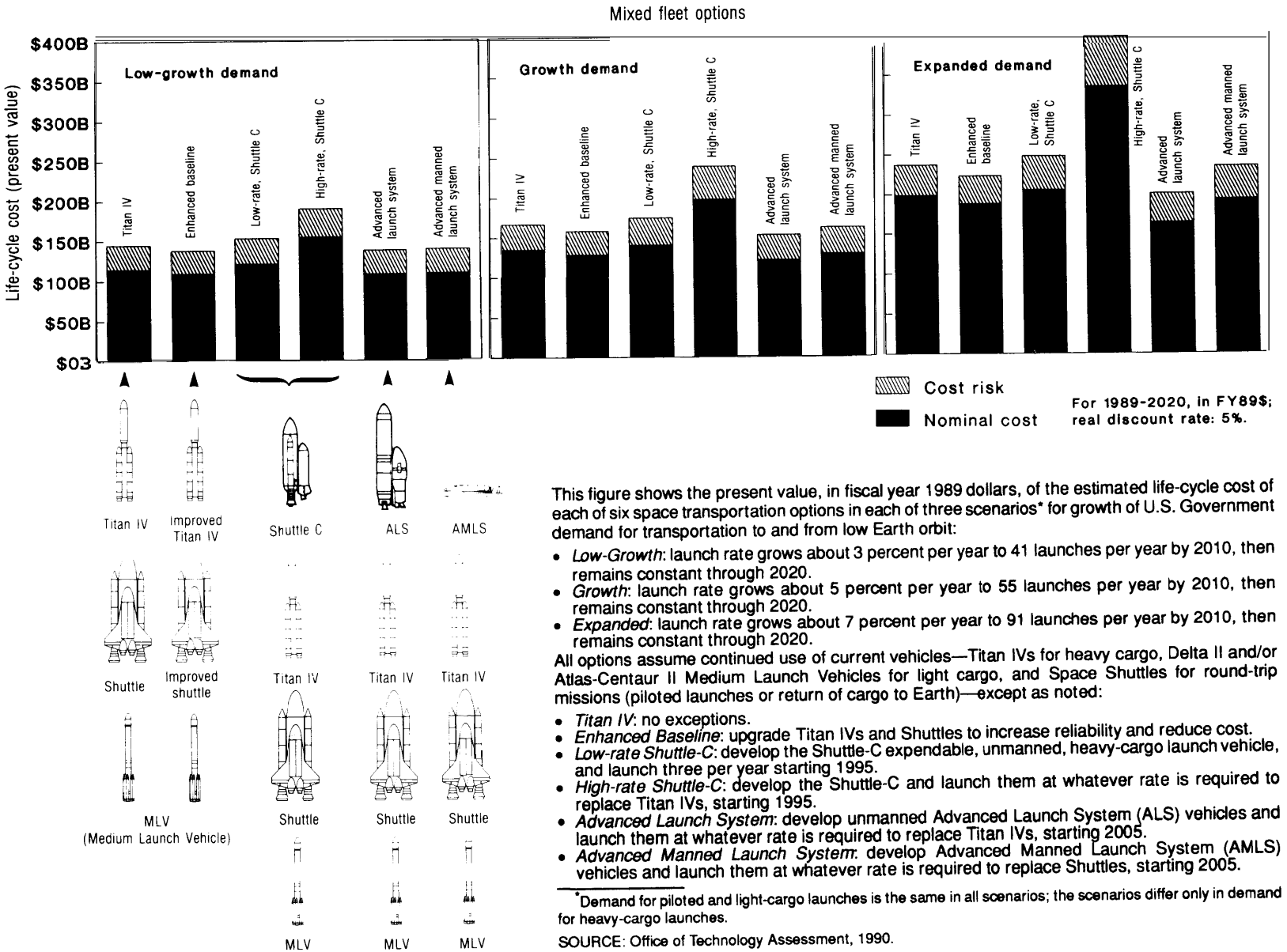
To estimate whether improving these launch systems, or developing a new one would be economical, OTA has estimated and compared the life-cycle costs of servicing postulated Government demand with each of five different mixed fleets. OTA considered using one of the mixed fleets in two different ways; hence a total of six mixed-fleet options were considered (see figure 3-1). Although most options were named after the new system under consideration, or the primary cargo vehicle (e.g., Titan IV), a mixed fleet of crewed and unmanned launch vehicles would be used in each option:

- *Titan IV:* Continue to use Titan IVS for heavy cargo, Delta II and/or Atlas-Centaur II Medium Launch Vehicles for light cargo, and Space Shuttles for round-trip missions (manned launches or return of cargo to Earth).
- *Enhanced Baseline:* Immediately begin upgrading Titan IVs and Space Shuttles to increase reliability and reduce cost. Meanwhile, use Titan IVs for heavy cargo, Delta II or Atlas-Centaur II Medium Launch Vehicles for light cargo, and Space Shuttles for round-trip missions.
- Low-rate Shuttle-C: Immediately begin developing Shuttle-C expendable, unmanned, heavy-cargo launch vehicles. In 1995, begin launching three per year to carry some cargo that would otherwise be launched on Titan IVs, Medium Launch Vehicles, and Space Shuttles. Continue to use Titan IVs, Medium Launch Vehicles, and Space Shuttles for the remaining missions,
- *High-rate Shuttle-C:* Immediately begin developing expendable, unmanned, Shuttle-C heavy-cargo launch vehicles. In 1995, begin launching them at whatever rate is required to replace Titan IVs. They would also carry some cargo that would otherwise be launched on Medium Launch Vehicles and Space Shuttles. Continue to use Medium Launch Vehicles and Space Shuttles for the remaining missions.
- *Advanced Launch System:* Begin developing unmanned Advanced Launch System (ALS) vehicles and facilities in time for them to supersede Titan IVs in 2005, They would also carry some cargo that would otherwise be launched on Medium Launch Vehicles and Space Shuttles. Continue to use Medium Launch Vehicles and Space Shuttles for the remaining missions.
- *Advanced Manned Launch System:* Begin developing Advanced Manned Launch System (AMLS) vehicles and facilities in time for them to supersede Space Shuttles in 2005. Continue to use Titan IVs and Medium Launch Vehicles for one-way missions.

Small launch vehicles-such as the Scout Conestoga, and Pegasus-are expected to carry a small fraction of total Government payload and contribute a small fraction of total launch cost. They were not explicitly included in the mixed-fleet options for this reason, not because of any judgment that they would be uneconomical for selected missions.

SOURCE: Office of Technology Assessment, 1990.

Figure 3-1—Discounted Life-Cycle Costs of Space Transportation Options



This figure shows the present value, in fiscal year 1989 dollars, of the estimated life-cycle cost of each of six space transportation options in each of three scenarios* for growth of U.S. Government demand for transportation to and from low Earth orbit:

- *Low-Growth*: launch rate grows about 3 percent per year to 41 launches per year by 2010, then remains constant through 2020.
- *Growth*: launch rate grows about 5 percent per year to 55 launches per year by 2010, then remains constant through 2020.
- *Expanded*: launch rate grows about 7 percent per year to 91 launches per year by 2010, then remains constant through 2020.

All options assume continued use of current vehicles—Titan IVs for heavy cargo, Delta II and/or Atlas-Centaur II Medium Launch Vehicles for light cargo, and Space Shuttles for round-trip missions (piloted launches or return of cargo to Earth)—except as noted:

- *Titan IV*: no exceptions.
- *Enhanced Baseline*: upgrade Titan IVs and Shuttles to increase reliability and reduce cost.
- *Low-rate Shuttle-C*: develop the Shuttle-C expendable, unmanned, heavy-cargo launch vehicle, and launch three per year starting 1995.
- *High-rate Shuttle-C*: develop the Shuttle-C and launch them at whatever rate is required to replace Titan IVs, starting 1995.
- *Advanced Launch System*: develop unmanned Advanced Launch System (ALS) vehicles and launch them at whatever rate is required to replace Titan IVs, starting 2005.
- *Advanced Manned Launch System*: develop Advanced Manned Launch System (AMLS) vehicles and launch them at whatever rate is required to replace Shuttles, starting 2005.

*Demand for piloted and light-cargo launches is the same in all scenarios; the scenarios differ only in demand for heavy-cargo launches.

SOURCE: Office of Technology Assessment, 1990.

Box *3-B--Cost Components*

Life-cycle cost-appropriately discounted to reflect risk and opportunity cost—is the most important economic criterion by which to compare different launch vehicle architectures. For each mission model examined here, the option that has the lowest discounted life-cycle cost would be must economical, if the assumed discount rate were appropriate and if the required funding were available. However, the most economical launch architecture might be deemed unaffodable if it would require more spending in a particular year than the Executive would budget or than Congress would authorize and appropriate for the purpose.

Life-cycle costs include both nonrecurring and recurring costs. The nonrecurring costs include costs of design, development testing, and evaluation (DDT&E), production of reusable vehicle systems, and construction and equipping of facilities. The recurring costs include all costs of planned operations, including production of expendable vehicle systems, as well as expected costs of failures. In general, early nonrecurring investment is required to reduce total discounted life-cycle cost.

Failure cost, a component of life-cycle cost, deserves special mention because: 1) it can be as great as the balance of life-cycle cost, 2) it is sometimes excluded from cost estimates, and 3) it is random-hence uncertain-and depends sensitively on the reliabilities of the launch vehicles used. These reliabilities are themselves very uncertain--even for vehicles that have been launched more than a hundred times, and especially for vehicles that have never been launched. Expected costs of failures are calculated from estimates of vehicle reliabilities and estimates of the costs that would be incurred in the event of a failure (see box 3-C).

Cost risk is included in the cost estimates quoted here. Cost risk was defined in the Space Transportation Architecture Study (STAS) as a subjectively estimated percentage increase in life-cycle cost (discounted at 5 percent) that the estimator expects would be exceeded with a probability of 30 percent, assuming certain ground rules are met. Basically, cost risk is intended to represent likely increases in life-cycle cost caused by unforeseen circumstances such as difficulties in technology development or facility construction. However, cost risk as defined in the STAS does not include risks of cost growth due to mission cancellations, funding stretch-outs, or standdowns after failure, which were excluded by the ground rules of the study. The cost risk estimates by OTA also exclude risks of mission cancellations, funding stretch-outs, and standdowns after failures; estimation of these risks in a logically consistent manner will require more sophisticated methods than were used here, or in the STAS. However, OTA's cost risk estimates do include the risk of greater-than-expected failure costs.

SOURCE: Office of Technology Assessment, 1990.

Box 3-C-Failure Costs

The cost of failures makes a substantial contribution to understanding the life-cycle costs of a launch system relative to any other. A system with a high purchase cost may nevertheless be cheaper in the long run than a lower-cost system if the former exhibits much higher reliability. Even if both reliability and acquisition costs are equivalent the life-cycle costs could be very different if one system requires a much longer standdown for analyzing and correcting a failure than another.

The expected cost of failures of launch vehicles are calculated by multiplying the number of launches planned by the estimated probability of failure on a single launch (one minus the estimated reliability), then multiplying the result by the estimated cost per failure. Cost per failure will generally include cost of accident investigation and corrective action. It may also include costs of replacing and reflying lost payloads, replacing reusable vehicle components, and delays pending completion of accident investigation.

In the Space Transportation Architecture Study (STAS), operations costs were estimated assuming that operations would be continuous (i.e., no "standdowns"), and failure costs were estimated assuming that all lost payloads would be replaced and reflown. The same assumptions were made in this report. Accident **investigation costs were** included, *but launch operations were not assumed to be suspended pending* their completion. To assume that a fleet would stand down pending completion of accident investigation requires that the opportunity costs of delaying missions be estimated. Moreover, because some missions would be canceled as a result of the delay, life-cycle costs would have to exclude missions not flown.

SOURCE: Office of Technology Assessment, 1990.

If facilities and fleets are sized for demand appropriate to the Low Growth scenario, all of the options OTA considered would have comparable life-cycle costs. The estimates of expected life-cycle costs of different options differ by only a few percent of the estimated uncertainties ("cost risk") in those estimates. Moreover, the theoretically most economical choice depends on the accounting horizon assumed (i.e., the last year for which estimated recurring costs are cumulated). Building an Advanced Launch System (ALS) to supersede Titan IVs is most economical for the nominal accounting horizon (2020), but improving current vehicles[7] would be most economical if the accounting horizon were instead 2010 (see figure 3-2).

The probability that building an ALS would be most economical increases with increasing demand. In the Expanded demand scenario, the ALS is estimated to yield savings (relative to continued use of Titan IVs) comparable to the estimated cost risk of the ALs option.

If demand for cargo flights were as in the Low-Growth mission model but crew-carrying flights were limited to 8 per year (policy option 2), all mixed-fleet options would cost between $9 billion and $10 billion less than indicated in figure 3-1 for the Low-Growth mission model, except that the AMLS option would cost about $7 billion less.

Thus **demand for launch services is the most important determinant of the economic value of investing in new launch systems. An** ALS is likely to be most economical at high launch rates, but if, instead, demand grows slowly above current launch rates, all of the options OTA considered would have comparable life-cycle costs. **The reader is cautioned that current methods of estimating launch system costs are subjective and unreliable, and that large development projects for new space transportation systems are not likely to achieve their cost or technical objectives without continuity in commitment and funding.**

The costs of options that include operational aerospace planes are highly uncertain and should be estimated by methods designed specifically to account for such uncertainties (see below).

Cost Estimation

OTA derived the estimates in figure 3-1 using the methods described in *Launch Options for the Future.*[8] *The* nominal cost-estimating relationships were used, but those for Shuttle-C, the ALS, and the AMLS have been revised.

OTA now assumes Shuttle-C development will cost $985 million, in fiscal year 1988 dollars.[10] A Shuttle-C could be launched with two or three engines; if it carries no more payload than a two-engine Shuttle-C could carry, a three-engine Shuttle-C could tolerate a failure of one of its Space Shuttle Main Engines (SSMEs) and hence could be more reliable than a two-engine Shuttle-C. OTA's cost estimates are for a three-engine Shuttle-C, which NASA estimates would cost $424 million per launch, if launched with engines that have been used one time on a Shuttle flight.11 NASA has not estimated the reliability of a three-engine Shuttle-C;[12] OTA's cost estimates are based on an assumed reliability of 97 percent. [13] NASA estimates a first launch could be attempted 54 months after authority to proceed (with development) is granted;[14] OTA assumes operational launches will begin in 1995.

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[6]Congress prohibited development of the Transition (or Interim Advanced) Launch System; see 101 Stat. 1066.

[7]The Shuttle, Titan IVs, and Delta IIs or Atlas-Centaur IIs.

[8]U.S. Congress, Office of Technology Assessment, op. cit., footnote 5. *Launch Options for the Future* contained some errors, most notably: (1) The inadvertent use of Design, Development, Testing and Evaluation (DDT&E) cost for the cost of procuring reusable hardware led to overestimation of the costs of the Transition, ALS, and Shuttle options. The magnitude of the errors in life-cycle cost estimates was smaller than the estimated uncertainty; correcting them did not change the rank of the most economical option for each mission model. OTA is indebted to Mitch Weatherly of General Dynamics Space Systems Division for pointing out anomalies that led to OTA's discovery of this error. (2) The statement on p. 40 that "Shuttle-C would pay for itself after being used for Space Station deployment alone" is incorrect; cf. box 7-3 on p. 69: "Shuttle-C . . . could provide useful flexibility . . . at a small premium in life-cycle cost."

[9]Ibid., table A- 1, p.82.

[10]$1,114.3 million in fiscal year 1991 dollars-Jack Walker, MSFC, facsimile transmission, Jan. 11, 1990.

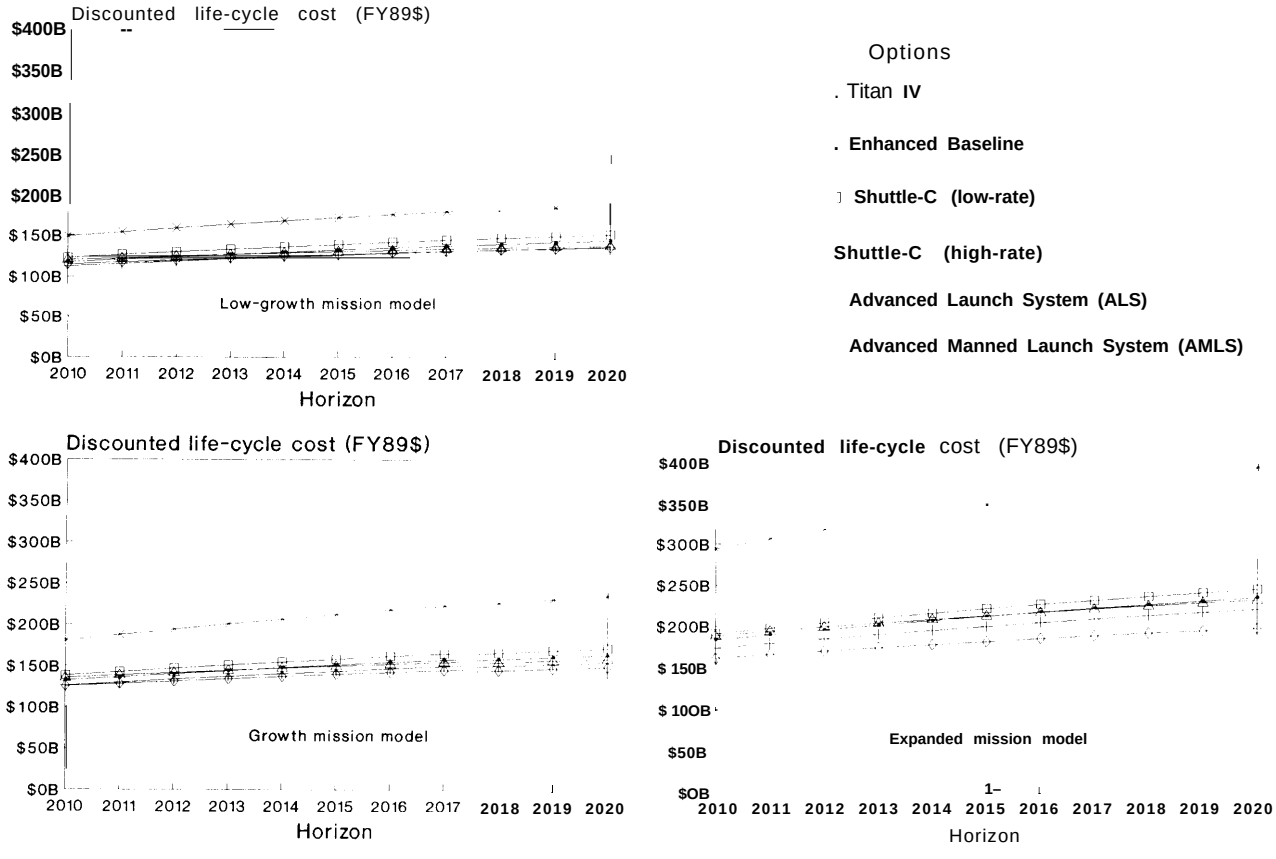
[11]$479.5 million in fiscal year 1991 dollars-ibid.

[12]Ed Gabris, NASA HQ, Code MD, personal communication, Jan. 17, 1990.

[13]"Shuttle/Shuttle-C Operations, Risks, and Cost Analyses," LSYS-88-008 (El Segundo, CA: L Systems, Inc., July 2 1, 1988), postulated a reliability between 97.5 and 98.9 percent, with 98 percent the "average." OTA multiplied this "engineering estimate" by 99 percent to account for the unreliability of humans and other unmodeled systems and processes. See U.S. Congress, Office of Technology Assessment, footnote 5, p. 85.

[14]Ed Gabris, NASA HQ, Code MD, personal communication, Jan. 17, 1990.

Figure 3-2-Sensitivity of Life-Cycle Costs to Accounting Horizon



SOURCE: Office of Technology Assessment, 1990.

OTA now assumes ALS development will cost $7.3 billion (in fiscal year 1988 dollars), facilities (including one pad) will cost $3.9 billion plus $150 million times the peak annual ALS launch rate in excess of 25 per year, operations will cost $70 million per launch (of which about $17 million will be for the expendable launch vehicle), and the "engineering estimate' of reliability on ascent is 98.4 percent.[15] The estimates of recurring cost per launch and reliability are for a liquid-fueled version of the proposed ALS expendable launch vehicle at a rate of 10 per year.[16]

OTA assumes Advanced Manned Launch System (AMLS) costs will be as estimated for the proposed Shuttle II described in *Launch Options for the Future* but now assumes AMLS will begin operating in 2005. NASA is considering several alternative concepts as follow-ons to the Shuttle, including the AMLS and Personnel Launch System (PLS) .[17] NASA has awarded Rockwell International a contract to flesh out several alternatives, estimate their costs, and help weed out the less promising ones.

The estimates in figure 3-1 include costs incurred from 1989 to 2020. In *Launch Options for the*

[15]The ALS Joint Program Office estimates that operation could begin in 1998, but a recurring cost of $70 million per launch would not be achieved until 2005.

[16]As before, and as for other launch vehicles, OTA assumes the operational reliability on ascent will be 99 percent of the engineering estimate of reliability, and the operational reliability on return, given successful ascent, will be 99 percent.

[17]See ch. 7. For a more detailed description of these alternatives, see: U.S. Congress, Office of Technology Assessment, *Round Trip To Orbit: Human Spaceflight Alternatives—Special Report*, OTA-ISC-419 (Washington, DC: U.S. Government Printing Office, August 1989), pp. 53-56.

Future, OTA did not accumulate recurring costs after 2010, because demand after 2010 is highly uncertain. However, not accumulating costs beyond 2010 might unfairly penalize options that include advanced systems, because it allows only 5 years for the annual savings expected from an ALS or AMLS to pay back the substantial initial investment that would be required to reduce annual costs. Hence it is also instructive to compare life-cycle costs over a longer life cycle. Figure 3-2 shows the life-cycle costs of the same options for accounting horizons ranging from 2010 to 2020, and shows that extending the accounting horizon did not significantly affect the ranking of the options: all are roughly comparable at Low-Growth launch rates, while an ALS is estimated to be significantly less costly than the other options at Expanded launch rates.

AEROSPACE PLANES

OTA has considered an option for developing and using aerospace planes incorporating NASP technology to supersede the Shuttle and complement Titan IVs. Aerospace planes, if successful, could be operated with greater responsiveness, flexibility, and economy than could rocket-powered launch vehicles.

However, it is not yet possible to estimate the life-cycle cost of such an option in the conventional manner, which depends on extrapolating or interpolating curves showing how subsystem costs depend on design parameters, such as subsystem weight. Similar curves are obtained for the costs of operational procedures as functions of labor and equipment requirements. Such curves are obtained by fitting a curve of a given type---g.,., a line—to points representing the costs and weights (etc.) of technologically similar subsystems that have been built and the costs of which are known.[18] However, the experimental X-30 and operational vehicles derived from NASP technology, which would use air-breathing engines for propulsion most or all of the way to orbit, would have systems so unlike any previously developed that no data points exist to which cost curves for key systems, such as engines, could be fit. Further, the feasibility of such aerospace planes remains unproven. Hence subjective engineering judgment must play a greater role than usual in estimating the costs of operational vehicles.

Moreover, the reusability of operational vehicles would make the average cost per flight extremely sensitive to parameters such as maintenance man-hours per sortie and the probability of catastrophic failure, both of which OTA regards as extremely uncertain. These quantities were underestimated in the case of the Space Shuttle, the orbiter of which was designed for 100 flights. This led to underestimation of average cost per flight. As currently envisioned, operational aerospace planes would be designed to last 500 flights, so their average cost per flight will be more sensitive to greater-than-expected probability of catastrophic failure. Current] y, the NASP Joint Program Office assumes that the probability of catastrophic failure will fall between 0.1 percent and 0.5 percent. The average cost per flight will also be sensitive to shorter-than-expected wearout life. Airplanes, of course, are designed for many more uses, but extensive reliability and maintenance data for technologically similar airplanes is usually available.

Building and flying X-30S would demonstrate the feasibility of single-stage, air-breathing, rocket-assisted, reusable launch vehicles and would provide data for anchoring cost estimates. It would also provide data on which reliability estimates could be based. Partially subjective but logically consistent methods will be needed to predict operational aerospace plane reliability on the basis of X-30 flight test data (see app. A).

Making aerospace planes extremely reliable will be important for reasons other than cost, because they might fly many—perhaps half---of the missions that Titans would otherwise fly, as well as the missions that the Shuttle or an AMLS could accept. Thus aerospace plane crews would have greater *exposure* to risk than would Shuttle or AMLS crews.

The life-cycle cost of an option that includes spaceplane development, flight testing, and—if successful—production and operation, will depend not on] y on the actual reliability of the plane but also on the reliability the plane is required to demonstrate in flight tests and on the type and level of confidence with which it is required to demonstrate that reliability (see app. A).

[18]See U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs New Technologies and Practices*, OTA-TM-ISC-28, (Washington, DC: U.S. Government Printing Office, September 1988), app. A, for a discussion of cost-estimating relationships.

Chapter 4

Existing Launch Systems

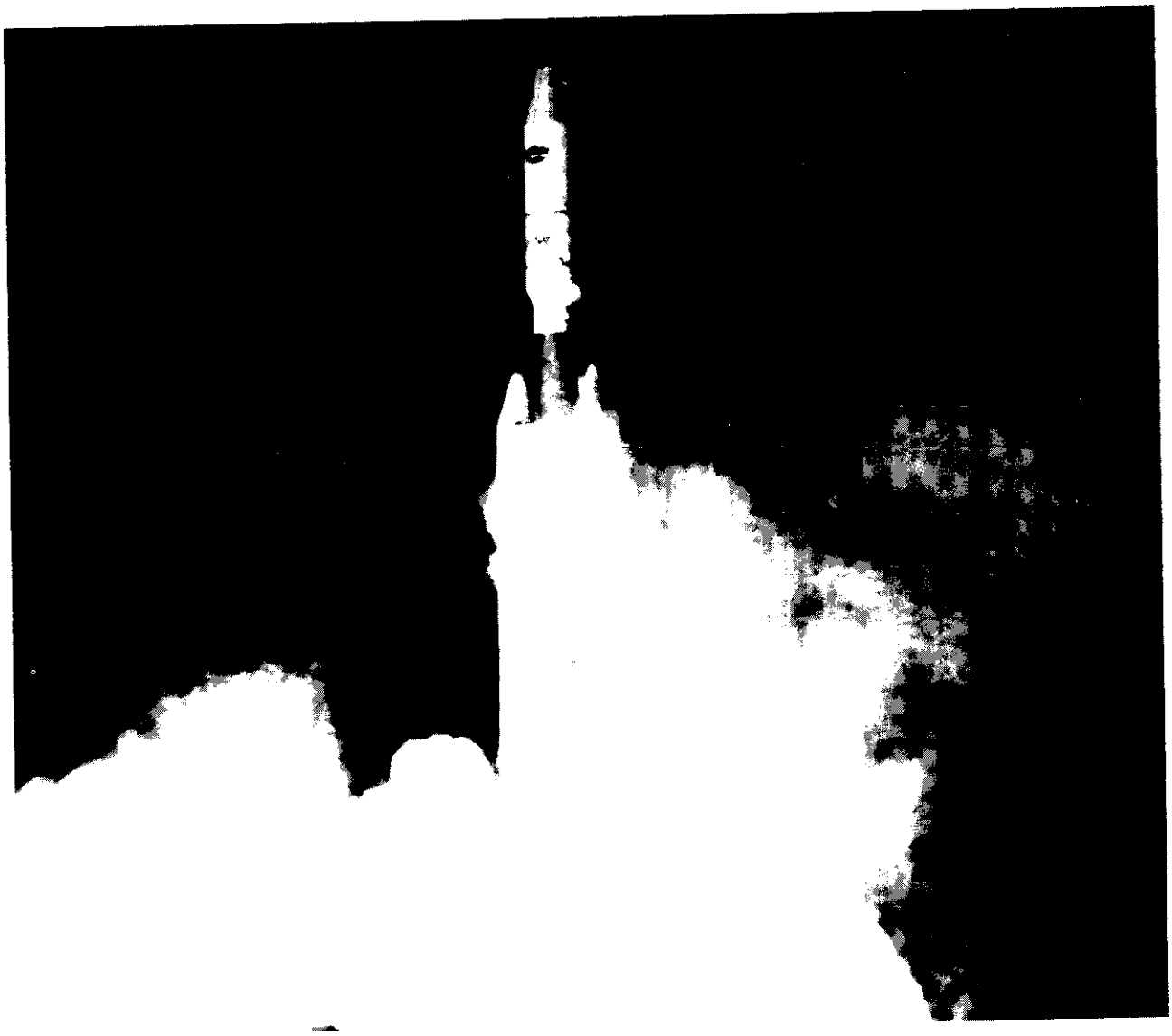


Photo credit: U.S. Air Force

The first commercialTitan lifts off from space launch complex 40 at Cape Canaveral Air Force Station. This commercial Titan carried a Japanese communications satellite and a Skynet communications satellite for the British Defense Ministry.

Chapter 4
Existing Launch Systems

EXPENDABLE LAUNCHERS

Originally developed in the 1960s from intermediate-range ballistic missiles (IRBMs) and intercontinental ballistic missiles (ICBMs), the three primary U.S. expendable launch vehicles (ELVs) have evolved into launchers capable of launching payloads of 7,600 pounds to 39,000 pounds into low Earth orbit (LEO)-(figure 1-1).[1] Though the Delta II, Atlas II, and Titan 111 were developed with Government funds, commercial versions of these vehicles are now owned and operated by private fins, which sell launch services to the Government and other domestic and foreign buyers (box 4-A). The U.S. Air Force owns and launches the Titan N. The Air Force also operates the launch complexes for all medium-lift ELVs, whether for Government or commercial launches.[2]

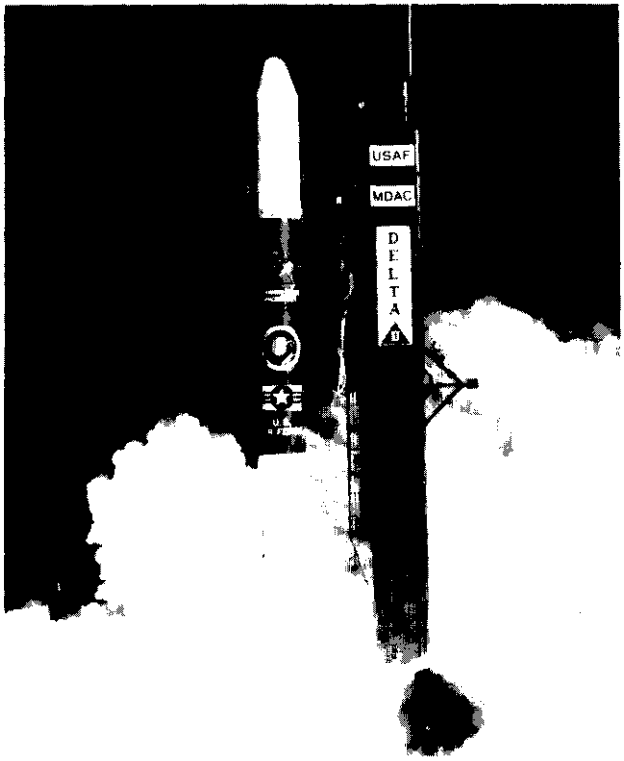


Photo credit: McDonnell Douglas Corp.

Delta expendable launch vehicle, lifting off from Cape Canaveral Air Force Station, carrying the Delta Star (Wooden Stake") Spacecraft for the Strategic Defense Initiative Organization.

Until the Shuttle was developed, these ELVs were the only means the United States had for placing payloads into orbit. During the early 1980s, when the United States was pursuing a policy to shift all payloads to the Shuttle, the Government decided to phase ELVs out of production. Although the Government had in theory turned its ELV fleet over to the private sector for commercial exploitation, it had priced Shuttle launch services so low that private launch companies were unable to make a profit competing with the Government.[3] However, following the loss of *Challenger,* policymakers realized that policies that forced reliance on a single launch system and prevented private launch companies from entering the market were unwise.[4] Hence, the Nation now follows a policy requiring a "mixed fleet" (both Shuttle and ELVs) to support Government needs, and a concomitant policy encouraging private ownership and operation of ELVs. The Commercial Space Launch Act of 1984 (Public Law 98-575), assigned the Department of Transportation (DOT) responsibility for overseeing commercial ELV operation.

THE SPACE SHUTTLE

Designed to carry crews as well as cargo to space, the Space Shuttle is a piloted vehicle capable of lifting 52,000 pounds to LE0.[5] It is the Nation's largest cargo carrier. It was the world's frost partially reusable Earth-to-orbit launch vehicle. Begun in 1972, the Space Shuttle was first launched in April 1981. As of February 15, 1990, NASA has launched the Shuttle 33 times, but experienced one tragic failure when one of *Challenger's* Solid Rocket Boosters burned through in January 1986.

[1]For example, a series of upgrades has increased the Delta's payload capability from several hundred pounds to 7,600 pounds (for the Delta 3920).

[2]The launch services companies reimburse the Air Force for use of the launch complexes for commercial launches.

[3]See the extensive discussion of Shuttle pricing in the mid-1980s and the contradictory policy of *encouraging* the *private* sector in: U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities, OTA-ISC-239* (Springfield, VA: National Technical Information Service, July 1985), ch. 5.

[4]See John M. Logsdon, "The Space Shuttle Program: A Policy Failure?" *Science,* vol. 232, pp. *1099-1105.*

[5]To a standard orbit 110 nautical miles high, at 28.5" inclination.

Box 4-A—US. Medium-Lift Expendable Launch Vehicles

- *Delta II is the* latest in a series of Delta ELVs manufactured by McDonnell Douglas. First launched in 1960, carrying a 137 pound payload (Echo IA), the Delta has undergone a long series of improvements that have increased its payload capacity to over 11,000 pounds to LEO, or 4,000 pounds to geosynchronous transfer orbit (GTO). It is powered by a liquid core engine (kerosene/liquid oxygen) and strap-on solids, Originally developed for NASA, the Delta launchers are now owned and operated by McDonnell Douglas as commercial launchers. McDonnell Douglas carried out the first U.S. commercial satellite launch on August 27, 1989, by launching the Marcapolo I direct broadcast satellite for British Satellite Broadcasting on a Delta 4925. It plans seven commercial launches in 1990.
- *Atlas 11* ELVs are manufactured by General Dynamics for the Air Force. The Atlas II can place about 14,500 pounds in LEO and over 6,000 pounds in GTO. A commercial version of the Atlas, designated the Atlas I, is also available. Both versions are powered by a first-stage liquid engine burning kerosene (RP-1), and a second-stage liquid hydrogen/liquid oxygen Centaur engine. Solid motor strap-on boosters provide extra lift for the Atlas II. The first commercial Atlas is expected to be launched in the summer of 1990, carrying a NASA payload—the Combined Release and Radiation Effects Satellite.
- Titan III is the commercial version of the Titan III originally built to Air Force specifications by Martin Marietta. The Titan III design derives directly from Titan II, which was used as an intercontinental ballistic missile by the Air Force, his propelled by a liquid core motor using hyperbolic liquids and two solid rocket motors mounted on either side. Titan III is capable of delivering 32,500 pounds to LEO, and about 4,000 pounds to geosynchronous orbit, In the near future, Martin Marietta plans to increase the thrust of the solid rocket boosters to allow delivery of 40,000 pounds to LEO. The relatively high capacity of the Titan IIIq makes it possible to launch two communications satellites to geosynchronous orbit Commercial Titan, Inc., a division of Martin Marietta, markets the Titan III. It uses Air Force launch facilities at Cape Canaveral (on a cost-reimbursable basis). The first commercial Titan III flight took place December 31, 1989, and sent two communications satellites to GTO.
- Titan IV is an ungraded version of the Titan III launch vehicle, manufactured for the Air Force by Martin Marietta. Capable of carrying 39,000 pounds of payload to LEO, the Titan IV is also powered by a liquid main engine and two solid rocket motors. The Titan IV successfully completed its maiden flight on June 14, 1989. In 1992, the Air Force plans to add improved solid rocket motors that will boost Titan IV performance to 48,000 pounds.

SOURCE: Office of Technology Assessment, 1990.

The United States today depends entirely on the Space Shuttle for transporting crews to and from space. In space, the Shuttle functions as a vehicle for launching spacecraft, and also serves as a platform for experiments in science and engineering. During the late 1990s, NASA intends to use the Space Shuttle to deploy and service the planned Space Station.

As the Nation looks toward the future of piloted spaceflight, it may wish to improve the Shuttle's reliability, performance, and operational efficiency. Eventually, additions to the Shuttle fleet or replacement Shuttles will likely be desirable. This section summarizes the major issues related to maintaining and improving the Space Shuttle.

Shortcomings of the Space Shuttle

The heavy U.S. dependence on the Space Shuttle raises questions concerning the longevity of the Shuttle fleet and the risk that orbiters might be unavailable when needed.

. *NASA Flight Schedule.* NASA has estimated that 14 Shuttles can be launched per year from the Kennedy Space Center with existing facilities,[6] yet it has never launched more than 9 Shuttles per year. Some experts[7] doubt that 14 launches per year can be sustained with a 4-orbiter fleet without adding new facilities and launch operations staff.

[6]Enclosure t. letter from Darrell R, Branscome, NASA Headquarters, to Richard DalBello, Office of Technology Assessment, Mm. 31,1988.

[7]National Research Council, Committee on NASA Scientific and Technological Program Reviews, Post-Challenger *Assessment of Space Shuttle Flight Rates and Utilization* (Washington, DC: National Academy Press, October 1986), p. 15; Aerospace Safety Advisory Panel, *Annual Report* (Washington, DC: NASA Headquarters, Code Q-1, March 1989), p. iv.

Keeping the "turnaround time," or total shifts required to prepare an orbiter again for launch after a flight, short is essential for reducing the cost per flight and increasing the sustainable flight rate. NASA will have difficulty reaching and sustaining a rate of 14 flights per year unless it is able to find ways of sharply reducing its current turnaround time.[8] Its present goal of 14 flights per year assumes a processing schedule having little margin for contingencies. Yet NASA is not achieving the reductions of turnaround time it had anticipated, especially for the orbiter.[9] In addition, some NASA officials have expressed concern that the planned 90-day standdown for each orbiter every 3 years, to make structural inspections and modifications, may not be sufficient to accomplish all necessary work.

- *Inflexibility.* If NASA were to prove capable of launching 14 Shuttle flights per year, scheduling launches at the maximum sustainable launch rate would leave no margin to accommodate a sudden change in launch plans or to fly extra missions on a surge basis.[10] If more margin were reserved in Shuttle launch schedules, an orbiter could be on hand to be outfitted quickly for an unplanned mission. However, even with more margin, preparing an orbiter for an unscheduled mission, such as a Space Station rescue, could take as long as a few months because of the lead time required for mission planning, orbiter processing, and crew training.[11] **If the Nation wishes to improve the safety of its crew-carrying space flight program while increasing its flexibility, NASA and the Defense Department will have to allow more margin in Shuttle launch schedules (which implies fewer launches per year) and provide alternative ELVs.**
- *Risk of Attrition.* Each time NASA launches the Shuttle it incurs a risk of losing an orbiter from equipment failure or human error. The Shuttle's success rate is 32 out of 33 flights, or 97 percent (table 2-2).[12] Estimates of Shuttle reliability generally vary between 97 and 99 percent. For example, the late Richard Feynman, a member of the Presidential Commission appointed to investigate the *Challenger* accident, called the Shuttle ". . .relatively unsafe. . . . with a chance of failure on the order of a percent."[13] A **NASA contractor estimated that** *post-Challenger* Shuttle reliability lies between 97 and 98.6 percent, with the most likely cause of failures identified as propulsion failures during ascent.[14] One NASA division estimated that on the Galileo mission, which was launched October 1989, the orbiter had a 99.361 percent probability of remaining intact until deployment of the Jupiter-bound Galileo space probe began,[15] yet another NASA division estimated the probability would likely lie between 35 in 36 (97.2 percent) and 167 in 168 (99.4 percent).[16] **If Shuttle reliability is 98 percent, launching Shuttles at the rates now planned would make it unlikely that Space Station assembly could begin before another orbiter is lost (figure 4-l).**

Options for Reducing the Risks of Depending on the Shuttle

- *Reduce the Shuttle flight rate. The* Nation could restrict Shuttle payloads to those requiring human intervention, and fly other payloads on ELVs.

[8]For instance, NASA is designing the Advanced Solid Rocket Motor, which is now under development, to be capable of much quicker assembly than the existing redesigned solid rocket motors.

[9]NASA Kennedy Space Center briefing, Apr. 26, 1989.

[10]When a launch accident or other incident causes a long delay in spacecraft launches, it may become necessary or prudent to fly off any backlog of payloads as quickly as possible after recovery in a "surge" of launches.

[11]Normally, Shuttle crews, payloads, and specific orbiter are chosen up to 2 years prior to a flight, in order to provide enough time fOr payload integration and crew training.

[12]For comparison, success rates experienced by expendable launch vehicles range between 85 and 95 percent (table 2-2).

[13]"Report of the Presidential Commission on the Space Shuttle *Challenger* Accident," app. F. (Washington, DC: U.S. Government Printing Office, 1986); R.P. Feynman, *What Do You Care What Other People Think? (New York, NY:* W.W. Norton & Co., 1988), p. 236.

[14]L-Systems, Inc., *Shuttle/Shuttle-C Operations,* Risks, *and Cost Analyses,* LSYS-88-008 (El Segundo, CA: 1988).

[15]General Electric Astro Space Division, *Final Safety Analysis Report II for the Galileo Mission,* doc. 87 SDS4213 (Valley Forge, PA: General Electric Astro Space Division, August 1988). However, NASA supplied no rationale for its estimates of failure probabilities from which General Electric calculated this probability, and NASA instructions had the effect of masking the overall uncertainty.

[16]NASA Headquarters, Code QS, *Independent Assessment of Shuttle Accident Scenario Probabilities for the Galileo Mission,* vol. 1, April 1989. The probability of orbiter recovery after the Galileo mission would k comparable to the mission success probability, because the most likely causes of a mission failure would probably destroy the orbiter,

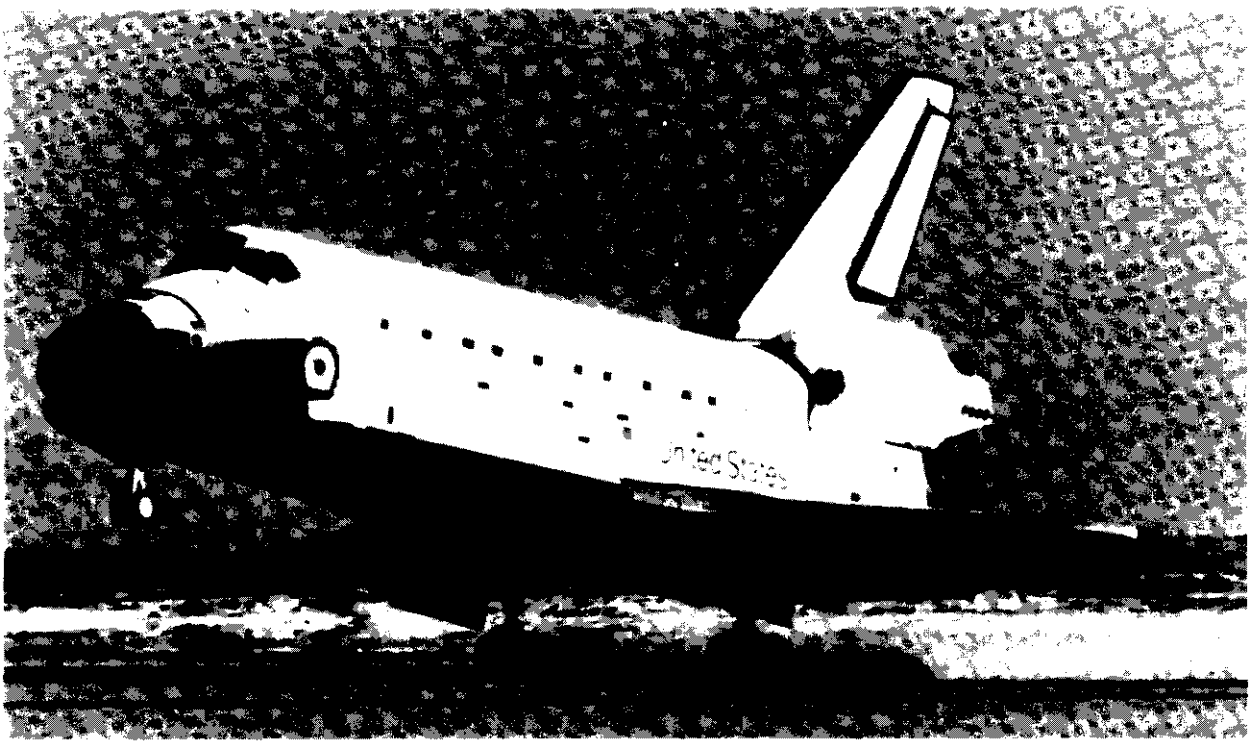


Photo credit: National Aeronautics and Space Administration

Space Shuttle orbiter *Atlantis* lands at Edwards Air Force Base after completing a successful 5-day mission in which astronauts deployed the Galileo planetary spacecraft, destined for Jupiter.

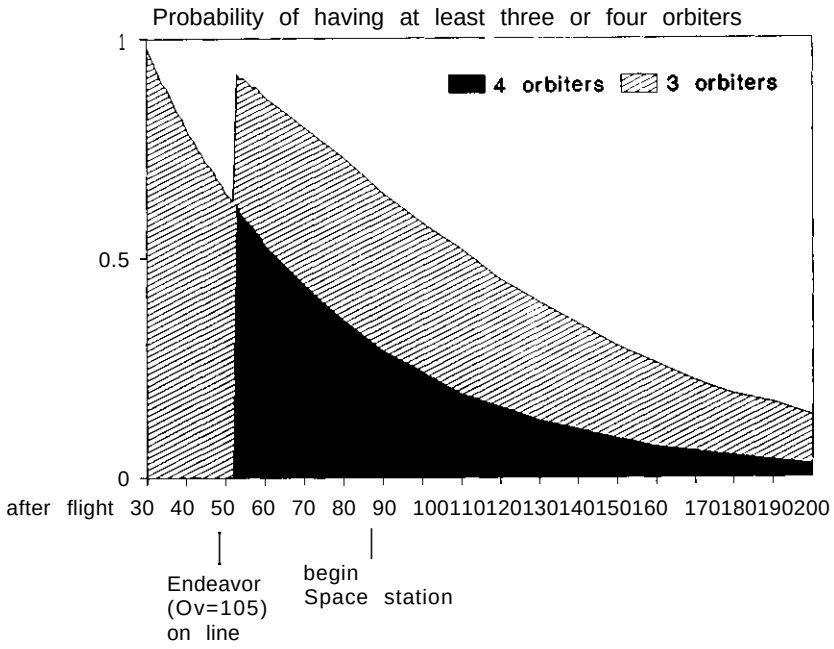
This would reduce the Shuttle flight rate and orbiter attrition. For example, the recently launched Galileo spacecraft, which is destined to explore Jupiter's atmosphere and moons,[17] could have been launched on a Titan III or Titan IV. Except for many materials processing or life science experiments, which require human attention, most payloads could be launched on unpiloted vehicles. The Air Force has now remanifested most of its payloads previously scheduled for the Shuttle on the Titan IV, which made its maiden flight on June 14, 1989.[18]

- *Purchase one or more additional orbiters.* If it is judged more important to have four orbiters available in the mid-1990s than to have high launch rates now, Congress may wish to allow for the potential loss of an orbiter by ordering one or more additional orbiters as soon as possible and limiting Shuttle launch rates.
- *Improve the safety and reliability of Shuttle orbiter.* Purchasing an additional orbiter of the same design as *Endeavour (OV-1O5)*, which is scheduled for delivery in 1991, would not reduce the risks to which Shuttle orbiters, crews, and payloads are now exposed. However, the safety and reliability of the orbiter could be improved (table 4-l). In addition, the orbiter could be modified to remain in orbit longer by adding additional life support equipment, and to carry additional payload by substituting lighter materials in current structures.
- *Improve the reliability of other Shuttle components.* As the *Challenger* loss demonstrated, the safety of the crew may depend critically on the reliability of systems other than the orbiter and on the practices and judgments of personnel. NASA has already improved the design of the solid rocket booster that failed during *Challenger's* last

[17] Launched on Oct. 18, 1989 on the orbiter *Atlantis*. Once Galileo was designed for launch on the Shuttle, changing it to allow launch on an ELV would have been prohibitively expensive.

[18] Considerable additional experience With assembling, processing, and launching Titan IV will be necessary before it will be considered an operational vehicle.

Figure 4-1-Probability of Retaining 3 or 4 Shuttle Orbiters Over Time



Shuttle reliability is uncertain, but has been estimated to range between 97 and 99 percent.[1] If the Shuttle reliability is 98 percent, there would be a 50-50 chance of losing an orbiter within 34 flights. At a rate of 11 flights per year, there would be a 50 percent probability of losing an orbiter in a period of just over 3 years. The probability of maintaining at least three orbiters in the Shuttle fleet declines to less than 50 percent after flight 113.

Although loss of an orbiter would not necessarily result in loss of life, it would severely impede the progress of the civilian space program, as it would likely lead to a long standdown of the orbiter fleet while the cause of the failure as determined and repaired.

[1] L-Systems, Inc., *Shuttle/Shuttle-C Operations, Risks, and Cost Analyses*, LSYS-88-008 (El Segundo, CA: 1988).

SOURCE: Office of Technology Assessment, 1990

ascent and successfully employed the redesigned solid rocket motors (RSRMs) in 8 flights since September 1988. NASA is currently working on an Advanced Solid Rocket Motor (ASRM) that will replace the RSRM. It has also studied the feasibility of replacing the Shuttle's solid rocket motors with Liquid Rocket Boosters (LRBs). NASA's studies indicate that developing Shuttle LRBs might cost about twice as much ($3 billion) as developing ASRMs. Nevertheless, LRBs may be safer than ASRMs because liquid engines can be ignited and checked before lift-off, then shut off if faults appear.[19] If one, or even two, liquid engines were to fail after lift-off, they could be shut down, allowing the Shuttle to land at an alternative landing site. They can even be throttled during launch without incurring loss of life. Although a solid rocket motor could be designed to have its thrust terminated during flight, doing so on the Shuttle would lead to destructive thrust

Table 4-1-Selected Possible Improvements for New Orbiters

Safety end reliability
• Improved propulsion
. Simplified hydraulics
. Increased strength skins
. Improved attitude control
. Suppressed helium overpressure
Cost reductions
• Simplified cooling
• Modernized crew displays
. Improved tile durability
• Modernized telemetry
Performance
• Extended duration orbiter
. Weight reduction
. Local structure strengthening
. Global Positioning Satellite receiver-computer for navigation

SOURCE: Rockwell International Corp. and Office of Technology Assessment, 1990.

[19] Richard DeMeis, "Liquid Lift for the Shuttle," *Aerospace America*, February 1989, pp. 22-25.

imbalance.[20] NASA is currently conducting studies to understand the potential benefits and drawbacks from substituting LRBs for solid rocket motors.

A Shuttle Improvement Program

Making major Shuttle enhancements on an individual project-by-project basis may not be the most efficient way to improve the Shuttle system. To choose one improvement may mean not pursuing another, worthwhile avenue. However, having a versatile, capable launch fleet that provides reliable human access to space will be essential if Congress wishes to maintain a policy of supporting the human presence in space. Hence, **Congress may want to consider an integrated approach to strengthening the Nation's space transportation capability by funding a Shuttle Improvement Program (table 4-2) lasting, for example, 10 years.** Such a program could include development of advanced solid rocket boosters, liquid rocket boosters, and the Shuttle-C, as well as additional, more modest, improvements summarized in box 4-B. To support this sort of program, which could cost as much as $850 million per year for 10 years above the current projected cost of the Shuttle program, would require finding extra space program funding, scaling down the Space Station program, or deferring other programs. In addition to leveling out budgetary requests for the 10-year period of the program, an integrated improvement program could lead to the development of technologies and systems that would be needed for new crew-carrying systems should Congress decide to pursue a more ambitious space program in the future.

SMALL LAUNCH SYSTEMS

Most of the Government's attention has focused on medium- or heavy-lift launch vehicles.[21] However, recent interest in lightweight spacecraft, designed for a range of specialized activities, such as store-forward communications, single-purpose remote sensing, and materials processing research, has generated a concomitant interest in small vehicles to launch them. Launchers of this class are particularly appropriate for private sector development, as the costs and risks are modest compared to higher capacity launch systems. If small payloads prove effective for a wide variety of military and civilian uses, the demand for small launchers could grow substantially .22



Photo credit: Orbital Sciences Corp. and Hercules Corp.

An artist's conception of the Pegasus air-launched vehicle ascending to orbit after being launched from an aircraft.

- *Scout.* Originally developed in the late 1950s and early 1960s, the Scout launcher is capable of carrying about 600 pounds to LEO. Scout is a four-stage vehicle, propelled by solid rocket motors, which is manufactured by the LTV corporation under contract to NASA. As soon as the remaining vehicles have been flown, NASA will retire it from service, unless LTV,

[20] See U.S. Congress, Office of Technology Assessment, Round Trip *to Orbit: Human Spaceflight Alternatives*, OTA-ISC-419 (Washington, DC: U.S. Government Printing Office, August 1989), pp. 45-48 and app. A, for a detailed comparison of solid and liquid engines.

[21] However, the relatively small Atlas-E (1,750 pounds to low-Earth Polar orbit) and Titan 11 (4,200 pounds to low-Earth Polar orbit) launchers, which originally served as intercontinental ballistic missiles, have been used to launch a variety of Government payloads. Neither of these vehicles are available for commercial use or for launching non-Government payloads.

[22] Lawrence H. Stern et. al., *An Assessment of Potential Markets for Small Satellites* (Herndon, VA: Center for Innovative Technology, November 1989); "Lightweight Launches to Low Orbit: Will a Market Develop?" *Space Markers,* Summer 1987, pp. 54-58.

Table 4-2-A Possible Shuttle Improvement Program

Options	cost	Benefit
Orbiter improvements:		
Develop alternate turbopumps for Space Shuttle main engines	$228 million[a]	Safety andeoonomy
Automate orbiter for unpiloted flight	$200 million[b]	Safety
Extend orbiter flight duration	$120 million	Utility
Built-in test equipment[c]	[?]	Safety and economy
Booster improvements:		
Increase thrust of redesigned solid rocket motor (RSRM)	$50 to $60 million	More payload
Continue to develop advanced solid rocket motor (ASRM)	$1.3 to $1.8 billion	Safety and more payload
Develop liquid rocket booster (LRB)	$3.5 billion	Safety and more payload
Other elements:		
Develop lightweight external tank	[?]	More payload
Complementary Vehicles:		
Develop Shuttle-C	$1.5 billion	For cargo
Develop capsule or lifting body for Space Station escape	$0.7 to $2 billion	Safety

[a]Already funded by NASA.
[b]Only $30M to $40M for each additional orbiter.
[c]See OTA-TM-ISC-28, *Reducing Launch Operations Costs.*

NOTE: Most of these options would increase Shuttle payload capability, but by different amounts; their other benefits and their dates of availability would differ. Therefore, two or more options might be pursued, for example, ASRMS to increase Shuttle payload capability and LRBs for increased safety and reduced environmental impact.

SOURCE: Office of Technology Assessment, 1990.

or some other private firm, decides to offer it commercially .23 On a cost per pound basis, Scout offers a relatively expensive way to reach space ($12,000 per pound).

- *Pegasus. The* Lightsat program, initiated by the Defense Advanced Research Projects Agency (DARPA), has created a market for at least one new small launcher, the Pegasus, capable of launching between 600 and 900 pounds to LE0.[24] Pegasus is a three-stage, solid-fuel, inertially guided winged rocket that is launched from a large aircraft. It is the first all-new U.S. launch vehicle design since the 1970s, though it depends heavily on propulsion and systems originally developed for intercontinental ballistic missiles; it uses engines designed for the Midgetman ICBM.

  Pegasus has been developed as a joint venture between Orbital Sciences Corp. (OSC) and Hercules Aerospace Co., and funded entirely with private capital. DARPA negotiated a price of $6 million per launch for a possible six launches. The Air Force has assumed responsibility for the oversight of the launch of Pegasus for Government payloads. To date, two launches have been ordered; the first one, which will carry two payloads, is scheduled for spring 1990.

  A mobile launch system such as Pegasus could provide a survivable means for launching small military satellites in wartime to augment satellites launched in peacetime or replace any satellite damaged by anti-satellite weapons. However, the Department of Defense has not stated a need for a survivable launch capability. The first flights of Pegasus will employ a B-52 as the carrier. OSC plans to acquire a large commercial aircraft, such as a Lockeed L1011, to serve as a launch platform for commercial flights.[25]

- *Industrial Launch Vehicle,* The American Rocket Company (AMROC) is developing a family of suborbital and orbital rockets, called the Industrial Launch Vehicle, powered by a hybrid, solid-fuel/liquid-oxygen engine. AMROC's hybrid design uses liquid oxygen to burn nonexplosive solid propellant similar to tire rubber. Such hybrids would have some safety advantages and might be allowed in areas where conventional solid- or liquid-fuel rockets are not. They could, for example, be used to launch small satellites from mobile

[23]LTV and the Italian corporation SNIA BPD are discussing developing an upgraded Scout H, capable of launching about 1,200 pounds to LEO at a cost of about $15 million per mission.

[24]Joseph Alper, "Riding an Entrepreneurial Rocket to Financial Success," *The Scientist,* July 25, 1988, pp. 7-8.

[25]On a per-pound basis, Pegasus currently costs $6,000 to $10,000 perpound of payload, which is much higher than competing, larger launch systems. However, for some customers, the ability to launch from many different locations and relatively quickly (once the concept has been proven and operational procedures are streamlined) will outweigh the relatively high per pound cost of the Pegasus.

Box 4-B—Maintaining and Improving the Current Shuttle System

Buying Additional Orbiters

Three basic options are available:

- *Build a copy of OV-]05*
  The Challenger replacement (OV-1O5), already being built includes several important improvements:
  -addition of an escape hatch and pole;
  —improved heat shielding tiles, strengthened landing gear, wing structure, and engine pod;
  —more than 200 internal changes, including electrical rewiring and improvements in the braking and steering systems.
- Implement additional *improvements*
  —safety/reliability;
  -cost reduction; and
  —performance.
  (Some of these upgrades may involve structural changes, and therefore could not be made in existing vehicles.)
- Reduce *airframe* weight-Orbiter airframe weight reduction of 8,000 to 10,000 pounds could be achieved through the use of:
  -composite materials;
  —alloys;
  —*intermetallic* alloys; and
  —high-temperature metallics.

Incremental Changes

Some alterations to the Space Shuttle system have already been accomplished, or are already underway:

- *Redesigned Solid Rocket Motors (RSRMs)*
- *Space Shuttle Main Engine Improvements*—Specific efforts directed at longer life and higher reliability include improved:
  —welds;
  —manufacturing techniques;
  -nondestructive testing;
  —heat exchangers;
  --controllers;
  -engine health monitoring; and
  —-turbopumps.
- *On-Board Computer Upgrades-Specific efforts* include:
  —identical computer modules 'mass-produced" for economy,
  --connection by optical fibers, and
  —a high degree of fault-tolerance.

Other improvements NASA has considered or is now working on:

- *Extended Duration Orbiter* (EDO)-NASA is building in the capacity to extend on-orbit stays from the current 7 days to 16-28 days.
- *Automatic Orbiter Kit—An existing* **Shuttle or**biter could be given the capability to fly an entire mission automatically without a crew.
- *Operation Improvements-Introducing* a numb&r of new technologies and management strategies to make Shuttle launch operations more efficient and cheaper, e.g., improved Shuttle tile inspection and repair, and expert systems for control.

Major Changes

Some candidates include:

- *Advanced Solid Rocket Motors (ASRMs)--These* would replace the existing RSRMs. Compared to the RSRMs, they offer:
  —up to 12,000 pounds additional lift capacity,
  --better manufacturing reproducibility,
  —reduced stress on the Space Shuttle Main Engines,
  —potentially higher reliability, and
  —potential for enhancing competition.
- *Improve Redesigned Solid Rocket Motors—l%* existing RSRMs could be improved further by redesigning them to increase their thrust. The Shuttle's payload capacity could be increased by 6,000 to 8,000 pounds by substituting a more energetic solid propellant and by making other requisite changes to the motors.
- *Liquid Rocket Boosters (LRBs)--They* would replace the solid boosters on the Shuttle. Compared to RSRMs, LRBs offer:
  —safer abort modes;
  -up to 20,000 pounds additional lift capacity;
  —long history, potentially greater mission reliability;
  -capability of changing mission profiles more easily;
  —safer Shuttle processing flow;
  —-potential application as an independent launch system; and
  —better environmental compatibility.
- *Materials improvements-'l'he* emphasis on improved materials has focused particularly on saving weight. For example, using aluminum-lithium (A1-Li) for the external tank instead of the present aluminum alloy could provide a 20 to 30 percent weight savings. Using composite materials in the orbiter wings and other parts could save an additional 10,000 pounds.
- *Crew Escape Module—-This* would allow for safe escape over a larger portion of the liftoff regime than now possible. It would replace the escape pole system presently in place, but would be heavier and much more costly.

launchers. AMROC's first attempted launch of its hybrid system on October 5, 1989 was aborted when a liquid oxygen valve failed to provide enough oxygen to support adequate thrust.[26] Significantly, the rocket neither exploded nor released toxic fumes, demonstrating one of the safety features of using hybrid systems. Instead, it burned on the pad, doing relatively little damage to the pad (between $1,000 and $2,000) or to the two payloads it was to carry on a suborbital flight. AMROC has several customers interested in its launch vehicle, but to date has no firm launch contracts.[27]

- *Standard Small Launch Vehicle (SSLV). The* SSLV is being developed by the Defense Advanced Research Projects Agency (DARPA). DARPA recently awarded a contract for purchase of SSLV launch services to Space Data Corp., a division of Orbital Sciences Corp. The first stage of Space Data's Taurus SSLV will be the first stage of an MX missile booster; the three upper stages of this vehicle will be the same solid rocket engines that power the Pegasus. Taurus is designed to carry a 1,500 pound satellite to a 400 nautical mile polar orbit, or a 3,000 pound spacecraft to LEO. It could even be used to launch an 830 pound satellite to geosynchronous transfer orbit.[28] Taurus will be fully transportable and capable of being launched quickly on a few months notice from a variety of launch sites. The first DARPA demonstration launch is scheduled for July 1991. DARPA holds options for four future flights on Taurus.
- *Conestoga.* Space Services Inc. (SSI) is developing a family of launch vehicles called Conestoga, which will use Castor solid rocket motors strapped together indifferent configurations to achieve payload lift capacities of 900 to 2,000 pounds to polar orbit and 1,300 to 5,000 pounds to LEO. Launch services to LEO will cost $10 million to *$20* million, depending on payload size and vehicle configuration. To date, SS1 has no firm orders for launch services on Conestoga, although it has several prospects. SSI successfully launched its Starfire I, the first U.S. commercial sounding rocket on March 29, 1989. However, on November 15, 1989, the second sounding rocket flight failed.
- *EPAC "S" Series.* E'Prime Aerospace Corp. (EPAC) is developing a series of ELVs propelled by rocket motors developed for the MX. EPAC is offering seven different launch vehicle configurations capable of placing payloads of up to 36,000 pounds in LEO. Prices charged commercial customers will range from $18 million (for 5,781 pounds to LEO) to $84 million (for 36,138 pounds to LEO). Government prices would be lower.[29] It plans to make its first orbital launch of the S-1 in 1991.

Other companies, both large established firms and smaller, startup companies, have offered small launch vehicle designs in the launch services market. Lockheed Missiles and Space Co. has designed a launch vehicle that would use Poseidon Fleet ballistic missile components to carry 850 pounds to polar orbit or 1,200 pounds to LEO. Pacific American Launch Services, Inc., is working on the design of a single-stage, liquid oxygen-hydrogen launcher that would carry 2,200 pounds to LEO.

In addition to these U.S. examples, several foreign firms are offering to sell launch services on small launchers. For example, a consortium in northern Europe is developing a small, solid rocket-powered launcher named LittleLeo. The Soviet Union has suggested converting some of its SS-20 mobile missiles for use as small commercial launchers.[30]

The market created by DARPA made possible the development of Pegasus and Taurus. At this time, it is unclear whether private sector demand for small spacecraft will be sufficient to support a truly commerical launch market for small launchers. However, several aerospace companies, including Orbital Sciences Corp., Hughes Aircraft Corp., and Ball Aerospace Co. are working on designs for small satellites for communications and remote sensing, which will test market potential over the next few

[26]The liquid oxygen valve failed to open sufficiently, probably as a result of heavy icing m the relatively humid climate of Vandenberg Air Force Base where the test launch was attempted. Michael A. Dornheim, "Amroc Retains Key Personnel Despite Cutbacks After Pad Fire, ''Aviation *Week and Space Technology*, Oct. 30, 1989, p. 20.

[27]James Bennett, AMROC, December 1989.

[28]"Pegasus, MX Boosters Combined for New Defense Launch Vehicle," *Aviation Week and Space Technology,* Sept. 18, 1989, pp. 47-48.

[29]Bob Davis, EPAC, Mar. 12, 1990.

[30]Marketed in the United States by Space Commerce Corporation.

years. The construction of non-Federal launch sites would assist the process of developing a market for small spacecraft and launchers.[31] Groups in the States of Florida, Hawaii, and Virginia have shown considerable interest in constructing launch sites for the private market.

Military demand for small launchers may be substantial, as some elements in the services are interested in developing small spacecraft for tactical surveillance and communciations. SDIO may have a near-term requirement for launching small spacecraft to support ballistic missile defense. Although the cost per pound of payload carried on small launchers is currently high, a large market for small launchers may help to bring costs down over time. However, private companies will have to amortize their development costs, which will tend to keep launch costs per pound of payload relatively high compared to larger systems for which the development costs were borne by the government years ago.

[31] However, additional launch sites might reduce the market for Pegasus by increasing availability of alternate launch sites.

Chapter 5

Space Transportation and the Space Station

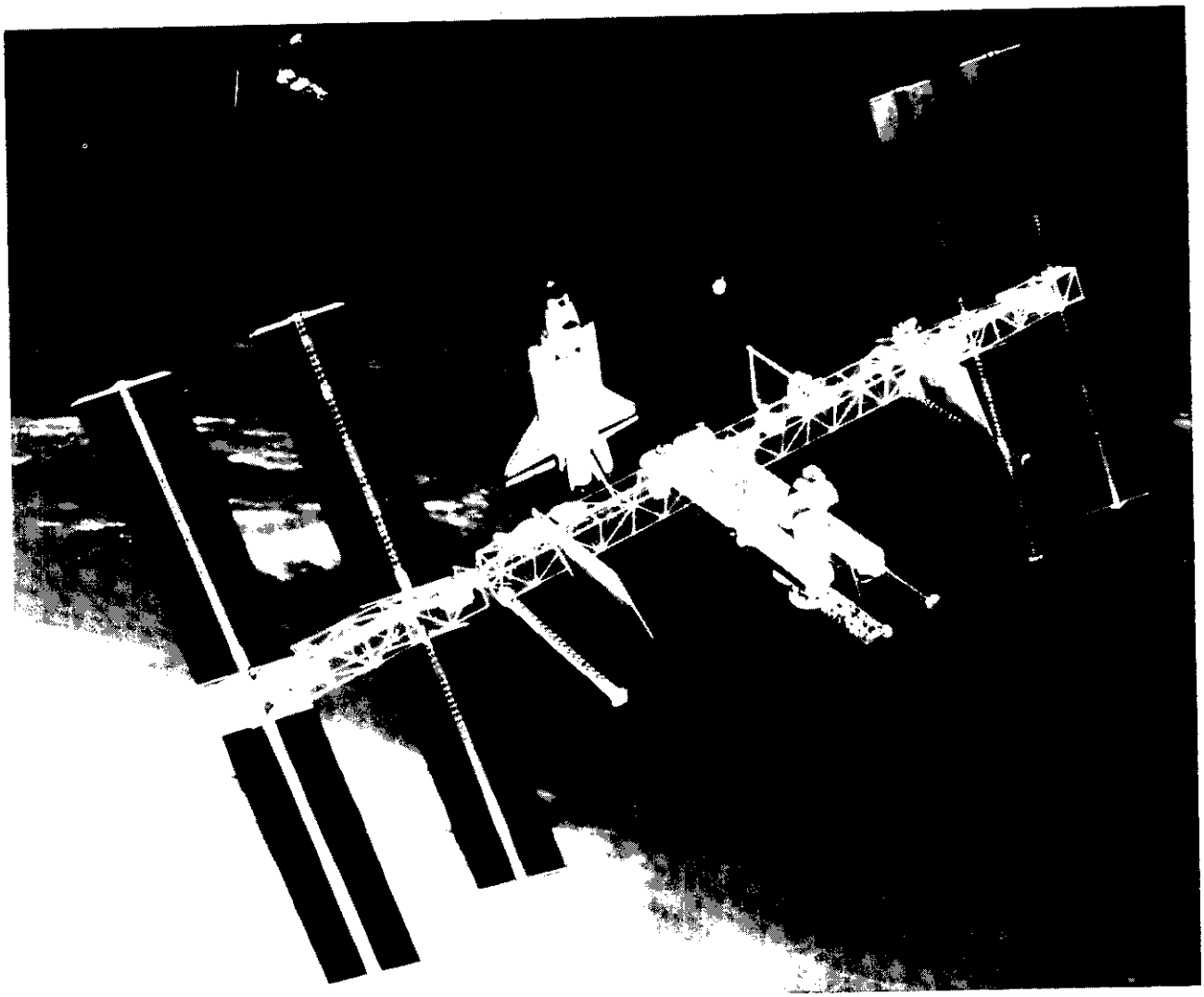


Photo credit' National Aeronautics and Space Administration

An artist's conception of Space Station *Freedom,* which is scheduled for completion by the end of the century.

Box 5-A-Escape Vehicles

Several contingencies could require emergency escape of personnel in space. These include medical emergencies of Space Station crewmembers, major equipment failures, damage from orbital debris, etc. Escape **could also be necessary if the Shuttle failed to meet its scheduled launch date by so long a time that the Station risked running out of critical supplies.**

Crew Emergency Return Vehicles (CERV)

NASA is considering two types of vehicles for emergency return from space to Earth:

- Capsule—This simple vehicle would have an ablative heat shield reminiscent of reentry capsules from the early days of spaceflight, and still used routinely by the Soviet Union. A capsule, which could closely resemble the Apollo capsule, would descend by parachute and land in the ocean. Its advantages include simplicity, relatively low cost, and proven technology, In addition, capsules need little or no piloting, which could be a major consideration if pilots are unavailable or unable to function as a result of injury or a long stay in orbit. Depending on its capability, a capsule could cost $0.75 billion to $1.0 billion to develop.
- Small Glider-A small, aerodynamically stable vehicle whose shape would provide lift and could land by parachute or at low speed on a runway. A glider could reach a wider range of landing sites and have more opportunities for reentry and recovery (particularly for a version with landing gear), and a softer ride than capsules (important if an injured crew member is returning). However, a glider would cost 20 to 50 percent more than the simplest parachute version of a capsule.

ingly, even eagerly, accept such duty despite the inherent risks of spaceflight. Although they should not expect to be exposed to unnecessary risks, their duty will never be risk free.

A rescue system, if built, would be needed for the life of the Space Station. Therefore, its total operating costs can be expected to exceed its development costs. **Before committing to a specific rescue strategy, system designers will have to address the costs of developing the necessary support infrastructure, which might include ground operations hardware and personnel at the mission control site, landing site crews, and the necessary subsystems and logistics support to resupply, replenish, and repair a rescue vehicle on orbit.**

The NASP program is also evaluating the potential for using an operational aerospace plane for Space Station crew rotation and rescue. Using an aerospace plane for rescue would provide two primary advantages: 1) there would be no need to build and support a dedicated vehicle and its associated infrastructure and personnel; and 2) it could be based on Earth, rather than in space, making it easier and cheaper to maintain. However, NASA expects to complete Phase I of the Space Station before 2000, and an operational aerospace plane could not be ready before it does so. Hence, an aerospace plane could not serve to replace or rescue crew from the Space Station until 2005 or later, if at all.

The planned international Space Station will make long-term demands on space transportation for construction, servicing, supply, and possibly emergency crew return. Current NASA plans call for making at least 29 Shuttle flights (including several logistics flights) between 1995 and 1999 to build the station, and about 5.5 flights per year thereafter to operate it. Some flights will be required to rotate station crew, some for delivering or returning cargo.

SPACE SHUTTLE

Uncertainty about the adequacy of the current Shuttle fleet for constructing and servicing the Space Station makes station planning uncertain and risky. Deployment, servicing, and resupply of the Space Station face the dual risks of delayed launch schedules and loss of one or more orbiters. In addition, losing a critical element of the Space Station in transit to orbit as a result of a Shuttle failure could lead to long delays in Space Station constructional

Chapter 4 outlined options for reducing the risk of using the Shuttle for Space Station construction and operation. However, most of these options would require additional funding beyond NASA's projected budget for Space Station or for space transportation. **Congress may wish to postpone Space Station construction and operation and focus on improving the Nation% ability to place crews in orbit safely and reliably. Alternatively, Congress could direct NASA to fly fewer non-Space Station-related Shuttle missions in order to reduce the risk that a Shuttle would be lost before Space Station construction is completed.**

NASA might, for example, plan to use Titan IVs to carry some Space Station elements into orbit rather than risking the Shuttle to do so. However, the availability of Titan IV is highly uncertain, as the Air Force appears to need all the Titan IVs it has purchased for the period of station construction. NASA might also develop the Shuttle-C for Space Station construction. Furthermore, as noted earlier, science payloads now tentatively manifested for the Shuttle, if properly designed, could be flown on ELVs purchased competitively from the private sector.

RESCUE OR ESCAPE VEHICLES

Crews living and working in the planned Space Station could be exposed to substantial risk from major failures of the Station or the Space Shuttle that transports the crew. For example, orbital debris from previous space activities could puncture one of the crew modules, causing a need to evacuate the crew and return them to Earth.* NASA is attempting to reduce such risk by building safety features into the Space Station and improving the Shuttle's design. Nevertheless, many analysts in NASA and the broader U.S. space community believe that the United States should develop some means independent of the Shuttle to rescue crews from the Space Station.

NASA is studying the possibility of building a specialized vehicle that could be launched into space atop an expendable launch vehicle as well as return from the Space Station (box 5-A). Such a vehicle, which NASA calls the Assured Crew Return Vehicle (ACRV),[3] could be used to provide:

1. crew emergency rescue,
2. access to space by crews,
3. small logistics transport, and
4. on-orbit maneuver.

Emergency rescue vehicles could be developed and launched on a Titan III or Titan IV by 1995 or 1996. Alternatively, a Shuttle could carry two at a time, to be docked at the Space Station.

To decide whether a risk-reducing effort is worth the investment required, Congress must be advised about how much the investment would reduce the risk. Even if an alternate crew return capability were provided and worked as planned, it would not eliminate all risks to station crewmembers. To gain perspective on the decision, Congress may wish to weigh the risks with and

[1]If a Space Station element for which there was no spare were lost, replacing that element would take many months.

[2]In 1983, a paint chip from a space object severely damaged a windshield on the Shuttle orbiter *Challenger*. Nicholas L. Johnson and Darren S. McKnight, *Artificial Space Debris* (Malabar, Florida: Orbit Book Company, 1987), pp. 4-5.

[3]Note, however, that although the ACRV may provide a high probability of return from space, it does not necessarily provide assured safe return, as there will still be a non-negligible degree of risk connected with the vehicle and the procedures required to operate it properly.

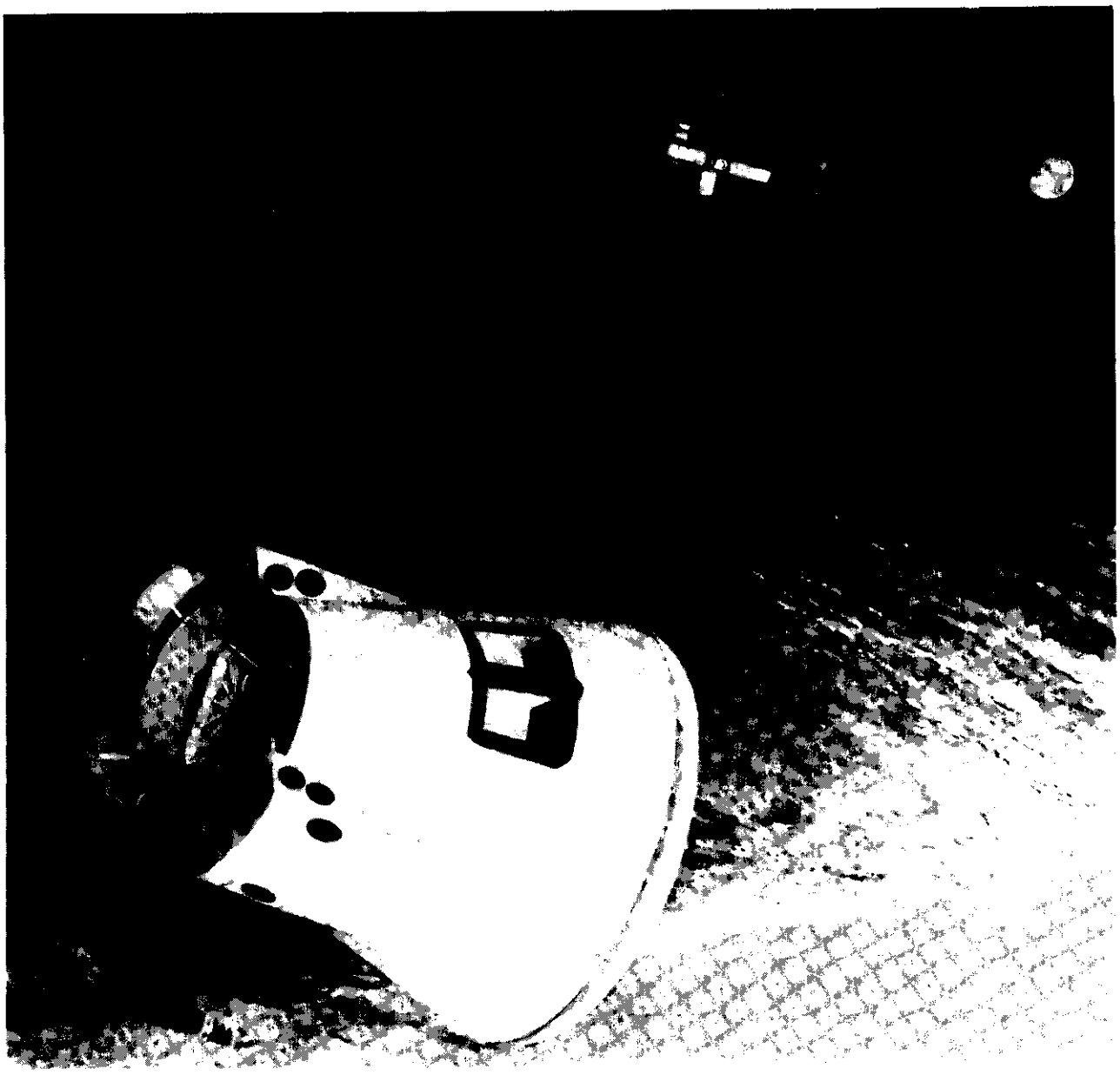


Photo credit: ***National Aeronautics and Space Administration***

Artist's conception of an Apollo-type emergency rescue vehicle entering the Earth's atmosphere after leaving the Space Station.

without a rescue vehicle against the risks of other hazardous duty in the national interest.[4]

A risk assessment of the Space Station should take into account all phases of the crews' experience in space. For example, if the greatest risk to Space Station crewmembers were experienced during flight to orbit, it may prove more cost-effective to improve the safety of the Shuttle or any later crew-carrying space transportation systems than to build a crew escape craft. **The use of a rescue system would itself expose Space Station crewmembers to a certain element of risk, which must also be assessed before making any decision about whether or not to build such a system.** Finally, it would be well to remember that the Space Station crew will be volunteers, who would will-

[4]For example, working on off-shore oil platforms, or piloting experimental aircraft.

Chapter 6

Reducing Space System Costs

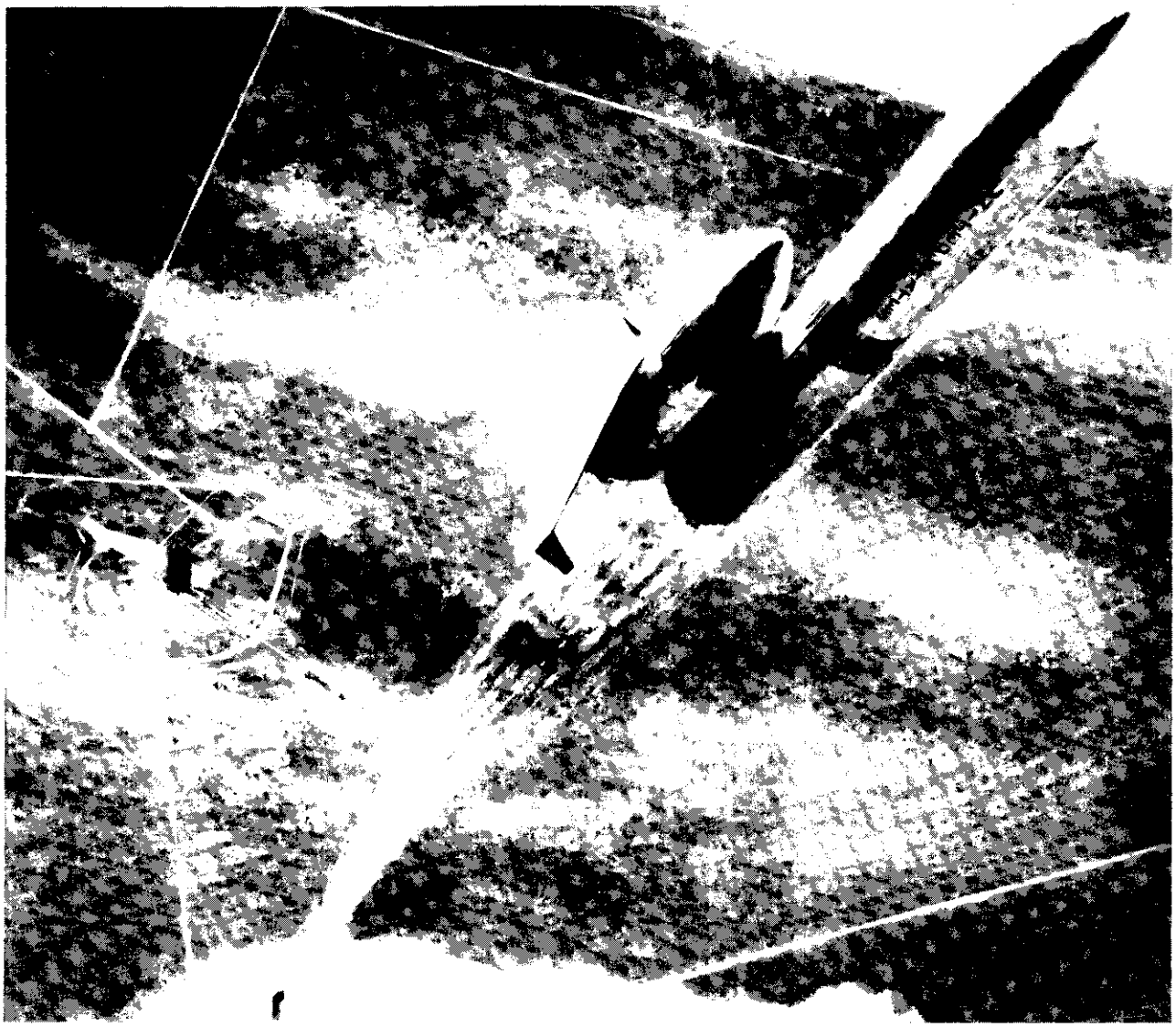


Photo credit: *General Dynamics Corp.*

Artist's conception of an Advanced Launch System launch vehicle

Reducing the cost of exploring and using the space environment is crucial to the continued development and exploitation of outer space. America's wish list for projects in outer space far exceeds its ability to pay, given the many pressures on the Federal budget. Launch costs currently range from $3,000 to $12,000 per pound to reach low Earth orbit (LEO), depending on payload weight and the launch system employed. Launching communications satellites into geosynchronous transfer orbit costs between $11,000 and $20,000 per pound. If these costs could be reduced significantly, outer space would be more attractive to potential users, both within Government and in the private sector. However, for many spacecraft, space transportation costs are relatively small compared to the costs of designing and building the spacecraft. Hence, reducing spacecraft costs plays an essential part in bringing down overall space program costs.

SPACE TRANSPORTATION

New technologies promise to make the process of manufacture, assembly, and processing of launch vehicles less expensive (table 6-l). The Advanced Launch System (ALS) program, for example, is exploring a wide variety of technologies that could be employed to reduce space transportation costs.[1] However, **for these technologies to be effective, new management practices must be introduced (table 6-2). Launch operations, for example, tend to be highly labor-intensive, and comprise a significant percentage of the cost of a launch.** As the example of the Delta 180 experiment for the Strategic Defense Initiative Office demonstrated, sharply reducing the burden of oversight and review in a project, and delegating authority to those closest to the technical problems, can result in meeting a tight launch schedule and reducing overall costs.[2] In addition, launch system designs that reduce the number and complexity of tasks requiring human involvement would also contribute to reducing costs (table 6-3). The ALS program is also assessing various management and organizational techniques that would speed launch processing and reduce its complexity. It has incorporated some of the features of the so-called Big Dumb Booster concept (box 6-A) in its planning, viz., the concept of designing a launch system to achieve minimum cost, rather than maximum performance.

Purchasing launch services competitively from private firms, rather than managing launches from within NASA or the armed services might well save money. The intent of purchasing launch services is to remove the Government as much as possible from setting detailed engineering specifications for the launch system and to reduce the burden of excessive oversight by Government managers. Several entrepreneurial launch vehicle firms are developing new launch systems for small or medium-size payloads (see *Small Launch Systems* in ch. 4). These projects present opportunities to incorporate low-

Table 6-1--Cost-Saving Technologies for Launch Systems

. Automated manufacturing processes
• Advanced, lightweight materials
• Automated data management system
. Automated test and inspection
. Automated launch vehicle and payload handling
. Modular subsystems
• Database management systems
. Computer-aided software development
. Expert systems

SOURCE: Office of Technology Assessment, 1990.

Table 6-2-Cost-Reducing Strategies

. Reduce documentation and oversight
. Create better incentives for lowering costs
. Provide adequate spares to reduce cannibalization of parts
. Develop and use computerized management information systems
. Use an improved integrate/transfer/launch philosophy[a]

[a]The integrate/transfer/launch (ITL) philosophy refers to the practice of separating categories of launch operations procedures to make each more efficient.

SOURCE: Office of Technology Assessment, 1990.

Table 6-3-Launch System Design Strategies

. Engage all major segments of launch team in launch system design process
. Design for simplicity of operation as well as performance
. Design for accessibility and modularity

SOURCE: Office of Technology Assessment, 1990.

[1]U.S. Congress, Office of Technology *Assessment, Reducing Launch Operations Costs New Technologies and practices,* OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988) for a detailed discussion of these points.

[2]Department of Defense Strategic Defense Initiative Office/Kinetic Energy Office> "Delta 180 Final Report," vol. 5, March 1987.

Box 6-A--The Big Dumb Booster Concept[1]

Some launch system analysts believe that a "Big Dumb Booster"[2] using modern technology could markedly reduce space transportation costs. Other analysts disagree. Current U.S. expendable launch vehicles (ELVs) are derived from 1960s intercontinental ballistic missile designs that used high-performance engines and lightweight structures in order to minimize launch vehicle weight and maximize payload and range. Launch system designers gave relatively little priority to reducing launch costs.

The genesis of the Big Dumb Booster debate derives from analysis done in the 1960s that indicated that launch vehicles could be designed to minimize manufacturing and operational costs by making them larger or heavier. Launch vehicles designed to achieve sharply reduced costs would be very different from today's launch vehicles. For example, according to this concept, the first stages of a rocket should be relatively unsophisticated, and heavier hardware produced at lower unit costs by relaxing manufacturing tolerances should replace expensive, state-of-the-art, lightweight hardware.

Although in the late 1960s several aerospace companies performed systems studies on minimum-cost launch vehicles, and the Government tested some demonstration pressure-fed engines, no systematic, thorough analysis of the overall life-cycle costs[3] of such a booster has been done. The Big Dumb Booster concept remains controversial. Supporters of the concept argue that it still has considerable merit and that it is not too late for the United States to adopt this rocket design philosophy. Opponents maintain that time and improved technology have passed it by.

Specific **designs that might have been the minimum-cost solution two decades ago are certainly not today% minimum-coat design. Technology has advanced since the early Big Dumb Booster studies, significantly altering potential trade-offs among cost performance, and weight.** Objective evaluation of the Big Dumb Booster concept would require systematic analysis, with attention to engineering details and costs. It would also involve some hardware development and testing. If a Big Dumb Booster study is done, it should be carried out as a systems study that integrates specific hardware choices with the entire system, including the launch facilities, logistics, launch and support. It should also include estimates of the demand expected for such a booster, as future demand would have a marked effect on program life-cycle costs. Such a study might also include consideration of recovery and reuse.[4] A Big Dumb Booster concept study might cost between $5 million and $10 million, depending on its scope. If Congress decides that the Big Dumb Booster requires more focused evaluation, it could task NASA or the Air Force to carry out such studies.

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[1]U.S. Congress, Office of Technology Assessment, *Big Dumb Boosters: A Low-Cost Space Transportation Option? Background Paper* (Washington, DC: International Security and Commerce Program, 1989).

[2]The term Big Dumb Booster has been applied to a wide variety of concepts for low-cost launch vehicles, especially those that would use "low technology" approaches to engines and propellant tanks in the booster stage. As used in this report, it refers to launch systems designed for minimum cost by using simplified subsystems where appropriate.

[3]Life-cycle costs include not only the costs of manufacturing the launch vehicle, but also the costs of ground operations and launch facilities, developing and testing. It also includes the discounting of all these costs to reflect opportunity costs and inflation.

[4]For example, the Naval Research Laboratory is now exploring a reusable sea-launched booster that would use a pressurized liquid propellant,

SOURCE: Office of Technology Assessment, 1990.

cost approaches at little direct[3] cost to the Government. 'However, launch firms complain that the cost of continued excessive government oversight and complicated procurement regulations unnecessarily raises the costs of launch services. They argue that the cost of government oversight far exceeds the actual cost risk of a failed mission. Launch firms suggest that the government role, which may be vital during the development and demonstration phases of a new, complicated technology, becomes counterproductive when the basic technology has been successfully acquired and is needed for ongoing operations. Then, matters of cost and reliability become paramount. However, Government users

[3]Private development will result in some indirect costs to the Government. However, if these firms are operating within a competitive market, the eventual cost to the Government should be lower than if the Government paid for the improvements directly.

[4]For a detailed discussion of the DoD acquisition system, especially rules and oversight, see U.S. Congress, Office of Technology Assessment, *Holding the Edge: Maintaining the Defense Technology Base*, OTA-ISC-420 (Washington, DC: U.S. Government Printing Office, April 1989), especially ch. 8.

may fear that boosters not built to government specifications might be too unreliable, especially for one-of-a-kind spacecraft.

Current space policy provides for the civilian agencies to "encourage, to the maximum extent feasible, a domestic commercial launch industry by contracting for necessary ELV launch services directly from the private sector or with DoD."[5] Extending this policy to all Government launches, both civilian and military, except those on the Space Shuttle, could also save the Government money, but only if Government oversight and paperwork were reduced.

The Federal Government might encourage the private sector launch industry by issuing space transportation vouchers to space scientists whose experiments are being supported by the government.[6] These vouchers could be redeemed for transportation on any appropriate U.S. launch vehicle, and would free scientists to choose the vehicle they thought most suitable to the needs of the spacecraft. This policy would free space scientists from dependence on the Shuttle and its schedule. It might also increase opportunities for researchers to reach space. By reducing scientist's dependence on the Shuttle, such a policy should help in raising the demand for ELVs and in bringing down the cost of space transportation.

PAYLOADS

Dramatic reductions in launch costs will not, by themselves, lower spacecraft program costs substantially, because it may cost from $40,000 to $650,000 per pound to design and build many payloads,[7] while it costs only about $3,000 **per pound to launch one to LEO.** Reducing launch costs to $300 per pound, a goal of the ALS program,[8] may reduce the total cost of procuring and launching an expensive spacecraft by less than 2 percent. Commercial communications satellites, however, often cost on the order of $10,000 per pound. Because they need to be placed in geosynchronous orbit, which is more expensive to achieve than LEO, the cost of a launch is comparable to the cost of the payload. Therefore, commercial operators are extremely interested in cost reductions in both areas.

To reduce payload costs, and for other reasons, novel approaches to payload design and fabrication have been proposed:

- *Provide for Weight Margin:* Designing payloads to fit launch vehicles while reserving ample size and weight margins can reduce the risk of incurring delay and expense after assembly has begun.

  Satellites often grow substantially heavier than expected as they proceed from design to construction. If a payload grows so heavy that its weight equals or exceeds the maximum allowable gross lift-off weight, the payload must be redesigned, which causes delay and increases cost. To reduce the risk of exceeding vehicle payload capacity, program managers could require designers to allow extra weight margin for such contingencies. However, this design philosophy would lead to more stringent size and weight constraints than would otherwise be imposed. In many cases, sufficient margin could be provided by clever design, e.g., by designing several smaller single-mission payloads, to be launched separately, instead of a single multimission payload.[9]
- *Fatsats:* If payloads were allowed to be heavier for the same capability, some could cost substantially less. For example, OTA estimates that Titan-class payloads that cost several hundred million dollars might cost about $130 million less if allowed to be five times as heavy. If payloads were allowed to be much heavier, a manufacturer could forego expensive processes for removing inessential structural material, as well as expensive analyses and tests. Standardized subsystems, which could be produced economically in quantity, could be used instead of customized subsystems. Designers could also add redundant subsystems to increase

[5]White House, Office of the press Secretary, "National Space Policy," Nov. 2, 1989, p. 11.

[6]Molly Macauley, "Launch Vouchers for Space Science Research," *Space Policy*, vol. 5, No. 4, pp. 311-320.

[7]The low end of this range is for payloads consisting mostly of fuel; the high end would be for some satellites carrying little or no fuel. U.S. Congress, Office of Technology Assessment, *Affordable Spacecraft: Design and Launch Alternatives—Background Paper*, OTA-BP-ISC-60 (Washington, DC: U.S. Government Printing Office, January 1990).

[8]101 stat. 1067.

[9]The number of new program starts allowed in a year tends to force program managers to add additional capabilities to the spacecraft. In addition, in some cases, a larger spacecraft bus can accommodate more functions at a reduced cost per function compared to multiple smaller buses.

reliability. An accurate estimate of potential savings requires a detailed trade-off analysis for each payload. Achieving these savings will probably require giving spacecraft program managers, and those who establish mission and spacecraft requirements, incentives crafted specifically for the purpose, and may require developing new launch vehicles.

- *Lightsats:* If allowed to be less capable, reliable, or long-lived, payloads could be both lighter and less expensive. Useful functions such as communications and weather surveillance could be performed by payloads small enough to be launched on small rockets from airborne or mobile launchers.

  Small, simple, and relatively inexpensive civil and military satellites have been, and still are, launched at relatively low cost on small launch vehicles or at even lower cost, sometimes for free, as "piggyback" payloads on larger launch vehicles. DoD is considering whether the increased survivability and responsiveness such spacecraft could provide would compensate for possible decreased capability. A swarm of several small satellites might accomplish a given mission as well as a single large one, and, in many cases, would also be cheaper because smaller satellites typically cost much less per pound than do large ones. Even if the satellites are launched individually, which would increase total launch cost, overall mission cost could be lower.

- *Microspacecraft:* Spacecraft weighing only a few pounds could perform useful space science missions and might be uniquely economical for experiments requiring simultaneous measurements (e.g., of solar wind) at many widely separated points about the Earth, another planet, or the Sun.

Each type of spacecraft-fatsat, lightsat, or microspacecraft--would impose unique launch demands. New, large, heavy-lift launch vehicles would be needed to launch the heaviest satellites. Lightsats could be launched on existing launch vehicles, but new, smaller launch vehicles might launch them more economically. In wartime, small launch vehicles could be transported or launched by trucks or aircraft to provide a survivable means of space launch. Microspacecraft could be launched on existing launch vehicles, but they might eventually be launched by more exotic means such as a ram accelerator, railgun, coilgun, or laser-powered rocket (see ch. 7). Within the next decade, experiments now being planned may establish the feasibility of some of these launch systems. Their costs cannot be estimated confidently until feasibility is proven. However, they may prove more economical than conventional rockets for launching microspacecraft at high rates.

If Congress wishes to promote spacecraft cost reduction and, thereby, reduce the cost of space programs:

1. Congress could order a comprehensive study of how much the Nation could save on space programs by:

   - designing payloads to reserve more weight and volume margin on a launch vehicle;
   - allowing payloads to be heavier, less capable, shorter-lived, or less reliable;
   - designing standard subsystems and buses for use in a variety of spacecraft;
   - designing spacecraft to perform single rather than multiple missions; and
   - using several inexpensive satellites instead of a single expensive one.

Lockheed completed such a study in 1972;[10] a new one should consider current mission needs and technology. It would complement the Space Transportation Architecture Study (STAS) and more recent and ongoing studies[11] that compare space transportation options but not payload design options.

As noted above, to estimate potential savings accurately, a detailed trade-off analysis must be done for each payload, or more generally, for each mission. So, for greater credibility,

2. Congress could require selected spacecraft programs-for example, those that might require a new launch vehicle to be developed-to award two design contracts, one to a contractor who would

[10] Lockheed Missiles & Space co., *Impact of Low Cost Refurbishable and Standard Spacecraft Upon Future NASA Space programs,* N72-27913 (Springfield, VA: National Technical Information Service, Apr. 30, 1972).

[11] E.g., the Air Force's Air Force-Focused STAS, NASA's Next Manned Space Transportation System study, the Defense Science Board's National Space Launch Strategy study, and the Space Transportation Comparison study for the National Aero-Space Plane Program.

consider the unconventional approaches mentioned above.

3. Congress could require both the Department of Defense and NASA to refrain from developing a spacecraft if the expected weight or size of the spacecraft, together with its propellants, upper stage, and support equipment, would exceed some fraction of the maximum weight or size that its intended launch vehicle can accommodate. Public Law 100-456 requires the Department of Defense to require at least 15 percent weight margin in fiscal year 1989.[12] New legislation could extend this restriction to NASA and could require size margins in future years.

In addition, Congress could promote the development of launch systems capable of launching small, inexpensive spacecraft at low cost or heavy spacecraft with generous weight margins.

INNOVATION AND THE U.S. TECHNOLOGY BASE

Building a new system, or even making substantial modifications to existing launchers, requires a vigorous private sector, well-supported research programs, a cadre of well-trained engineers, and an institutional structure capable of putting a vast variety of technologies to use in innovative ways. According to several recent reports, our existing space technology base has become inadequate in recent years.[13] Yet a strong technology base is an investment in the future; it provides insurance that the United States will be able to meet future technological challenges.

Government Programs

Several studies have recommended greater attention to improving the Nation's technology base for space transportation.[14] Though specific proposals differ in detail, these studies have cited propulsion, space power, materials, structures, and information systems as areas in need of special attention.

In response to these and other expressed concerns, NASA and the Air Force have initiated four programs to improve the Nation's launch system technology base (box 6-B). As currently organized, these programs are directed primarily toward developing new, advanced capabilities. **In the existing budgetary climate, it may be more realistic to redirect funding toward technologies that could be used to improve existing launch systems and make them more cost-effective to operate.** Each of the three ALS prime contractors are exploring ways to insert technology conceived in the ALS program into existing launch systems.

Although launch operations and logistics are labor-intensive and therefore expensive compared to manufacturing or materials, launch system designers have focused little attention on technologies that would reduce these costs. NASA's technology programs are addressing issues in automation and robotics, technology areas that could significantly reduce launch operations costs. However, to date NASA has spent relatively little on applying these technologies more effectively to Shuttle launch operations. In the yearly budget process, when budgets are cut, technology programs tend to be cut more sharply than operational programs because they focus on future efforts, rather than near-term results. Launch operations is the direct focus of about 30 percent of the ALS program. Outside of this effort, however, no well-organized or well-funded plan exists to *apply the* technologies developed in these programs to launch operations procedures, or to coordinate research being carried out through the existing technology R&D programs.

It may be appropriate to institute a long-term National Strategic Launch Technology Plan that would set the agenda for developing and incorporating new technologies into existing and future launch systems. It should include work in all development phases:

- broad technology exploration (basic research);
- focused research leading to a demonstration; and
- implementation to support specific applications.

Even if specific applications have not been identified, the United States needs to fund basic and

[12] See S. Rept. 100-326, p. 36, and H. Rept. 100-989, p. 282.

[13] National Research Council, Aeronautics and Space Engineering Board, *Space Technology to Meet Future Needs* (Washington, DC: National Academy Press, December 1987); Joint DoD/NASA Steering Group, National Space *Transportation and Support Study*, Summary Report, May 14, 1986,

[14] Ibid.

Box 6-B--Technology ***Development Programs***

- *Advanced Launch System* **(ALS)** *Focused Technology Program*—A joint program **between NASA and the Air Force, carried out as an integral part of the ALS Demonstration/Validation Program. Its aim is to pursue research on specific technologies of interest to the development of an ALS. The program's contribution to crew-carrying capabilities will be limited, but important. As much as possible, ALS program managers have deliberately targeted their research at generic space transportation issues, in order to develop a broad technology base for designing an ALS. The ALS program plans to spend most of its fiscal year 1991 budget of $125.3 million on focused technology development.**
- ***Civil Space Technology Initiative*—A NASA program designed to revitalize "the Nation's civil space technology** capabilities and **enable more efficient, reliable, and less costly space transportation and Earth orbit operations. Funding for fiscal year 1990 is $123.8 million (1991 request-$ 171.0 million).**
- *National Aero-Space Plane*—**A DoD/NASA program to develop an aerospace plane capable of reaching orbit** with a single propulsion stage. Although this program does not have the specific focus of improving the Nation's technology base, some of the technology under development necessary for building the NASP, particularly new materials and structures, new propulsion techniques, new computational techniques, and methods of handling liquid and slush hydrogen, will find application elsewhere. The NASP Joint Program Office is spending $150 million over a 30-month period on materials development alone.
- *Pathfinder-A* NASA program especially directed at technologies for future human space exploration. Very few of this program's technologies will be usdful for Earth-to-orbit transportation, as it is directed primarily toward cm-mbit and interplanetary transportation and life-support issues. Congress appropriated $26.9 million for Pathfinder in fiscal year 1990. The Administration has requested $179.4 million-a 567 percent incease--in fiscal year 1991 to prepare for lunar and Martian exploration.

[1]National Aeronautics and Space Administration, Office of Aeronautics and Space Technology, "CSTI Overview," April 19$8.

SOURCE: Office of Technology Assessment, 1990.

focused research in order to build an adequate base for future applications.

The Private Sector's Role

In space transportation, the private sector now serves primarily as contractor for Government-defined needs. It is just beginning to act as a commercial service provider.[15] Two firms launched their first commercial payloads in 1989.[16]

Private firms are unlikely to develop major new launch systems until well into the next century unless Congress and the Administration set a high priority on involving them more directly in setting the terms of space transportation development.[17] The Government controls access to space[18] and most of the technology. It will continue to determine launch specifications and provide most of the funding. Government control of systems involving crews in space will continue, in large part because such systems are costly and represent a major national commitment.

Harnessing industry's innovative power in a more competitive environment could lead to reduced launch costs and more effective use of U.S. resources for outer space. By promoting private sector innovation toward improving the design, manufacture, and operations of launch systerns, the Government could reduce the cost of Government launches, yet relatively few incentives to involve private firms exist today. As a result, firms have spent little of their own money on R&D

[15]The Department of Transportation regulates the private launch industry.

[16]McDonnell Douglas (Delta) and Martin Marietta (Titan)

[17]The NASP program, for example, has sent a high priority on directly involving private firms and the universities in materials and other advanced research on the X-30.

[18]According to the 1967 *Treaty on Outer Space,* which the United States signed, and to which it adheres, "States parties to the Treaty shall bear international responsibility for national activities in outer space . . . whether such activities arc carried on by governmental agencies or by non-governmental entities. . ." The *Commercial Space Launch Act of 2984,* which sets out the basic provisions regulating the commercial launch industry, recognizes this responsibility by stating,". . . the United States should regulate such launches and services in order to ensure compliance with international obligations of the United States . . ."

to improve the capability of launch systems or reduce their costs.

If outer space becomes a more important arena for private investment, competitive pressures will provide the incentives for launch system innovation. For the near term, however, incentives must come from the Government because projected future demand for commercial launch services is extremely small compared to Government demand.[19]

Incentives could include:

- direct grants to develop new technology for launch systems specifically directed toward saving costs rather than increasing performance;
- cash incentives to firms for reducing the manufacturing costs of specific items procured by the Government;[20]
- encouragement of industrial teaming arrangements in focused technology areas such as the National Aerospace Plane Materials Consortium (see ch. 7).

In addition, the U.S. Government could stimulate the private sector's innovative creativity by issuing a request for proposal for launch systems or services similar to the Advanced Launch System, and have industry bid for them. Such an approach assumes minimum Government oversight over the design and manufacturing processes. It would also require the aerospace community to assume much greater financial risk than it has taken on in the past. In order to offset that risk, the Government might have to agree to a minimum purchase that would allow the companies involved to earn a profit on their investment

Finally, America's ability to foster the innovative process depends directly on having an adequate supply of scientists and engineers. In order to assure that the United States has sufficient trained personnel to contribute to the development of new launch systems and other space activities, the Government could strengthen its support for science, mathematics, and engineering education from grade school through graduate school.[21]

[19]Richard Brackeen, *Space Challenge'88: Fourth Annual Space Symposium Proceedings Report* (Colorado Springs, CO: U.S. Space Foundation 1988), pp. 76-79,

[20]For example, Rockwell International earns 20% of every dollar it saves NASA on building orbiter OV-105.

[21]U.S. Congress, Office of Technology Assessment, *Educating Scientists and Engineers Grade School to Graduate School, OTA-SET-377* (Washington, DC: U.S. Government Printing Office, June 1988).

Chapter 7

Potential Future Launch Systems

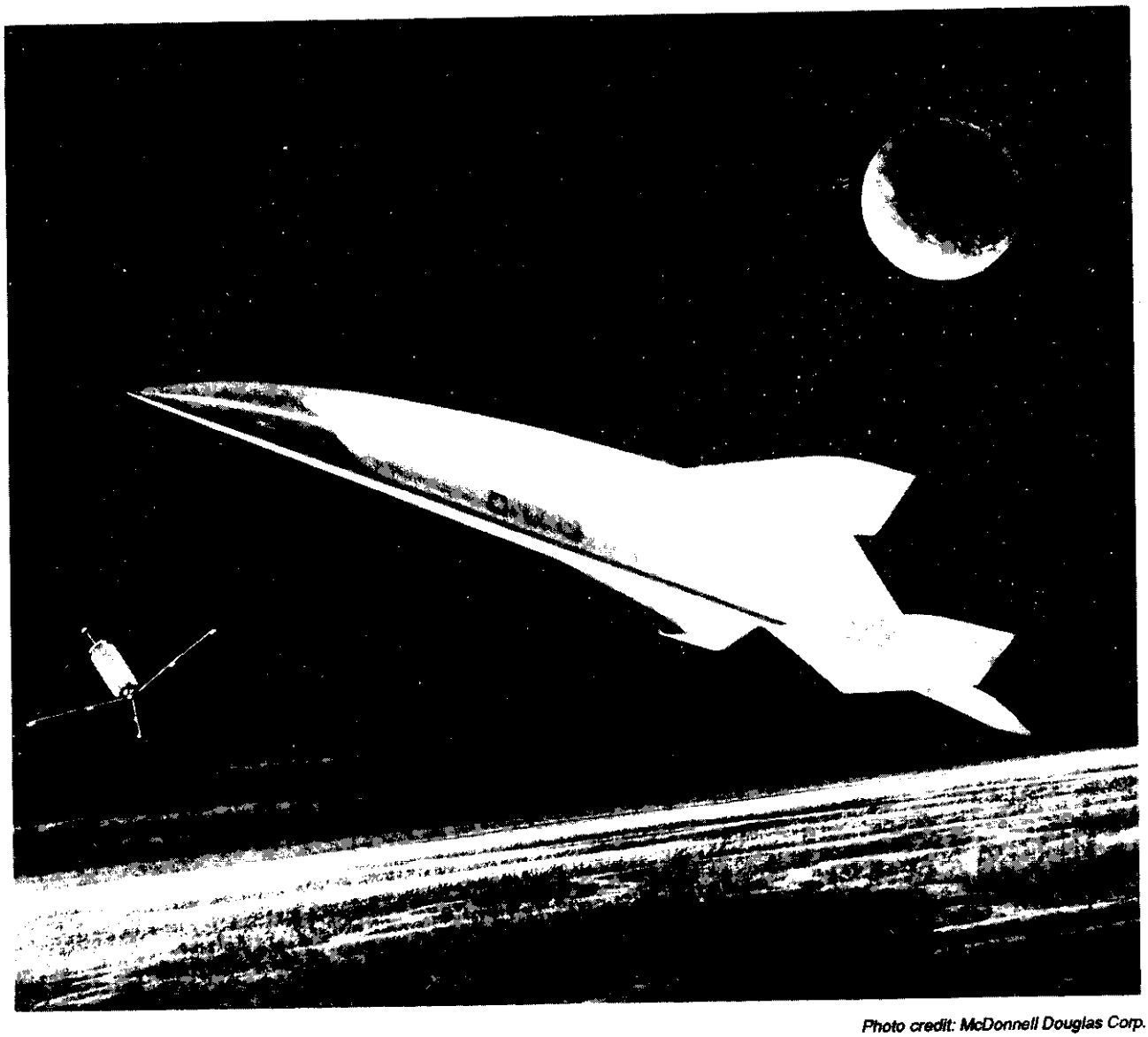


Photo credit: McDonnell Douglas Corp.

Artist's conception of an X-30 aerospace plane

Chapter 7
Potential Future Launch Systems

The Space Transportation Architecture Study (STAS)[1] and later studies conducted by NASA and the Air Force identified a wide range of technologies and management practices that could reduce the costs of space transportation and also increase reliability and operability. This chapter describes several options for meeting future space transportation demand.

CARGO ONLY

The Nation's existing fleet of expendable launch vehicles (ELVs) can carry payloads weighing up to 39,000 pounds (figure l-l) to low Earth orbit (LEO). Eventually, as cargoes gradually increase in size and weight, and as the Nation seeks to do more in space than it currently plans, new launch systems offering higher lift capacity will become attractive, if they can reduce costs while improving reliability and operability.

Some have argued that the Nation needs a heavy-lift launch vehicle (HLLV), similar in capacity to the Soviet *Energia*,[2] which can lift about 220,000 pounds to LEO. Indeed, for tasks requiring the launch of many pounds of cargo to space at one time in a single package, an HLLV would be necessary. If available, an HLLV would be useful for building large space structures, such as the Space Station, because launching pre-assembled structures would obviate much risky and expensive on-orbit assembly.

Some also argue that if the United States had an HLLV, the Government and the private sector would find a way to use it, for example, in bringing down launch and payload costs. OTA's analysis of future space transportation costs indicates that average cost *per pound* can be reduced substantially only if there is a marked increase in demand—that is, the number of pounds launched per year. Unless the Nation plans to increase investment in space activities significantly over current levels, development of an HLLV in order to reduce launch costs appears unwarranted.

Box 7-A—Potential Uses for Shuttle-C

- *Space Station Support--Shuttle-C* could reduce both the number of launches required to assemble the planned Space Station and the extravehicular work in space required to assemble and outfit the station.
- Science *and Applications* Payloads-Shuttle-C could launch large, heavy platforms for missions to planet Earth, and for the planetary sciences, astrophysics, and life sciences disciplines. If launched on the Shuttle, equivalent platforms might require on-orbit assembly by human crews.
- *Technology Test Bed* --Shtttde-C could be used to test new or modified systems, such as liquid rocket boosters, or new engines.
- *National security Applications* --Shuttle-C could place large payloads into polar orbit from Cape Canaveral, and Vandenberg Air Force Base.[1] It could place large payloads into retrograde orbits from Vandenberg Air Force Base.

[1]If the Shuttle launch complex (SLC-6) at Vandenberg AFB were reactivated.

SOURCE: Adapted from NASA Marshall Space Center, ''Shuttle-C Users Conference, Executive Summary," May 1989.

As noted earlier, if the Nation were to pursue the goals of building a permanent settlement on the Moon and/or sending explorers to Mars, one or more HLLVs would be required to carry the requisite fuel and other support infrastructure to LEO (box 7-A).[3]

Shuttle-C

NASA has investigated the potential for building a cargo-only HLLV, which would use Shuttle elements and technology. As envisioned by NASA, Shuttle-C could launch between 94,000 and 155,000 pounds to low Earth orbit (figure 7-1).[4] Such a system could lift large, heavy payloads if the risk or cost of using the Shuttle would be high as a result of

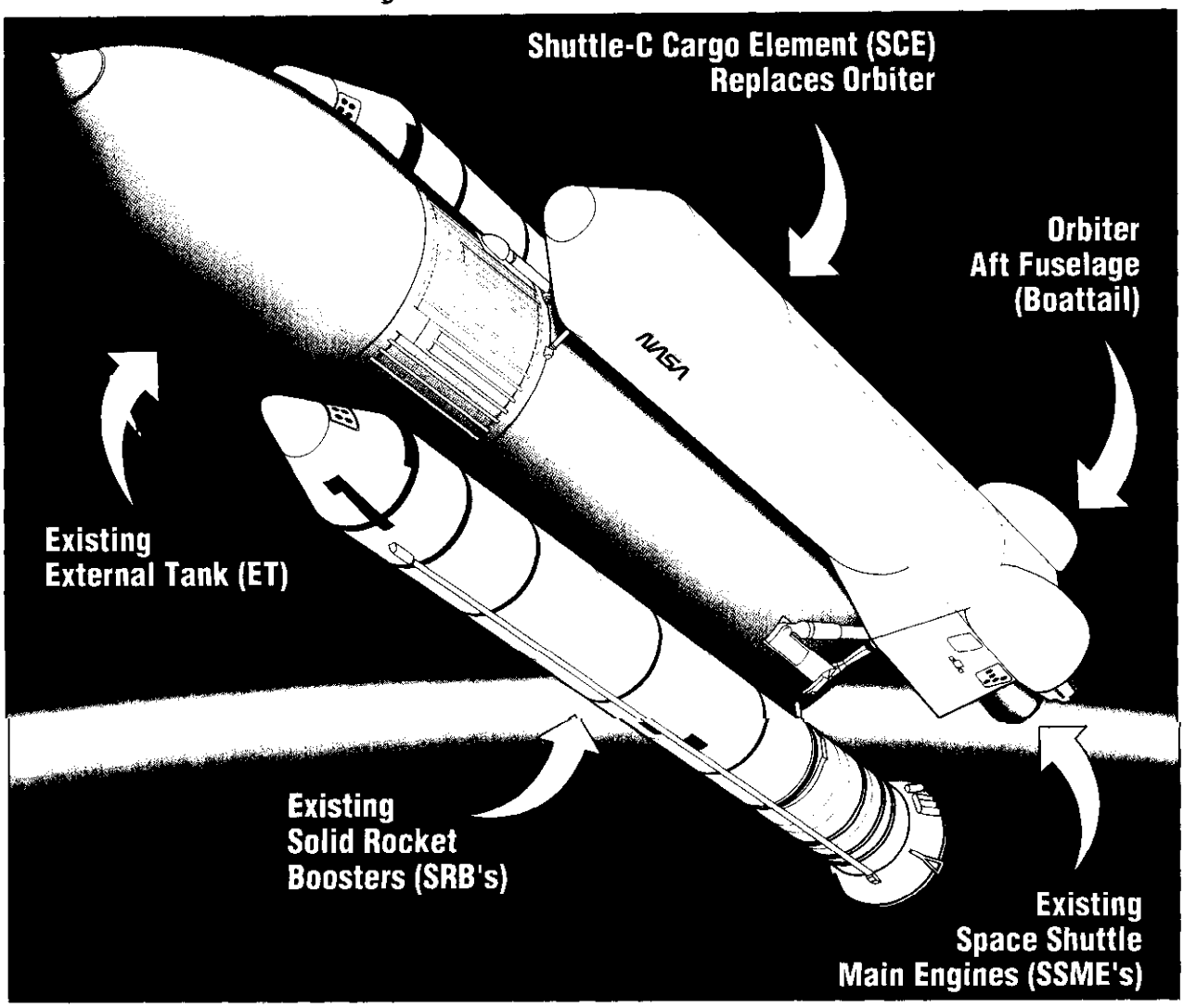
[1]U.S. Department of Defense and National Aeronautics and Space Administration, *National Space Transportation and Support St@ 1995-2010*, Summary Report of the Joint Steering Group, May 1986.

[2]The *Energia* can carry either cargo or the Soviet Shuttle into space, *Energia* may be used to lift elements of a new Soviet space station.

[3]Richard Truly, "Testimon, before th, Subcommittee on Space Sciences and Applications of the House Committee on Science, Space, and Technology, Sept. 26, 1989; National Aeronautics and Space Administration, *Report of the 90-Day Study on Human Exploration of the Moon & Mars*, November 1990.

[4]Shuttle is currently capable of lifting 52,()(XI pounds to 110 nautical miles above Kennedy Space Center.

Figure 7-1—Potential Shuttle-C Performance



Shuttle-C Ascent Performance Capability (lb)

		ETR				WTR
		220 nmi 28.5 deg.	110 nmi 28.5 deg.	110 nmi 98.7 deg.	30x200nmi 28.5 deg.	110 nmi 98.7 deg.
BASELINE DESIGN	2 SSME @ 100%	82,750	93,700-	n/a	105,900	57,460
	@ 104%	88,180	99,100	n/a	112,40	62,800
	3 SSME @ 100%	141,300	151,100	53,200	162,900	111,000
	@ 104%	145,200	155,000	57,200	167,400	115,100
BASELINE + ASRM	2 SSME @ 104%	99,620	110,540	13,900	124,400	74,300
	3SSME @ I04%	156,600	166,500	68,600	179,400	126,400

KEY: ETR = Eastern Test Range (Cape Canaveral); WTR = Western Test Range (Vandenberg Air Force Base)
SOURCE: National Aeronantics & Space Administration, 1989.

"orbital assembly or multiple Shuttle launches."[5] For example, it could enable the launch of large elements of the planned Space Station, already outfitted, reducing the risks that are associated with extensive on-orbit assembly using the Shuttle, or the Shuttle plus smaller ELVs (box 7-A).

Because the Shuttle-C would use most of the subsystems already proven on the Shuttle, NASA asserts that the Shuttle-C would cost about $1.8 billion to develop and could be ready for the first flight about 4 years after development begins. NASA planners suggest that it would serve to "bridge the gap" in launch services for large payloads between the mid-1990s and the beginning of the 21st century when an Advanced Launch System (ALS) could be available.[6]

Shuttle-C would avoid some costs by using Shuttle facilities and subsystems. For example, each Shuttle-C would use and expend two or three Space Shuttle Main Engines (SSMEs), but it could use SSMEs that had been used on the Shuttle until permitted only one more use by safety rules; these would be almost completely depreciated. However, Shuttle-C planners now propose to use SSMEs that have been used on the Shuttle only once; they would cost the Shuttle-C program $20 million each if they can be procured for $25 million each (versus $38 million currently) and refurbished for $15 million (fiscal year 1991 dollars), and if half the cost of two flights is allocated to Shuttle-C. In this case, the incremental cost per launch would be about 480 million fiscal year 1991 dollars[7] for a 3-engine Shuttle-C.[8]

Advanced Launch System (ALS)

In 1987 the Air Force and NASA began preliminary work on the (ALS), with the goals of dramatically reducing launch costs and improving vehicle reliability and operability. ALS program officials expect the ALS efforts to result in a modular family of cargo vehicles that would provide a broad range of payload capacity (figure 7-2). The ALS program estimates that development would cost about $7.3 billion (1989 dollars), and facilities would cost about $4 billion.

The ALS approach is to trade launch vehicle performance efficiency for low cost and high reliability by incorporating design and operating margins, and using redundant subsystems that are highly fault-tolerant. In addition, ALS designs would simplify and standardize interfaces, manufacturing processes, and operations procedures. New technologies would be developed and used only if they would further the goals of low cost and high reliability. ALS managers expect these approaches to improve the operability of the ALS compared to existing launch systems, by providing:

- high availability and reliability;
- high throughput and on-time performance; and
- standard vehicle-cargo operations

The ALS Program Office has defined a reference vehicle using liquid propulsion and capable of lifting between 80,000 and 120,000 pounds to LEO. It would use low-cost, 580,000-pound thrust engines that would be developed specifically for the ALS. The ALS program is also exploring the possible use of solid rockets for strap-on boosters.

Recent] y, the Department of Defense decided not to proceed with procurement of an ALS at this time, but to continue the program as a technology development effort. The primary thrust of the restructured ALS program would be to develop a new engine and other critical technologies for an ALS family of vehicles that could be started later in the decade if the need for such vehicles arises. The technology and subsystems developed for the ALS technology development program could provide the basis for building an HLLV system, if needed, in the early part of the 21st century. In the meantime, the program could provide important improvements for existing ELVs (table 7-l).

[5]NASA Marshall Space Center, "Shuttle-C Users Conference, Executive Summary," May 1989.

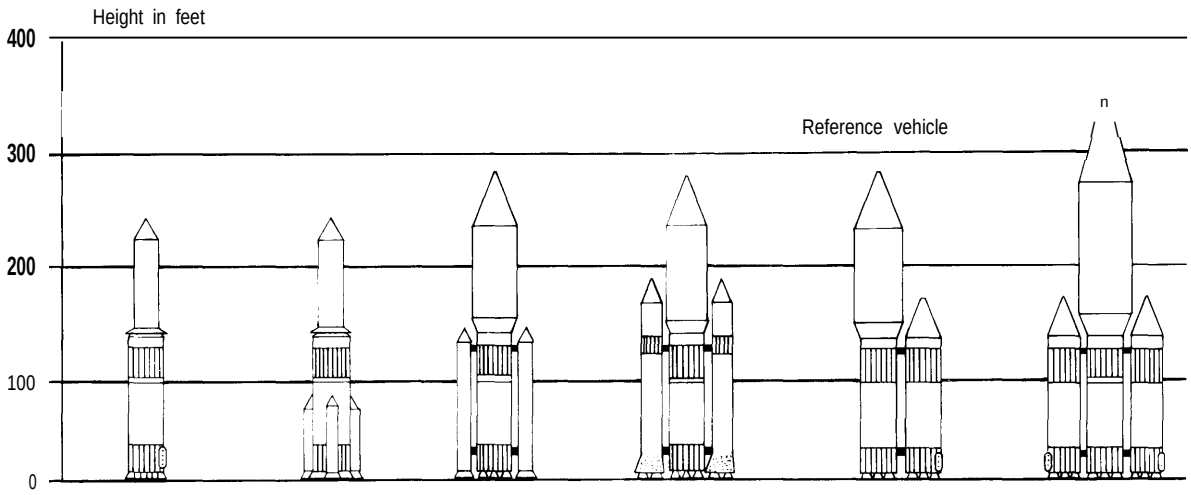
[6]Ibid.

[7]About 424 million fiscal year 1989 dollars.

[8]The other half of the cost should be allocated to Shuttle operations. OTA's cost estimates for Shuttle assume 10 or more uses per SSME. See U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide*, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988), p. 68, footnote 5.

[9]ALS Program Office briefing to OTA, September 1989.

Figure 7-2—Advanced Launch System: The ALS Famiiy



Payload (thousands of lbs)	40 to 80	40 to 80	80 to 110	100 to 251	80 to 120	120 to 300
Booster:						
Type	Stage & half	ALS-SRM	SRMU	STS LRB	ALS LRB	ALS LRB
Propellant	L 0_2/ L H_2	Clean solid	Clean solid	L o_2/ L H_2	L 0_2/ L H_2	L 0_2/ L H_2
Number	N/A	3 to 8	2 to 4	2 to 6	1	2 to 4

KEY: ALS . Advanced Launch System; LRB = Liquid Rocket Booster; SRM = Solid Rocket Motor, SRMU = Solid Rocket Motor Unit; STS = Space Transportation System.

SOURCE: Advanced Launch System Program Office.

Unconventional Launch Systems

A number of launch systems have been proposed that would use "exotic" technologies to propel payloads into space. For example, a payload might ride to orbit on a plastic cylinder, the bottom of which is heated from below by the beam from a powerful ground-based laser. As the plastic on the bottom decomposes into vapor and expands, it will exert pressure on the cylinder, producing thrust. The SDIO estimates development and construction of a laser for launching 44-pound payloads would require about $550 million over 5 or 6 years. It estimates that a laser system could launch up to 100 payloads per day—more than 20 Shuttle loads per year-for about $200 per pound, assuming propulsive efficiencies 300 percent greater than those achieved in lab tests. The cost would be closer to $500 per pound if efficiency is not improved.

Railgun proponents predict a prototype railgun capable of launching 1,100-pound projectiles carrying 550 pounds of payload could be developed in about 9 years for between $900 million and $6 billion, including $500 million to $5 billion for development of projectiles and tracking technology. If produced and launched at a rate of 10,000 per year, the projectiles (less payload) might cost between $500 and $30,000 per pound (estimates differ). The cost of launching them might be as low as $20 per pound -—i.e., $40 per pound of payload.[10]

Several other gun-like launchers have been proposed. One is the ram cannon (or ram accelerator), the barrel of which would be filled with gaseous fuel and oxidizer. The projectile would fly through this mixture, which would be ignited by the shock wave of the passing projectile and would exert pressure on it, accelerating it. A ram cannon designed for space launch would be about 2 miles long.

Many uses have been proposed for such launch systems, but to date only the Strategic Defense Initiative Organization has identified a plausible

[10]Note, however, that such rates are more than 100 times the current launch rate.

Table 7-l—Potential ALS Technology Improvements to Existing Systems

Propulsion
- Simplified engine designs
- Low cost manufacturing processes
- Low cost, dean solid propellants
- Automated nondestructive testing for solid rocket motors
- Enhanced liquid propulsion performance

Avionics and software
- Highly reliable avionics
- Weather and mission adaptive guidance, navigation, and control
- Expert systems for vehicle/mission management
- Automated software production
- Electromechanical actuators

Aerothermodynamica
- Engine and avionics reuse
  - recovery
  - landing
  - maintenance
  - reentry systems

Structures, materials, and manufacturing
- Low weight materials for propellants
- Composite structures for shroud and innertank
- Low cost manufacturing
  - automation: welding
  - processes: spinning, casting, extrusion, forging

Operations
- Automated checkout and launch operations
- Paperless management
- Expert system monitoring and control
- Engine and avionics health monitoring
- Operational subsystems
  - pyrotechnic alternatives
  - hazardous gas detection
  - remote cable transducer

SOURCE: Advanced Launch System Program Office,

demand for high-rate launches of microspacecraft, which could use such systems economically. However, demand for launches of scientific, commercial, and other microspacecraft could increase, perhaps dramatically, if launch costs could be reduced to a few hundred dollars per pound.

Most of these exotic launch technologies are still in the exploratory stage and therefore much less mature than rocket technology. Because of this, the costs cited must be regarded as highly speculative. Nevertheless, Congress may wish to fund continued research in order not to foreclose the opportunity exotics may pose for reducing future launch costs, especially for extremely small payloads such as the microspacecraft discussed in chapter *6--Reducing Space Space System Costs.*

CREW-CARRYING LAUNCH SYSTEMS

Even if the Shuttle is made more reliable, the Shuttle% high operational costs will eventually lead to a decision to replace it with a successor capable of more effectively fitting the needs of the Government's activities for people in space and reducing the recurring cost of launching piloted vehicles. The most important goal of each Shuttle mission is to return the reusable orbiter and crew safely to Earth.[11] This goal, an essential aspect of flying human crews and an expensive reusable vehicle, nevertheless adds to mission costs by requiring additional attention to payload integration, extra payload safety systems, and additional preflight payload handling. In addition, humans require special environments not needed by many payloads.

For the 1990s, the primary need for transporting people to and from outer space will be to operate the Shuttle orbiters and experiments aboard them, and to assemble and operate the Space Station. NASA now estimates that Phase I Space Station construction will require 29 Shuttle flights (including some logistics flights) and about 5.5 flights per year thereafter to service Space Station. If the Nation decides to build a lunar base or to send a crew-carrying mission to Mars, NASA estimates that additional crew-carrying capacity would be needed to supplement or replace the Shuttle.

NASA is studying several launch concepts that could supplement or replace the current Shuttle. Most could not be available before the turn of the century. NASA and the Air Force are collaborating on the development of an aerospace plane using advanced, airbreathing engines that could revolutionize spaceflight. However, even if development were pushed, an aerospace plane based on airbreathing technology is unlikely to be available for operational before 2005.

PERSONNEL CARRIER LAUNCHED ON UNPILOTED LAUNCH VEHICLES

NASA is exploring the possibility of developing a personnel launch system (PLS) that would use a

[11] Returning the orbiter and crew safely is not necessarily equivalent to completing the mission, although it is often confused with the same. NASA will abort the mission rather than knowingly risk crew safety, if problems appear. Launching payloads on unpiloted vehicles avoids the added complexity and cost provided by the human factor.

small reusable glider, capsule, or lifting body launched atop an expendable launch vehicle rated to carry crews.[12] This option would separate human transport from cargo delivery, and could, in principle, be made safer than the Shuttle. The Soviet Union,[13] The European Space Agency,[14] and Japan[15] have all adopted this approach to placing people in orbit. Candidate launchers could include a Titan III, a Titan IV, a Shuttle-C, or perhaps a new, as-yet undeveloped launcher such as the ALS.

The ALS Joint Program Office has recognized the potential benefit of having a flexible launch vehicle rated for launching crews. It has therefore required that contractor proposals for an ALS provide for a launch vehicle capable of meeting both the design and quality assurance criteria for carrying crews. Designing an ALS launch vehicle at the outset to provide additional structural strength would be much less expensive than redesigning, rebuilding, and retesting it after it is developed. 'b As currently envisioned, ALS would also provide previously unobtainable levels of safety by incorporating fault-tolerant subsystems and engine-out capability.

Having a crew-rated automated launcher in addition to a Shuttle has three strong advantages: 1) the crew-rated vehicle could launch new orbiters designed for launch with other boosters; 2) it could enhance crew safety (intact abort is a design requirement for the PLS); and 3) there may be cases where it will be necessary only to deliver personnel to the Space Station. In that case, there is no need to risk a Shuttle orbiter. Separation of crew- and cargo-carrying capabilities is especially important, as carrying both on the same vehicle adds to the payload costs and may reduce crew safety, **In view of the concerns over Shuttle fleet attrition, it may be important for NASA to investigate the potential for using a crew-rated ALS or other launcher to reduce the risk of losing crew-carrying capacity early in the next century.**

Advanced Manned Launch System (AMLS)

NASA's program investigating the set of concepts for an AMLS, previously called the Shuttle II, is studying new designs with the goal of replacing the Space Shuttle early in the next century. A vehicle significantly different from the existing Shuttle would result (box 7-B). If activities involving crews in space increase markedly in the next century, an AMLS using advanced technology might be needed. It could offer significant improvements in operational flexibility and reduced operations costs over the existing Shuttle. However, development, testing, and procurement of an AMLS fleet could cost $20 billion or more (1989 dollars).

The timing of the development phase for an AMLS should depend on NASA'S need to replace the Shuttle fleet. It would also depend in part on progress reached with technologies being explored in the Advanced Launch System and National Aero-Space Plane (NASP) programs. In any event, a decision on AMLS will not have to be made for several more years. For example, if Congress decided that an operational **AMLS was** needed by 2010, the decision to start the early phases of development would have to be made by about 1995. By that time, Congress should have had adequate opportunity to assess the progress made in the NASP program (see below), which could be competitive with an AMLS.

An Aerospace Plane

Developing a reusable vehicle that could be operated like an airplane from conventional runways, but fly to Earth orbit powered by a single propulsion stage would provide a radically different approach to space launch and a major step in U.S. launch capability. However, building such a vehicle poses a much larger technical challenge than building a two-stage, rocket-propelled vehicle such as the AMLS. A successful aerospace plane might also provide greater benefits to industry and to U.S. technological competitive-

[12] A NASA or Air Force launch vehicle is said to be crew, or "man-rated," if it has been certified as meeting certain safety criteria. These include design criteria as well as quality assurance criteria.

[13] Although the Soviet Union has also developed a shuttle orbiter similar to the U.S. Space Shuttle, it will continue to rely on its *Soyuz* vehicle fOr transporting people to the *Mir* space station atop the Proton launcher, and on its *Progress* transport for launching cargo.

[14] The reusable, piloted *Hermes* spaceplane will b, launched atop an Ariane V launcher sometime in the late 1990s. Ariane V is currently also under development.

[15] Japan plans to develop a small, unpiloted spaceplane, HOPE, that would be launched atop its H 11 launch vehicle, now under development. HOPE may experience its first flight in the early years of the next century.

[16] It would, however, add a small amount to the cost of each flight in which cargo only were carried.

Box 7-B—The Advanced Manned Launch System (AMLS)

The goal of the NASA AMLS program is to define advanced manned launch system concepts, including their development, system and operational characteristics, and technology requirements. A vehicle significantly different from the existing Shuttle would result. NASA is presently evaluating five concepts:

- an expendable in-line two-stage booster with a reusable piloted glider;
- a partially reusable vehicle with a glider atop a core stage;
- a partially reusable drop-tank vehicle similar to the fully reusable concept below but with expendable side-mounted drop tanks;
- a fully reusable rocket with a piloted orbiter parallel-mounted (side-by-side) to an unpiloted glideback booster;
- a two-stage horizontal takeoff and landing air-breather/rocket, which would be fully reusable.

Critical technology needs for all AMLS concepts include:

- light-weight primary structures,
- reusable cryogenic propellant tanks,
- low-maintenance thermal protection systems,
- reusable, low-cost hydrogen propulsion,
- electromechanical actuators,
- fault tolerant/self-test subsystems, and
- autonomous flight operations.

SOURCE: National Aeronautics and Space Administration.

Box 7-C-The National Aero-Space Plane Program (NASP)

NASP is a program to build the X-30, an experimental, hydrogen-fueled, piloted aerospace plane capable of taking off and landing horizontally and reaching Earth orbit with a single propulsiom stage. The design of the X-30 would incorporate advanced propulsion, materials, avionics, and control systems and make unprecedented use of supercomputers as a design aid and complement to ground test facilities. NASP is a technically risky program that, if successful, could spur the development of a revolutionary class of reusable, rapid turn-around hypersonic flight vehicles, that would be propelled primarily by air-breathing "scramjet" engines.

Operational follow-ons to the X-30: An aerospace plane derived from NASP technology offers the promise of dramatically reduced launch costs if the vehicle can truly be operated like an airplane using standard runways, with minimum refurbishing and maintenance between flights.

SOURCE: Office of Technology Assessment, 1990.

ness than an AMLS, as a result of the development of new materials and propulsion methods. The Department of Defense and NASA are jointly funding the NASP program to build the X-30 (box 7-C),[17] a research vehicle intended to demonstrate both single-stage access to space and endoatmospheric hypersonic cruise capabilities.

NASP is a high-risk technology development program. Building the X-30 to achieve orbit with **a single stage would require major technological advances in materials and structures, propulsion systems, and computer simulation of aerodynamic and aerothermal effects from Mach 1 to Mach 25.[18] The** uncertainties in meeting design goals are compounded because a successful X-30 would require many of the key enabling technologies to work in concert with one another. Because ground test facilities cannot replicate all of the conditions that would be encountered in ascent to orbit, it is impossible to predict precisely how the X-30 would perform when pilots make the first attempts to push it far into the hypersonic realm.

If funded, the X-30 would be a research vehicle, not a prototype of an operational vehicle. To develop an operational vehicle would require an additional program beyond NASP. A development cycle that took full advantage of lessons learned in the X-30'S planned test program could not commence until the late 1990s at the earliest. An operational vehicle derived from the proposed X-30 would therefore be unlikely until approximately 2005 or later unless it were closely modeled on the X-30. However, if the X-30 were designed to provide the maximum data

17 Debates over NASP funding within the Administration and within Congress have left the long-term status of the program in doubt. In Spring 1989 DoD decided to cut its contribution to NASP by two-thirds for fiscal year 1990 and to terminate funding for it in subsequent years. A reexamination of the program by the National Space Council led 10 the replacement of program funds, but delayed the decision concerning whether or not to proceed with construction of the X-30 for2 years, to 1993. Congress decided to appropriate $254 million for NASP research in 1990 ($194 from DoD; $60 million from NASA).

18 Mach 1 is the speed of sound. Hypersonic usually refers to flight at speeds of at least Mach 5—five times the speed of sound, or about 4,000 miles per hour. Mach 25 (25 times Mach 1), is the speed necessary to reach Earth orbit.

about the feasibility of an operational aerospace plane, it would be unlikely to serve as an appropriate prototype of an operational vehicle. Although the X-30 would be piloted, aerospace planes based on the X-30 could be designed to carry cargo autonomously. [19]

If the X-30 proves successful, the frost operational vehicles that employ NASP technologies are likely to be built for military use, possibly followed by civilian space vehicles. Commercial hypersonic transports (the 'Orient Express") are a more distant possibility. Recent studies have shown that from an economic standpoint, commercial hypersonic transports would compare unfavorably with proposed slower, Mach 3 supersonic transports based on less exotic technology and conventional fuels. Therefore, the most economic route to commercial high-speed air transport is unlikely to be through the X-30 development program. However, the X-30 program could provide technical spin-offs to aerospace and other high-technology industries through its development of advanced materials and structures and through advances in computation and numerical simulation techniques. It is too early to judge the economic importance of such spinoffs.

Even assuming a rapid resolution of the myriad of technical issues facing the creation of an X-30 capable of reaching orbit with a single propulsion stage based on airbreathing technology, translating this technology into an operational spaceplane might come late in the period when an AMLS **could be ready, and perhaps after the time when replacements for the Shuttle would be necessary.** With their less exotic technologies, rocket propelled AMLS vehicles could probably be funded in the mid to late 1990s and still be developed in time to replace aging Shuttles. An AMLS program begun in this period would also benefit from the technical base being developed in the NASP program, which is exploring concepts based solely on rocket propulsion as well (see below). **However, the technical and economic uncertainties of both programs suggest that Congress would benefit from monitoring their progress and comparing the probability of success of each before committing development funds for operational vehicles in the mid-1990s. The development costs of each program, as well as other competing budget priorities, will play a major role in such a decision.**

Additional Reusable Launch Concepts

Routine flight to space with reusable vehicles offers tremendous economies if the United States can master the underlying technologies-materials, structures, propulsion, and avionics to produce a highly reliable and maintainable reusable vehicle. [20] The technologies needed for fully reusable space launch systems are being developed primarily by the NASP program, although the ALS and AMLS programs are also investing in reusable concepts. Future operational cargo systems may combine the best technologies developed by each program. Ranging from rocket-powered vehicles that might be available by the beginning of next century, to airbreathing propulsion systems that would be available later, such vehicles could support intermediate to near Shuttle-size payloads. Operated as fully reusable vehicles able to fly to orbit without an expendable stage, such vehicles offer some of the economies associated with aircraft.

[19] The Soviet shuttle *Buran* has demonstrated the feasibility of launching and landing a reusable space plane without a human crew.

[20] See app. A for a discussion of the effect of reliability on life-cycle cost estimates of future launch systems.

Chapter 8

International Competition and Cooperation

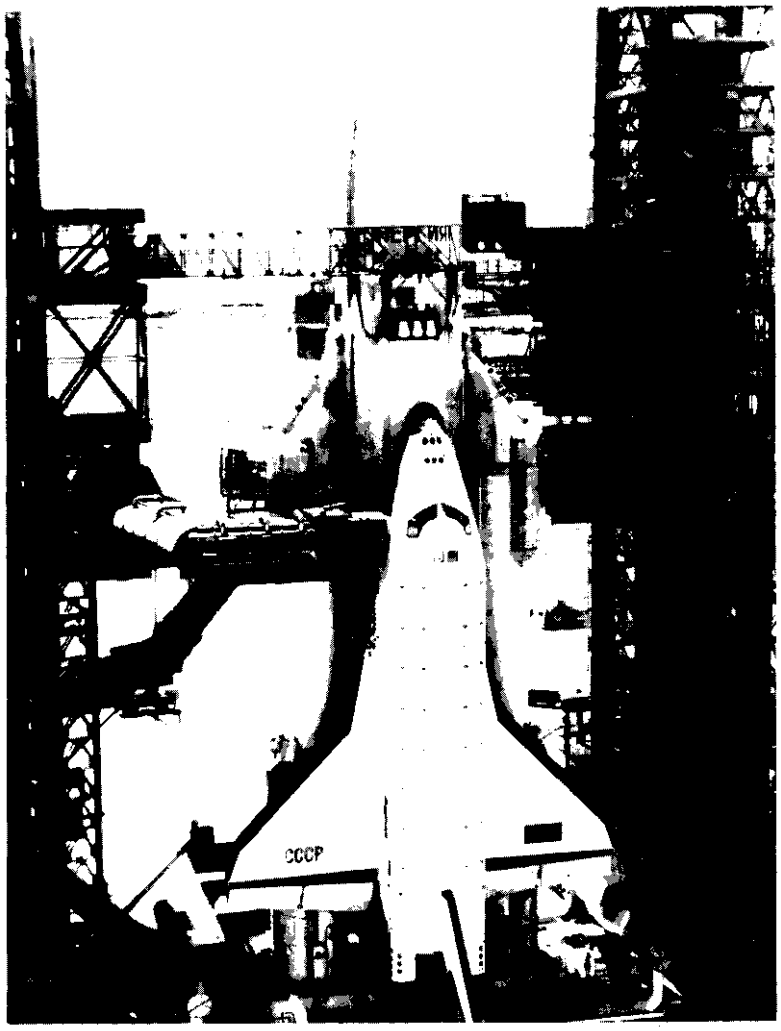


Photo credit: Novosti

Soviet Shuttle *Buran* on the launch pad at the Soviet launch complex

Chapter 8
International Competition and Cooperation

COMPETITION

This decade has seen the rise of intergovernmental competition in space transportation. The development of space transportation systems is a national achievement that signals a nation's status as a space power, able to develop and use advanced technology. The Soviet Union, Europe, Japan, and China now operate launch systems capable of reaching space with sizable payloads. Although only the United States and the Soviet Union are currently able to send humans to and from space, ESA, France, Germany, Japan, and the United Kingdom are all in various stages of developing their own reusable launch systems, which, if successful, would be capable of transporting human crews.

Recently, commercial competition subsidized by governments has become an important part of space transportation competition. Europe, the Soviet Union, and China now compete with U.S. private firms for the international space launch market. Each government has developed its own mechanisms for assisting its launch fins. For example, Glavcosmos (U. S. S. R.) and the Great Wall Corp. (China) are government corporations, for which sales of launch services are an integral part of international policy. Arianespace, S.A. (France) is a private corporation owned in part by the French Governmental Although it operates as a private firm, Arianespace receives considerable indirect support from the European Space Agency, which has developed the various Ariane launchers, built the launch complexes, and purchases launch services. The United States Government has assisted U.S. private firms by developing the expendable launch vehicles and launch facilities (which are leased to the firms), by purchasing launchers and launch services from them, and in numerous other ways.[2]

A number of experts have raised doubts about the capability of the U.S. private sector to compete for providing launch services in the world market, especially in the face of a relatively small market for commercial launch services. Projected launch services supply far exceeds expected demand. Launch firms in the United States, France, the Soviet Union, and China expect to be able to supply about 35 to 40 vehicles per year to launch only 15 to 20 commercial payloads per year over the next decade.

A launch industry capable of competing on the basis of price as well as capability in the world market could contribute several hundred million dollars per year toward improving the current strong negative balance of payments with foreign countries, directly by making sales to foreign customers, and indirectly by keeping U.S. payload owners from going off-shore to purchase launch services. Congress could assist the U.S. private sector by helping the Executive work to develop and maintain a' 'level playing field" in the marketplace, in which prices are arrived at by rules based on justifiable economic rationales and agreed on by the launch providers.[3] The recent negotiations with China in which that country agreed to price its launch services to reflect actual manufacturing and launch cost have been a step in the right direction, but similar arrangements need to be negotiated with all launching nations who are offering their launch vehicles in the commercial market.

COOPERATION

The United States has always maintained a vigorous program of international cooperation in space in order to support U.S. political and economic goals. However, it has cooperated very little with other countries in space transportation, in large part because most launch technology has direct military applications and much of the technology has been classified or sensitive.

Today, because other countries have developed their own indigenous launch capabilities, reducing much of the competitive edge the United States once held, and because progress in space will continue to be expensive, cooperating on space transportation and sharing costs could be beneficial. Several cooperative ventures have been suggested:

- *Space Station resupply.* The United States could share responsibility for resupply of the international Space Station with its Space Station partners. In order for other countries to

[1] Arianespace is owned by 35 companies, 13 banks, and CNES, the French Space Agency

[2] The commercial market alone is insufficient t. support more than one U.S. commercial medium-capacity launch system. No large launch system has yet been privately developed, and at least for the next decade or two commercial traffic levels will probably not justify future private development.

[3] See Public Law 100-657 (102 Stat. 3900), "The Commercial Space Launch Act Amendments of 1988."

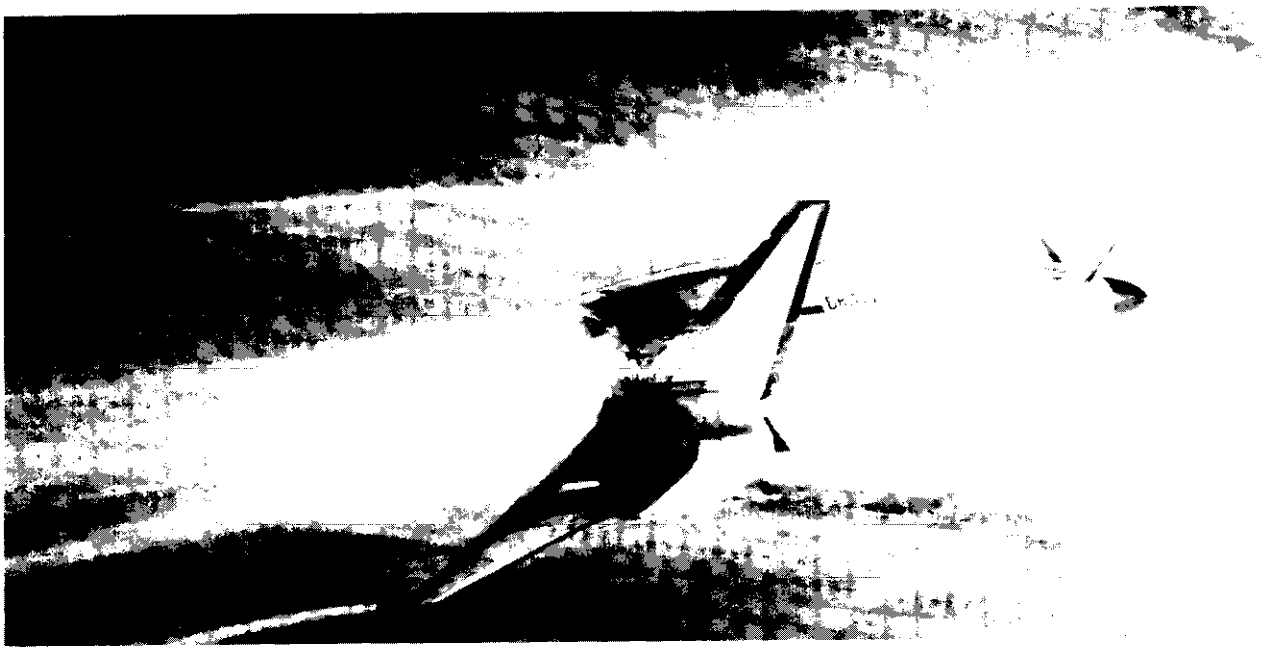


Photo credit: British Aerospace

Artist's conception of British Aerospace's Hotol aerospace plane taking off. If successful, this space plane would reach Earth orbit with a single propulsion stage.

use their launch systems to supply the Space Station, or to dock with it, the countries will have to reach agreement with the United States on appropriate standards for packaging, docking, and safety. ESA and NASA have now established a working committee to discuss these matters. If successful, such cooperation could be extended to include cooperation on more sensitive aspects of space transportation. In particular, because Europe and Japan have now developed and operated their own launch systems, they may have specific technologies or methods to share with the United States in return for access to some U.S. technology.

- *Emergency rescue from Space Station.* As noted in an earlier section, NASA is planning to provide some sort of emergency crew return capability for the Space Station. NASA estimates that developing such a capability would cost between $1 billion and $2 billion, depending on its level of sophistication. If properly outfitted, the European Hermes or the Japanese HOPE might **be used as an emergency return vehicle. In addition, Hermes could even back up the Shuttle for limited space station crew replacement.** However, such international cooperation would also require a degree of international coordination and technology sharing for which the United States has little precedent.
- *Cooperative space rescue efforts.* At present, the Soviet Union is the only country beyond the United States with the capability to launch people into space. As Europe and Japan develop their crew-carrying systems, the potential for emergencies requiring rescue from a variety of space vehicles will increase. Broad agreements on docking standards, and procedures for space rescue,[4] could increase astronaut safety for all nations and lead to more extensive cooperative activities in the future. Initial meetings have been scheduled this spring to discuss the nature and extent of such cooperation. Both this cooperative project and the use of foreign vehicles to supply Space Station have the advantage that they risk transferring very little U.S. technology to other participants.[5]

[4]The United States, the U. S. S. R., the European countries and Japan have signed the *Agreement* On *the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space*—UST 7570; TIAS 6599.

[5]The Apollo-Soyuz Test *Program,* for example, was designed to minimize the potential for technology transfer.

- *Aerospace plane research and development.* With strong encouragement from their private sectors, Germany, Japan, and the United Kingdom are working independently toward development of aerospace planes. The level of foreign sophistication in certain areas of advanced materials, advanced propulsion, and aerodynamic computation is on a par with U.S. work. A joint development program with one or more of these partners might allow the United States to develop an aerospace plane faster and with lower cost to the United States than the United States could on its own. Although a joint project would risk some technology transfer, if properly structured, such a joint project could be to the mutual benefit of all countries involved.
- *U.S. use of the Soviet Energia heavy-lift launcher. The* U.S.S.R. has offered informally to make its *Energia* heavy-lift launch vehicle available to the United States for launching large payloads. As noted throughout this report, the United States has no existing heavy lift capability. Thus, the Soviet offer could assist in developing U.S. plans to launch large, heavy payloads, such as Space Station components. However, concerns about the transfer of militarily useful technology to the Soviet Union would inhibit U.S. use of *Energia* for such high-technology payloads. As well, NASA would be understandably reluctant to make use of a Soviet launcher because such use might be seen as sufficient reason for the United States to defer development of its own heavy-lift vehicle.

Although cooperation in space transportation can be expected to be more difficult than cooperation in other areas of space endeavor, it could assist the United States to achieve much more in space than this country can afford to attempt on its own. However, it will require that NASA and the U.S. aerospace industry make a greater effort to tap the expertise and technology now available in other industrialized countries.



Photo credit: Arianespace

Night launch of Ariane 3 launcher from the European Space Agency launch pad in Kourou, French Guiana.

Appendix A

The Sensitivity of Operational Aerospace Plane Costs To Required Confidence and Actual Reliability

Appendix A

The Sensitivity of Operational Aerospace Plane Costs To Required Confidence and Actual Reliability

The proposed experimental National Aero-Space Plane (NASP), the X-30, is being designed with a goal of 99.999 percent reliability—i.e., to have only 1 chance in 100,000 of failing catastrophically during a flight, assuming no human error. NASP program officials have said that later first-generation aerospace planes, which they term NASP-Derived Vehicles (NDVs), would probably be designed to have a similar reliability. Recognizing that the design reliability does not account for possible human error in maintaining and flying the vehicle, NASP program officials assume the actual reliability of a first-generation NDV would be lower—nominally 99.8 percent, but 99.9 percent in the "best case, " and 99.5 percent in the "worst case."[1]

NASP program officials assume there is little risk that an NDV of lower reliability would be flown on operational missions, because they expect NDV development would be halted if the proposed X-30, or a later prototype NDV, fails to demonstrate acceptable reliability (99.5 percent) in its flight test program. Thus, in their view, the cost at risk would be not billions of dollars of greater than expected failure costs but only those funds spent to develop and build X-30s.[2]

This argument hinges on a critical assumption: that if the test vehicles turn out to be unacceptably unreliable, the test program will detect that fact with high confidence. The validity of this assumption cannot yet be decided, because the NASP program office has not yet specified what kind of confidence (statistical or subjective) they require, nor how much is enough, nor how it will be calculated from test results. These details are important, because a test program cannot determine the reliability precisely. The test flights might be a lucky streak, or an unlucky streak; the actual reliability could differ significantly from the successful percentage of test flights. However, a properly designed test program can determine the confidence level with which the required reliability has been demonstrated.

In choosing a required confidence level, NASP program officials face a dilemma—as would any manager of a launch vehicle development program: Requiring too little confidence could allow acceptance of a vehicle that is actually unacceptably unreliable; operational vehicles of similar design and reliability would probably fail often enough to incur staggering failure costs. If, on the other hand, too much confidence is required, a vehicle that is actually highly reliable might be rejected, and the savings potentially realizable by using operational vehicles of similar design and reliability would be forfeit.[3]

NASP program officials must also choose the *type of confidence* to require. They could require statistical confidence to be demonstrated, or they could calculate the confidence level by Bayesian inference, which would use the results of the flight tests to update a subjective prior probability distribution over possible values of reliability (see box A-A).[4] The former choice would require a very large number of flights to demonstrate the required reliability with high statistical confidence.[5] A problem with the latter choice is that there would be risks of optimism and pessimism. If the prior distribution is optimistic, the reliability might be low but the vehicle would be accepted and later losses incurred. If pessimistic, reliability might be high but the vehicle would be rejected and potential savings unrealized.

Because the type and level of confidence with which 99.5 percent reliability must be demonstrated has not been specified, and because the actual reliability will never be known precisely, this appendix shows how the life-cycle costs of acquiring and operating a mixed fleet of launch vehicles-including NDVs, if accepted—would depend on the type and level of confidence required in testing and on the actual reliability.

Cost Estimates, If Statistical Confidence Is Required

The type and level of confidence required and the actual reliability determine the probability that the test program will be successful; if it is, NDVs will be acquired and operated, and their actual reliability will affect the failure costs incurred.

Figure A-1 shows estimates of the probabilities with which test vehicles of various reliabilities would demonstrate 99,5 percent reliability with various levels of statistical confidence in 100 test flights. If 40 percent

[1]NASP Joint Program Office staff, personal communication, Jan. 18, 1990.

[2]Furthermore, they expect that the value of NDV technology "spun off" to other applications such as aircraft and launch vehicles would compensate for some of the cost at risk.

[3]If more test flights were conducted, a reliable Vehicle could demonstrate acceptable reliability with acceptable confidence and allow these potential savings to be realized, but against this must be weighed the expense and delay of the extra tests.

[4]National Research Council, *Post-Challenger Evaluation* of *Space Shuttle Risk Assessment and Management* (Washington, DC: National Academy *Press,* January, 1988), app. D.

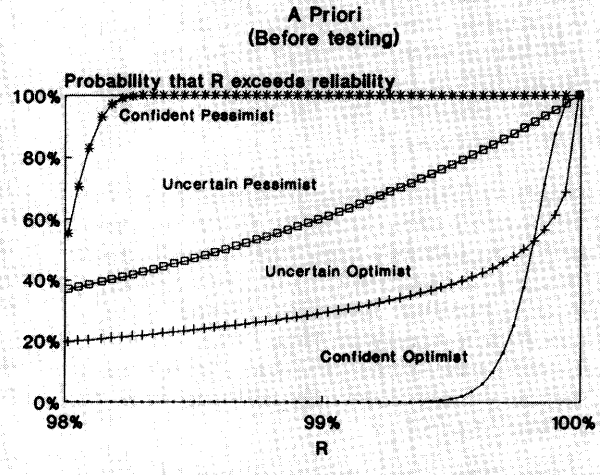
[5]One hundred test flights, if all successful, would provide only 39.4 percent statistical confidence in a 99.5 percent lower confidence bound on reliability.

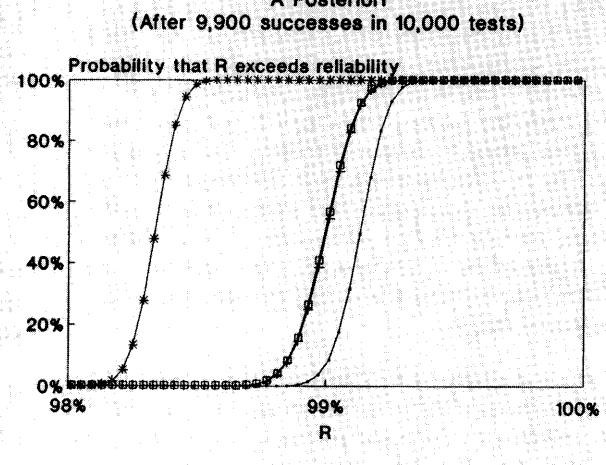
Box A-A—Estimation of Reliability by Bayesian Inference

In classical probability theory, a system is assumed to *have* a definite reliability, even though the reliability is not known precisely. The percentage of tests (or uses) that are successful is an estimate of the reliability, and statistical confidence bounds indicate the uncertainty of estimates. If no tests have been done, reliability cannot be estimated by statistical methods.

In contrast, the Bayesian view is that the reliability of a system may be 10 percent, or 90 percent, or any other possible value. A person's beliefs and uncertainty about the reliability, even before tests have been conducted, may be expressed by a set of probabilities: the probability that the reliability is less than 10 percent, the probability that it is less than 20 percent, and so forth. Collectively, such probabilities specify what is called a cumulative probability distribution over reliability. Because it represents one person's beliefs about the reliability, the distribution is called a subjective probability distribution (SPD). Another person may have different beliefs about the reliability of the same system; that person's beliefs would be represented by a different SPD. The Bayesian interpretation of probability does not require the SPDs of different subjects to agree, but it does require each subject's SPD to be self-consistent. For example, an SPD cannot specify that a subject believes the reliability to be less than 10 percent with 50 percent probability and less than 20 percent with 30 percent probability!

Four Subjects' Subjective Probability Distributions Over Reliability





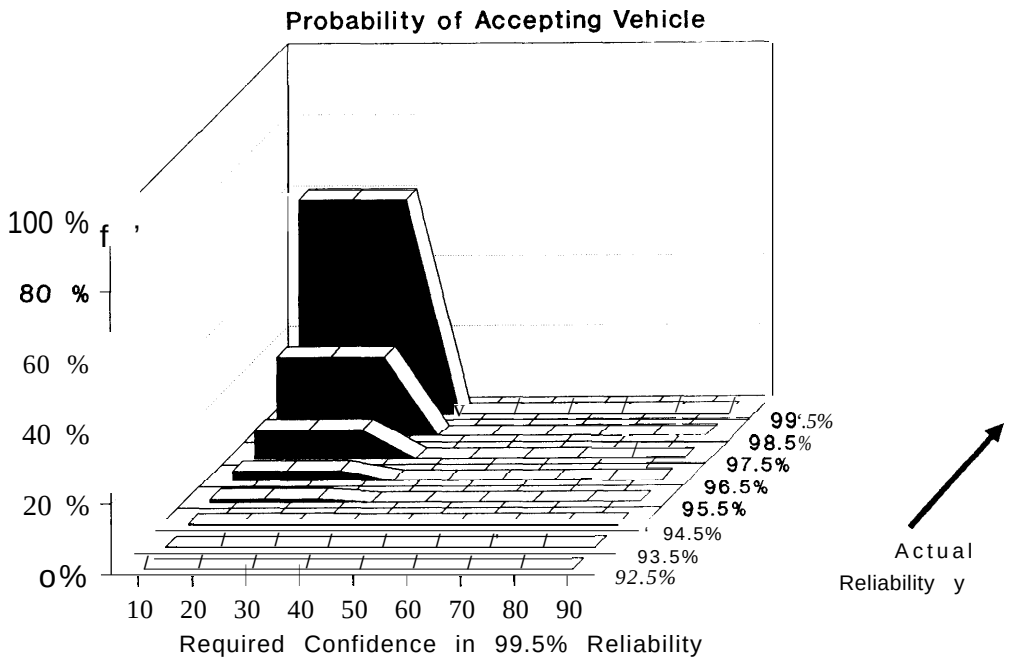
SPDs which are not based on actual tests of the system are called prior SPDs: they are SPDs estimated prior to testing. Prior SPDs may be based on expert judgement, considering tests of subsystems or analogous systems. They may also reflect guesses, hunches, mysticism, or complete ignorance. When test data become available, SPDs may be updated; however—*and herein lies the value of Bayesian inference*—each SPD must be updated in a logically consistent manner, using Bayes's theorem, which is stated and proved in many textbooks on probability. SPDs updated in this manner are called posterior SPDs: they are SPDs estimated *a posteriori* (after testing).

Differing prior SPDs become more similar after Bayesian updating, as the figures below illustrate. The figure on the left shows portions of the prior SPDs of four subjects, who are identified as "Confident Pessimists," "Uncertain Pessimist," "Uncertain Optimist," and "Confident Optimist." The prior SPD of the Confident Pessimist indicates that the Confident Pessimist is about 55 percent confident that the reliability is less than 98 percent and almost 100 percent confident that the reliability is less than 98.25 percent. The Uncertain Pessimist is

less than 40 percent confident that the reliability is less than 98 percent even though his SPD implies the same expected value of reliability—98 percent-as does the SPD of the Confident Pessimist (the expected value of reliability cannot be read from a graph of the SPD; it must be calculated from the SPD). Similar readings of points on the SPDs of the Uncertain optimist and the Confident Optimist reveal why they are so named.

The figure on the right shows portions of the posterior SPDs of the same four subjects, updated after 9,900 successes have been observed in 10,000 tests-a success rate of 99 percent. The posterior SPDs of the Uncertain Pessimist and the Uncertain Optimist are almost indistinguishable; influenced by the test results in a logically consistent manner, their prior SPDs have converged, that of the Uncertain Pessimist (who expected 98 percent reliability *a priori)* becoming more optimistic, and that of the Uncertain Optimist (who expected **99.8 percent reliability** *a priori)* becoming more *pessimistic.* The SPDs of the Confident Pessimist and the Confident Optimist also became more similar but did not fully converge; the high confidence implicit in the prior SPDs (and apparent as steep slopes in the graphs) caused them to be influenced less by the test results.

Figure A-1—Probability That Test Vehicles Will Demonstrate Acceptable Reliability If Statistical Confidence Is Required



Based on 100 Monte Carlo samples.

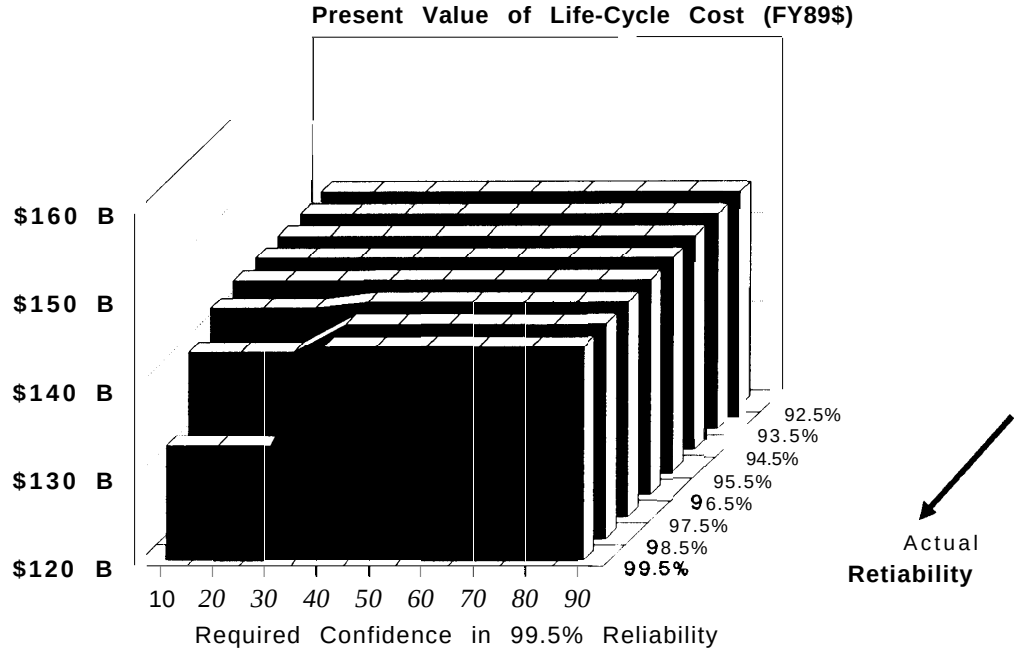
SOURCE: Office of Technology Assessment, 1990.

statistical confidence, or more, is required, a vehicle would be rejected even if all flights were successful. If, however, only 30 percent statistical confidence is required, a 99.5-percent reliable vehicle would be accepted with a probability of about 80 percent.

Figure A-2 shows how the expected present value of the life-cycle costs of flying the missions in OTA's Low-Growth mission model[6] through the year 2020 would depend on actual reliability and required confidence, if statistical confidence is required. The greater the

[6]U.S. Congress, Office of Technology Assessment, *Launch Options for the Future—A Buyer's* GM'&, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988).

Figure A-2—Expected Present Value of Mixed-Fleet Life-Cycle Cost If Statistical Confidence Is Required and NDV Costs Are As Estimated by NASP JPO



Based on 100 Monte Carlo samples.

SOURCE: Office of Technology Assessment and National Aero-Space Plane Joint Program Office.

X-30'S reliability turns out to be, the greater the savings can be.[7] If managers require at least 10 percent statistical confidence, they risk little or nothing compared to the costs if NDVs were not attempted (figure 1-2) if the X-30'S reliability turns out to be low, because there is little chance that an unreliable vehicle would be accepted, and no NDV development costs are assumed to be incurred before the decision on whether to proceed with NDV development.[8]

Methodology

OTA calculated these estimates assuming that NDV-related costs are uniformly distributed over ranges estimated by the NASP Joint Program Office (JPO), which are shown in table A-1. OTA also assumed:

1. X-30 development costs are sunk costs.
2. The test program will consist of 100 test flights *to orbit and back;* other (e.g., suborbital) test flights may be conducted but will not be used to estimate reliability on orbital flights.[9]
3. During the test program, the X-30S will not be modified in any way, or operated in different ways, that would make reliability differ from flight to flight.[10]
4. The government will decide in 2000 whether to proceed with NDV development,[11] based on whether

[7] The actual reliability of operational NDVs is assumed to be the same as that of the X-30s or prototype NDVs used to demonstrate reliability in the flight test program.

[8] These estimates exclude the costs of developing the x-30 (or other prototype); if Congress decided now to forego development of an NDV, it could save a few billion dollars by hatting the NASP program. See U.S. Congress, Congressional Budget Office, *Reducing the Deficit: Spending and Revenue Options* (Washington, DC: U.S. Government Printing Office, 1990), pp. 68-70.

[9] The JPO actually plans only about 75 to 100 test flights, most of them suborbital. Data from suborbital test flights and ground tests of vehicle systems and components could be used to estimate reliability on orbital flights, but this would require developing a component-level reliability model that describes how component failures could cause vehicle loss and how component failure probabilities depend on details of vehicle assembly, maintenance, and operation (e.g., on the speeds and altitudes at which the vehicle has flown).

[10] This assumption simplifies analysis. In fact, the X-30s could be modified—e.g., after a failure—in an attempt to increase reliability, but "wiping the slate clean" late in the test program might reduce confidence that the required reliability has been demonstrated.

[11] Some have suggested that if the X-30 is successful, NDVs might be developed privately to service the market for space tourism. For estimates Of the demand for round trips to orbit as a function of ticket price, see DoD & NASA, *National Space Transportation and Support Study 1995-20)0, Annex* B: Civil Needs Data Base, Version 1.1, vol. I—Summary Report, Mar. 16, 1986, pp. 3-3 1—3-32, and Gordon R. Woodcock, "Economics on the Space Frontier: Can We Afford It?," SS[*Update* (Princeton, NJ: Space Studies Institute, May/June 1987).

Table A-l—Ranges of Costs Estimated by NASP Joint Program Office (index **year not specified)**

	Best Case	Nominal	Worst Case
Development	$3,000 M[a]	$4,000 M	$6,000 M
Facilities (per NDV)	$25 M	$50 M	$75 M
Production (first NDV)	$700 M	$800M	$1,100 M
(% learning[b])	85 %	90 %	95 %
Operations (per NDV-year)	$10 M	$15 M	$30 M
(per flight)	$0.8 M	$1.2 M	$2.2 M
Failures (per failure)	$1,500 M	$2,000 M	$2,500 M

a M = million
b i.e., the incremental unit cost of the nth NDV will be (%/1 OF)@@ times the incremental unit cost of the first NDV, where % is the percentage learning.

SOURCE: NASP Interagency Office, 1990

the required reliability (assumed to be 99.5 percent) is demonstrated with a specified *statistical* confidence.

5. If the government decides not to proceed with NDV development, the missions in the mission model will be flown by Shuttles, Titan IVs, and Medium Launch Vehicles. Construction of facilities required for launching Titan IVs at the rates required (which began earlier as a hedge) will continue.
6. If instead the government proceeds with NDV development,
   (a) Construction of only those Titan IV facilities required for launching at the rates required to complement the NDV will continue, possibly after a delay .12
   (b) The actual reliability of operational NDVs will be the same as that of the X-30s or prototype NDVs used to demonstrate reliability in the flight test Program.[13]
   (c) Enough NDVs will be procured to make the probability of losing them all to attrition no greater than one percent, assuming a reliability of 99.5 percent.[14]
   (d) NDVs will fly all the reamed missions in OTA's "Low-Growth" mission model on a 1:1 basis (i.e., one NDV flight substituting for one Shuttle flight) and half of Titan missions 1:1, beginning the year of initial operational capability, which OTA assumes will be 2005.
   (e) [f and when all NDVs are lost to attrition, another NDV will be procured at the same incremental unit cost as the first NDV.[15]

The probability that X-30S or prototype NDVs would demonstrate the required reliability (99.5 percent) with the required confidence during the flight test program was calculated for each combination of actual reliability and required confidence considered. This probability-the "acceptance probability ''-was used in calculating the life-cycle cost of the mixed fleet. Titan and Shuttle costs depend on the number of missions Titans and Shuttles are required to fly, which depends on whether NDVs are accepted and used to complement Titans and supersede Shuttles.

For the case in which they are, the costs of NDV development, facilities, production, operation, and failures are estimated by Monte-Carlo techniques-i. e., random-event simulation. For each of 100 scenarios, values for each of the uncertain costs in table A-1 were generated pseudorandomly[16] and used to calculate the life-cycle costs of the NDV fleet. The number of operational failures in each year was also generated pseudo-randomly, based on the actual reliability assumed, and used to calculate NDV failure costs. For each value of actual reliability y considered, the difference between the 70th percentile of NDV costs and the median value of NDV costs was used as the "STAS cost risk''--i.e., the cost risk as defined in the Space Transportation Architecture Study[17]—for the NDV fleet.

Sensitivity to Greater-than-Expected NDV Costs

To gauge the sensitivity of the estimates in figure A-2 to greater-than-expected NDV costs, OTA estimated costs by the same procedure but assumed NDV-related costs are uniformly distributed over the ranges in table A-2. The lower bounds of these ranges areas estimated by

[12] Because they may not be needed as soon, and delaying expenditures for facilities allows them to be more heavily discounted.

[13] Operational NDVs could be designed to differ from the X-30s or prototype NDVs—e.g., to have more engines-with the intent of making them more reliable. If so designed, detailed reliability models (footnote 9) of both X-30s and operational NDVs would be needed to estimate operational NDV reliability on the basis of X-30 flight tests. If operational NDVs differ significantly from X-30s, X-30 flight tests may provide little information about NDV reliability; in any case, the updating procedure would be much more complicated than updating based solely on test flights of similar vehicles under similar conditions.

[14] According to this criterion, the fleetsize should be eight for the Low-Growth mission model (534 NDV flights).

[15] This is Optimistic; it neglects procurement delay and the remote possibility that one NDV may be required to fly more flights than the NASP JPO assumes it will be able to: 250 to 500, but nominally 400.

[16] The costs were assumed to be distributed uniformly between the worst-case and best-case values in table A-1.

[17] U.S. Congress, Office of Technology Assessment, op. cit.. footnote 6.

the NASP JPO (table A-l); the upper bounds of these ranges are twice the upper bounds of the ranges estimated by the NASP JPO (in the case of percentage learning, the upper bound is twice as close to 100 percent). Figure A-3 shows the resulting cost estimates.

Cost Estimates, If Subjective Confidence Is Allowed

OTA has also estimated savings and losses for cases in which the government decides whether to proceed with NDV development based on the *subjective* (rather than *statistical)* confidence with which the required reliability (assumed to be 99.5 percent) is demonstrated. The confidence level is calculated by Bayesian inference. For illustration, the estimates were calculated assuming the prior distribution of the "Confident Optimist" of box A-A, which implies an expected reliability of 99.8 percent-the same nominal reliability estimated by the NASP JPO. Figure A-4 shows the proto-NDV acceptance probabilities, and figure A-5 the life-cycle costs, estimated under these assumptions, assuming OTA's Low-Growth mission model and NDV-related costs uniformly distributed over ranges estimated by the NASP JPO (table A-l).

To gauge the sensitivity of the estimates in figure A-5 to greater-than-expected NDV costs, OTA estimated costs by the same procedure but assumed that NDV-related costs are uniformly distributed over the ranges in table A-2. Figure A-6 shows the life-cycle costs estimated under these assumptions.

Figure A-5 shows that if NDV costs areas estimated by the NASP JPO, there is little risk that an unacceptably unreliable vehicle would be accepted and, as a consequence, the mixed-fleet life-cycle cost (figure A-5) would exceed that of the current mixed fleet (the Titan-IV option in figure 1-2).

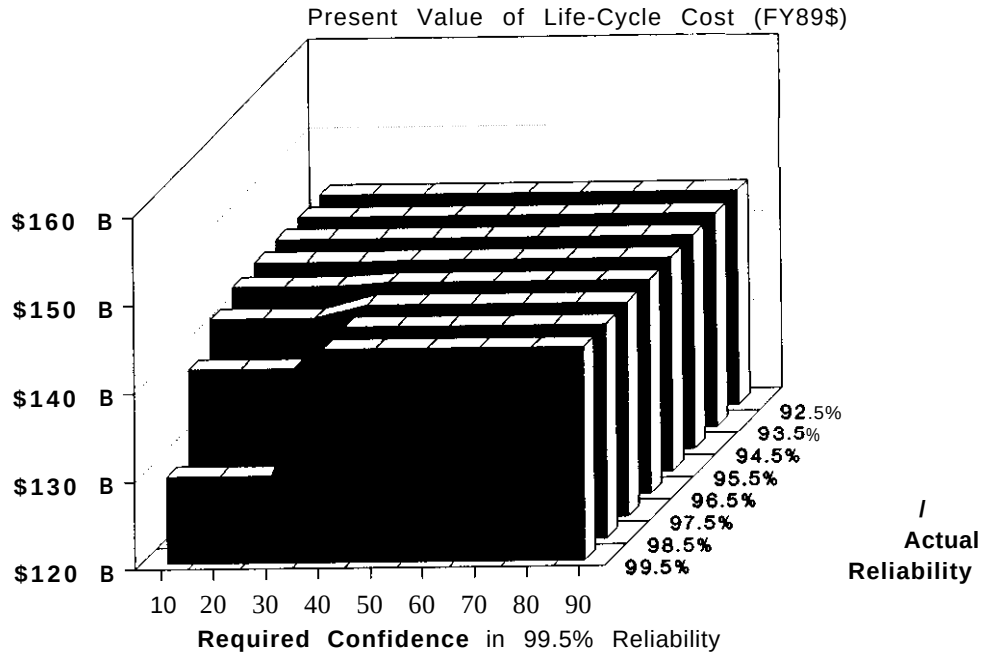
Table A-2—Ranges of Costs Assumed by OTA for Sensitivity Analysis

	Best Case	Worst Case
Development	$3,000 M[a]	$12,000 M
Facilities (per NDV)		$150 M
Production (first NDV)	$700 M	$2,200 M
(% learning)	857.	97.570
Operations (per NDV-year)	$10 M	$60 M
(per flight)	$0.8 M	$4.4 M
Failures (per failure)	$1,500 M	$5,000 M

[a]M = million.
SOURCE: Office of Technology Assessment, 1990.

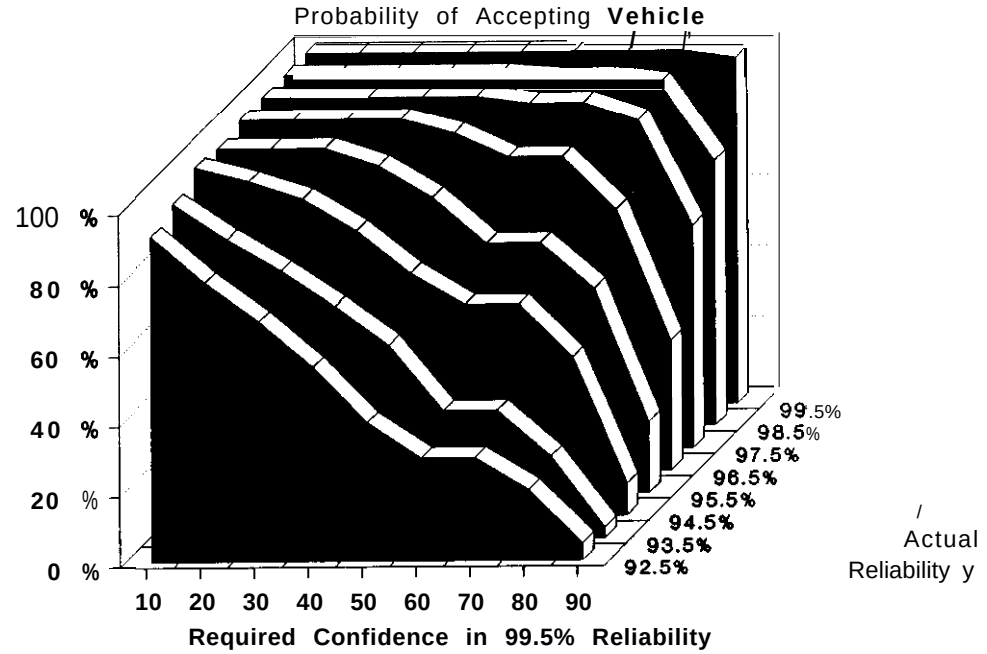
However, if NDV costs can range up to twice the upper bounds estimated by the NASP JPO, figure A-6 shows that there could be a significant risk of loss caused by accepting an unacceptably unreliable vehicle. For example, if only 10 percent confidence is required and actual reliability turns out to be 92.5 percent, the median life-cycle cost would be about $16 billion more than if the NDV were rejected, or not attempted, because the failures that would occur in the test flight program would probably not reduce the confidence in NDV reliability (over 98.9 percent, a priori) below 10 percent. If 90 percent confidence were required (see figure A-6), or 10 percent statistical confidence were required (see figure A-3), or prior confidence in NDV reliability were lower, this risk could be made negligible, but this would also reduce the probability of accepting, and benefiting from, a reliable NDV,

Figure A-3-Expected Present Value of Mixed-Fleet Life-Cycle Cost If Statistical Confidence Is Required and NDV Costs May Be 2X NASP JPO Estimates



Based on 100 Monte Carlo samples.

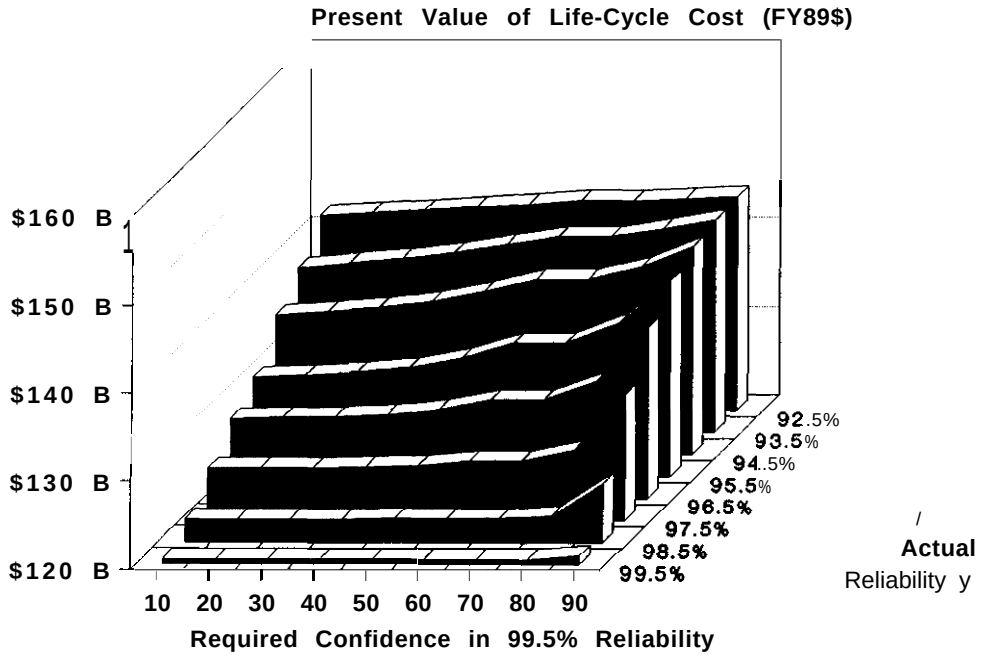
Figure A-4--Probability That Test Vehicles Will Demonstrate Acceptable Reliability If Subjective Confidence Is Allowed



Based on 100 Monte Carlo samples.

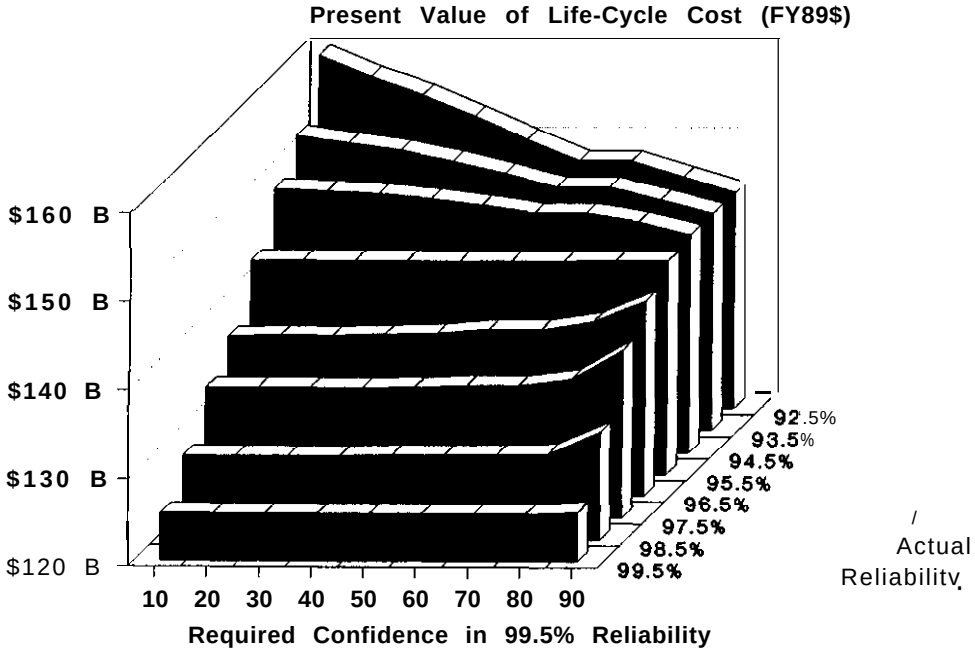
SOURCE: Office of Technology Assessment and National Aero-Space Plane Joint Program Office, 1990.

Figure A-5-Expected Present Value of Mixed-Fleet Life-Cycle Cost If Subjective Confidence Is Allowed and NDV Costs Are As Estimated by NASP JPO



Based on 100 Monte Carlo samples.

Figure A-6--Expected Present Value of Mixed-Fleet Life-Cycle Cost If Subjective Confidence Is Allowed and NDV Costs May Be 2X NASP JPO Estimates



Based on 100 Monte Carlo samples.

SOURCE: Office of Technology Assessment and National Aero-Space Plane Joint Program Office, 1990.