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.

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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.

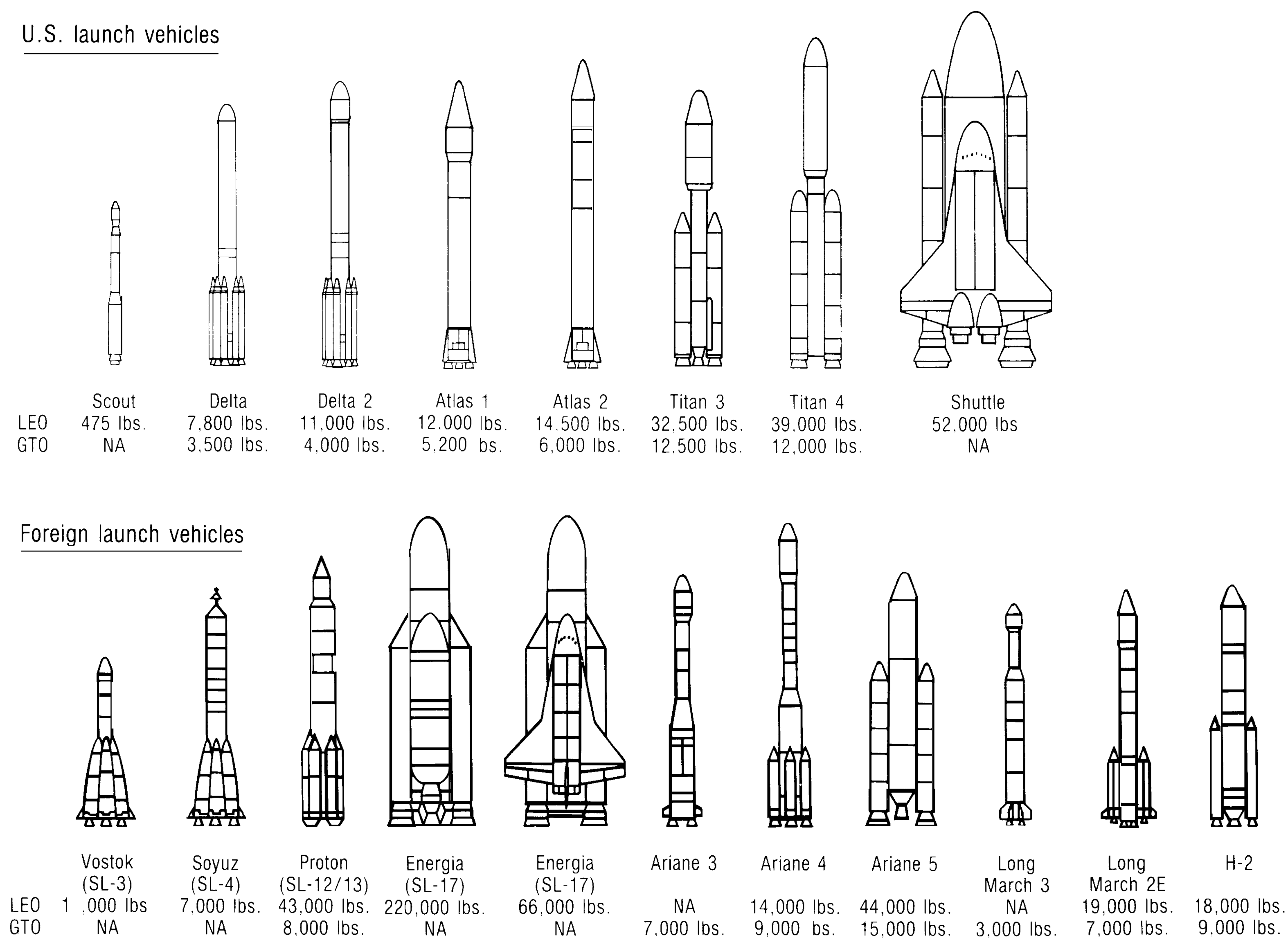
The U.S. future course in space is uncertain, especially in light of the tremendous political and economic changes in progress around the world and the strong pressures to reduce Federal spending. Will the Government cut back on civilian and/or

[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 Veh c es 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.

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

2Of 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 Assessment, 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**

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

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

6In 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.

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

8The 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[4] 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 it 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

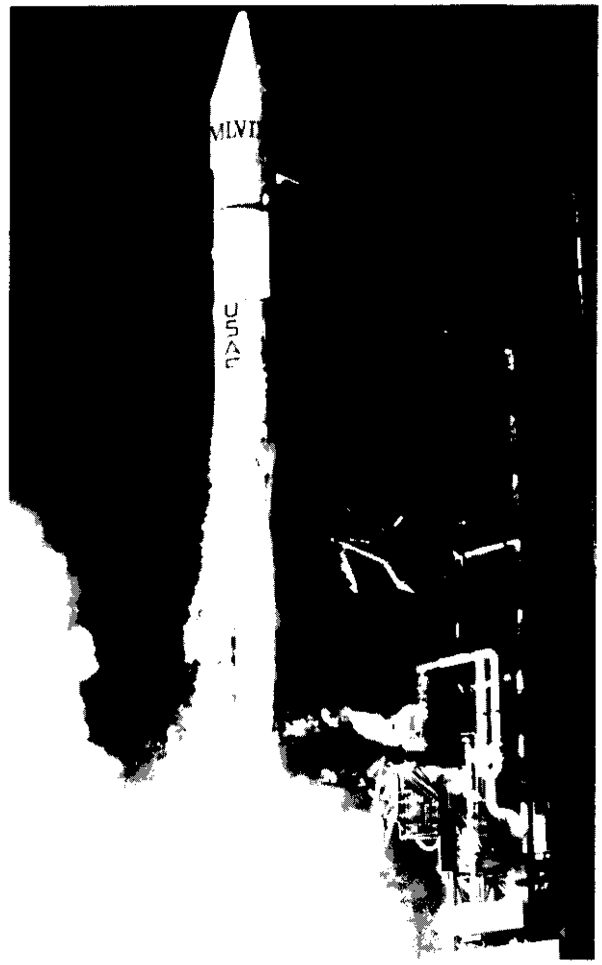


Photo credit: General Dynamics Corp.

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.

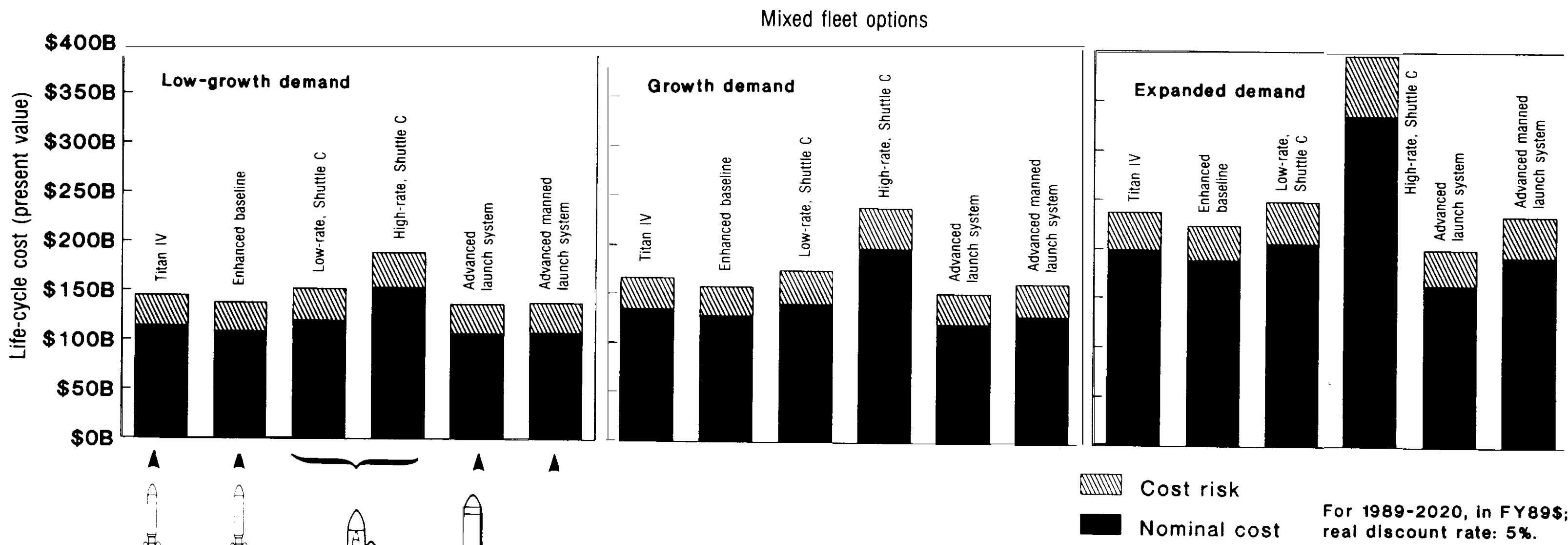
Although the United States has always maintained a vigorous program of international cooperation in space in order to support U.S. political and **economic goals, it has cooperated very little with** other countries in space transportation, in large part because most launch technology has direct military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

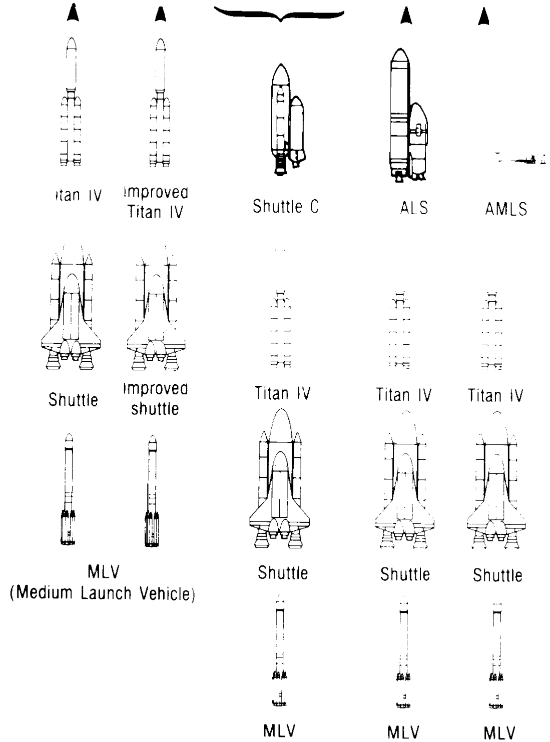
As it debates the direction and magnitude of the space program, Congress will have to decide, as a matter of policy, how much of our publicly supported space program we want to pursue alone and how much we wish to involve foreign partners. International cooperation lessens our ability to use space to 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.

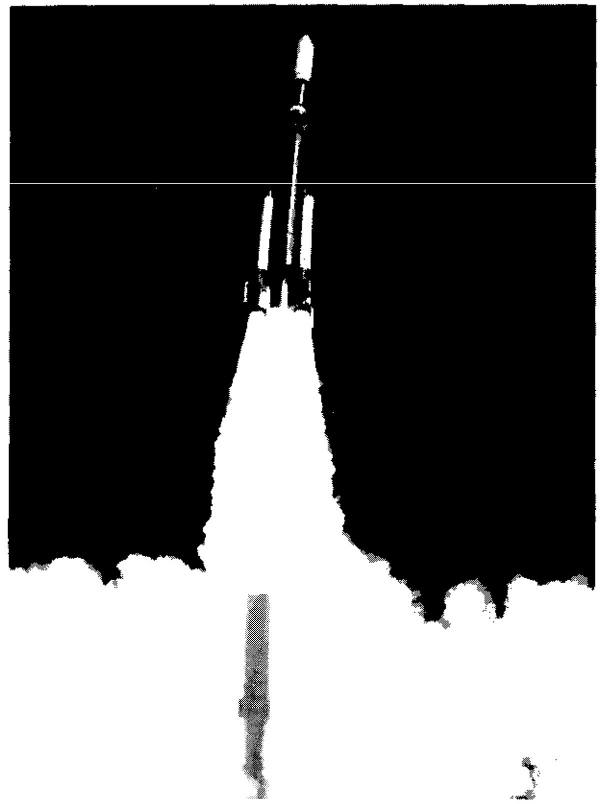


Photo credit: Japanese **National Space Develepment Agency**

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.