Chapter 2

Major Issues in Launch and Mission Operations

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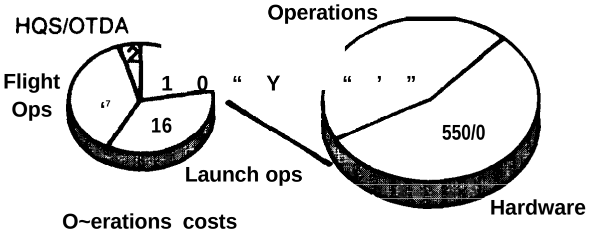
Major Issues in Launch and Mission Operations

INTRODUCTION

Launch and mission operations constitute a significant fraction of the cost of launching payloads to orbit. For example, prior to the loss of Challenger, Shuttle operations costs, including mission operations, accounted for about 46 percent of the cost of a flight. Of that, ground operations totaled at least 24 percent (fig. 2-l). Projected life-cycle costs of the Shuttle suggest that some 86 percent of the total can be attributed to the recurring costs of launch and mission operations.[1] Because of recently mandated safety-related modifications, recurring costs are likely to be higher when the Shuttle flights resume. For today's expendable launch vehicles (ELVs), operations costs are generally a smaller percentage of the total, in large part because these vehicles do not contain reusable components and do not carry humans. However, they are still significant. For example, in the Titan series, launch operations costs can reach about *20* percent of total costs per flight (fig. 2-2).

[1] National Aeronautics and Space Administration, "Shuttle Ground Operations Efficiencies/Technologies Study," Kennedy Space Center, NAS1O-11344, May 4, 1987.

Figure 2"1.—Shuttle Recurring Cost (percent per flight)



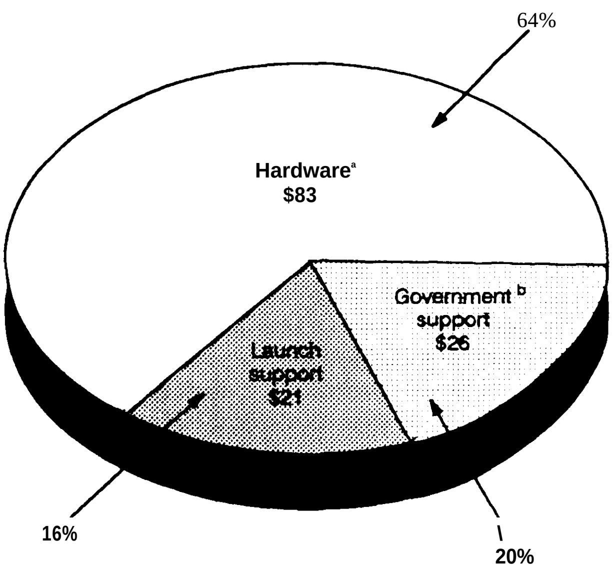
O~erations costs (percent of total recurring costs)

SOURCE' National Aeronautics and Space Administration.

Attempts to reduce operations costs must cope with the complexity of launch and mission operations, and the relative lack of policy attention they have received over the years. Workshop participants and others who contributed to this study[2] identified the following primary issues that should be addressed in developing a sound Federal policy toward reducing costs and increasing efficiency of launch and mission operations.

[2] The many interim reports related to the Space Transportation Architecture Study and the Advanced Launch System effort provided much of the initial information for OTA's effort. In addition, the study team interviewed officials from the Air Force, NASA, and private industry.

Figure 2-2.-Titan IV Estimated Cost per Flight (in millions)



[a] Hardware costs based on annual buy rote of 6/yr
[b] Government costs include propellant, range support, incentives, Aerospace Corporation support, etc

SOURCE: Aerospace Corp

MAJOR ISSUES

ISSUE A: Can New Technologies and Management Strategies Reduce Operations Costs?

Existing Systems

Evolutionary improvements to existing launch systems appear to provide opportunities for making modest, but meaningful, reductions in ground and mission operations costs. Reducing operations costs for existing launch systems generally means reducing the size of operations staffs and shortening the time it takes to prepare and launch a vehicle. Vehicle subsystems, such as avionics, and many ground-based support facilities can be improved through redesign, automation, and standardization.[3]

It is extremely costly to shorten vehicle turnaround and processing substantially by making incremental upgrades of the vehicle, because vehicle subsystems are highly integrated and interdependent. As a result, altering one subsystem often requires changing others. For example, even small alterations of the orbiter outer structure may require significant changes of parts of the thermal protection system. Box 2-A presents a list of changes that could be required in other systems if the design of the Shuttle main engines were materially altered. Such changes would involve multiple NASA centers and contractors, and require considerable coordination.

Commercial launch companies are investing in performance improvements and exploring ways to reduce launch operations costs. For example, General Dynamics has developed a new avionics package for the Atlas-Centaur that reduces the weight of the avionics package and increases its reliability. It also includes self-testing procedures that will reduce operations costs slightly. Other launch companies are exploring similar ways of reducing costs of the launcher and launch operations.

Because changes in the design of vehicle subsystems often have a direct effect on ground operations or mission operations procedures, it is important for design engineers to work closely with operations personnel to establish the best way to proceed in making changes appropriate to operations and maintenance processes. Whether particular changes will result in net reductions in life-cycle costs will depend on a variety of economic, technical, and managerial factors. Chapter 4 discusses these factors for several specific cases.

Although new technology or design changes may lead to reduced costs, management changes may be more important. For example, a recent Strategic Defense Initiative Organization experiment called the Delta 180 Project used new management techniques to achieve reduced project costs. Project managers found that decreasing the burden of oversight and review, and delegating authority to those closest to the technical problems, resulted in meeting a tight launch schedule and reducing overall costs.[4] Maintaining a short

Box 2-A.—Required **Changes to Other Shuttle** Subsystems If Shuttle Main Engines Are Altered Significantly

- *Main Engine Controller (computer) hardware and software.*
- *Engine interface Unit Hardware—device* that couples the main engine controller computer to the General Purpose Computer network.
- *Flight Software Applications* executing in the General Purpose Computer Complex.
- *The Pulse Code Modulation Master Unit data access programs and telemetry formats*—device that receives data from the main engine for telemetry to Earth.
- *Various Ground Checkout hardware and software at* K!K—especially the Launch Processing System applications software.
- *Mission Control Center software—used* for monitoring of engine performance during launch.
- *Main Engine Environment* Models—used in the following simulation and test facilities:
  - —Software Production Facility
  - —Shuttle Mission Simulator
  - —Shuttle Avionics Integration Facility
  - —Various flight design engineering simulators

[3] National Aeronautics and Space Administration, "Shuttle Ground Operations Efficiencies/Technology Study, " KSC Report NASIO-11344 Boeing Aerospace Operations Co., May 4, 1987.

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

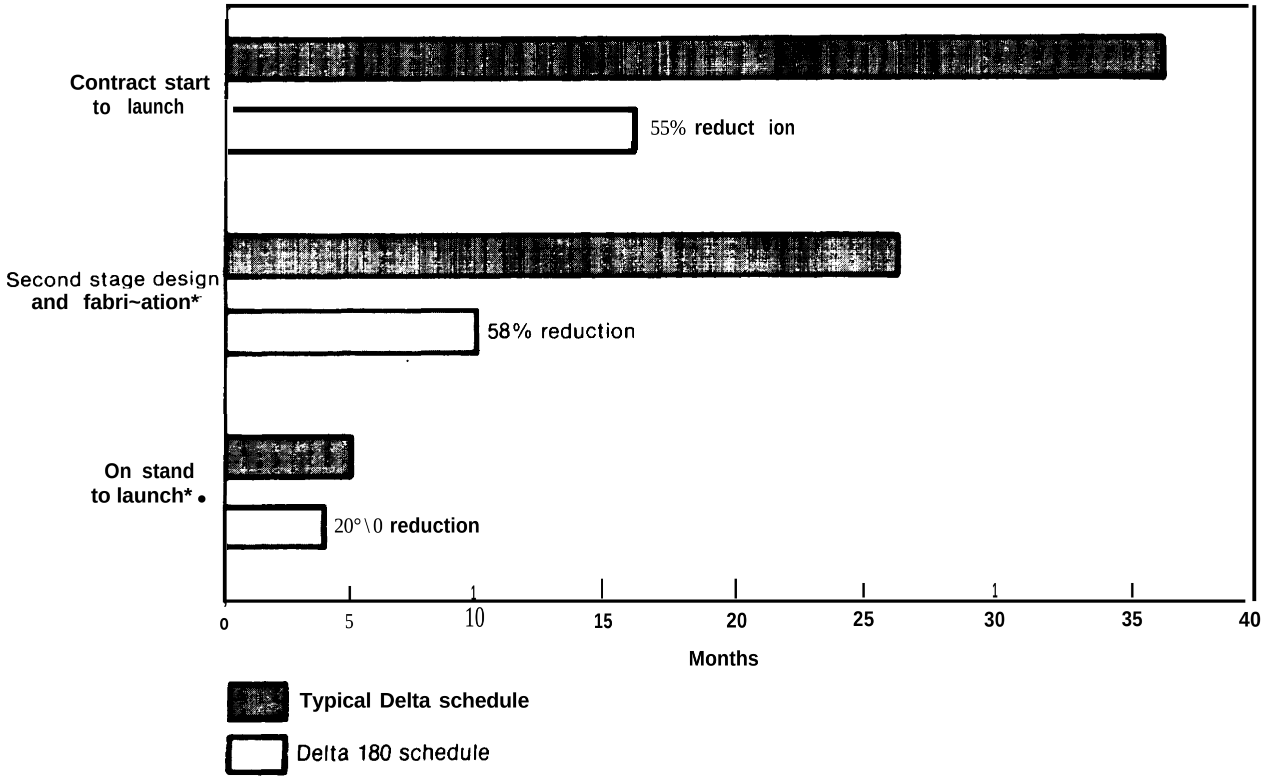
schedule (fig. 2-3) reduced overhead costs of the entire project by about 50 percent. In part this was achieved by giving contractors cash incentives to achieve the demanding project schedule. Company employees shared in bonuses paid to the company for meeting deadlines, which gave them strong incentives to increase productivity. Table 2-1 lists the major factors that led to lower costs and shorter project schedules for the Delta 180 project. Although the team was able to achieve some of its cost savings as a result of a focused, narrow effort, which would be difficult to maintain for routine launches, the project nevertheless demonstrated that management philosophy can play a significant role in reducing the costs of launch operations.

Today launch system planners are focusing directly on reducing the labor and attendant costs of launch operations. Historically, the chief means of reducing operations costs, relative to achieved lift capacity, is to increase vehicle performance. Over the years, NASA, the Air Force, and the launch vehicle manufacturers have made incremental improvements to launch system performance and reliability that have also led to operations cost savings. For example, in its early flights in the 1960s, the Delta was able to launch only 100 lbs. to geosynchronous transfer orbit (GTO). Today, the Delta can launch over 2,800 lbs. to GTO. Launch operations costs' are now about 10

[5]The Space Shuttle presents a counter example. Because of the desire to improve the safety of Shuttle crews and payloads, the payload capacity of the Shuttle has actually decreased over the years. Originally designed to carry about *65,000* lbs. to low Earth orbit (at *160* nautical miles), the Shuttle's payload capacity is now only about *48,000* lbs.

[6]These costs include only contractor personnel and other recurring costs directly attributed to the launch. They do not include maintenance and other general costs associated with the launch pad.

Figure 2-3.— Delta 180 Project Schedule Reductions



● Represents design and fabrication of the PAS—essentiaily a new third stage.
•'Includes the PAS which doubles requirements of a normal Delta launch.

SOURCE National Aeronautics and Space Admlnlstratlon

Table 2=1.—Cost Reduction Factors for the Delta 180 Project

- Given program autonomy—minimum program management and reporting
- Short statements of work—2 pages
- Organized in terms of working groups responsible for specific tasks—given autonomy to solve problems within working groups
- Within working groups, contractors worked as an integrated team from the beginning—close contact among all team members, open discussion

SOURCE: Department of Defense Strategic Defense Initiative Office/Kinetic Energy Office, "Delta 1S0 Final Report," vol. 5, March 1987.

percent of the total costs per flight. Performance improvements to the Delta[7] (designated a Delta II) should increase its lift capacity to 4,000 lbs. to GTO, but are not expected to alter significantly the complexity or the cost of ground operations, though the cost of the vehicle has certainly increased. s Hence, should the per flight costs directly attributable to operations remain constant, operations costs of the Delta II per pound[9] could decrease by about 40 percent compared to the current Delta launcher.[10 11] Historically it has taken about 150 resident McDonnell Douglas personnel at Cape Canaveral to perform the launch vehicle processing activity at a 6-launch-per-year rate. This includes all administrative functions, ground support equipment operation and sustaining, procedure preparations, payload integration and launch vehicle processing through launch.

New Launch Systems

Several recent studies'[z] have suggested that starting fresh and designing to cost rather than for performance would lead to significant reductions in the costs of launch operations. These studies identified several approaches to system design. The OTA workshop generated its own list of design goals (table 2-2). The discussion in chapter 4 elaborates on these goals, and lists a number of technologies that would serve them.

NASA and the Air Force are working on a variety of new launch system designs. In particular, they are collaborating on a major study of an Advanced Launch System (ALS), whose goals are to increase the payload capacity per launch by a factor of 3 or 4 and to reduce the cost per pound of launching payloads to space by an order of magnitude.[13] Although a "clean sheet of paper" approach to launch system design offers potential benefits in reducing life-cycle costs, it also increases the technical and cost risk of launch system manufacturing and operations. In addition, the non-recurring investment in new facilities, and research and development, will offset part of the savings in recurring costs anticipated from such changes.[14] Thus it is necessary to address the entire set of launch procedures, including aircraft, trains, barges, and other auxiliary facilities, which function as a single integrated system.

ISSUE B: Is the United States Devoting Adequate Attention To Reducing the Costs of Space Transportation Operations?

Both NASA and the Air Force are funding research on new technologies for launch systems. Yet only a small percentage of this research is devoted to development of technologies for space transportation operations and only part of this is directed toward improving existing operations.

'McDonnell Douglas is making these improvements in connection with the Air Force MLV program. The first Delta II launch is expected in ***1989.***

'Lyle J. Holloway, McDonnell Douglas Astronautics Co., ***1987.***

'This example illustrates one kind of savings possible as vehicles are improved. However, for many purposes, figuri‹g costs of launching payloads on a per pound basis may not be appropriate. The life-cycle cost of a launch system for a given collection of payloads over the years is often a more appropriate measure. 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).

*"These performance improvements will be accomplished by improved solid rocket booster engines and an improved main engine.

"Concurrently, the Delta launch crew efficiency has also improved, resulting in a higher percentage of launch successes, and the potential for a higher launch rate (box 2-B). Delta has improved its launch success rate over the years from 93 percent (170 out of 182 launches) in the 1960s to nearly 98 percent in recent years (one failure in 48 launches since 1977).

"U.S. Government, ***National Space Transportation and Support Study 1995-2010,*** Summary Report of the Joint Steering Group, Department of Defense and National Aeronautics and Space Administration, May 1986; Advance Launch System Phase I Study briefings, 1987, 1988.

[13] 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), ch. 5.

[14] 1 bid., ch. 7.

Box 2-B.—The Delta Experience

The following illustrates one company's experience in providing launch services to the Government.

- *Minimal oversight.* Part of the key to lowering launch operations costs is to keep the number of Government personnel devoted to overseeing contractor preparations as small as possible. Responsibility for management of the Delta program has recently shifted to DoD. When under the management of NASA, McDonnell Douglas' main customer for Delta launches was the NASA Goddard Space Flight Center (GSFC), whose primary mission is the preparation and launch of NASA's scientific payloads. GSFC employed 15 to 20 engineers to oversee the Delta launch operations. The GSFC team was kept deliberately small, to avoid the temptation to over-manage McDonnell Douglas' launch preparations. McDonnell Douglas attempted to discuss launch problems and resolve them with GSFC immediately. GSFC personnel worked with the contractor's internal documentation, and if a Government or military specification or procedure showed greater risk in cost than it was likely to return in increased reliability it was discarded or tailored. Documentation requirements were kept to a minimum.
- *Self-sufficiency.* McDonnell Douglas has minimized the number of associate contractors or subcontractors with their own independent documentation procedures and systems necessary to work on the vehicle or facility. In addition, the Delta team prepares the vehicle on the basis of a single Launch Preparation Document, which includes inputs from all departments. It gives all requirements for assembly and test of the vehicle, traceability and accountability of all flight and non-flight hardware, and of all test and operational requirements. Daily meetings near launch time with all the technicians, inspectors, test engineers, managers, and the customer for the launch, enables significant problems to surface. This results in a single, informed team with a common objective.
- *Mindset toward economy.* Although the Delta has always been operated on a budget typical of small scientific or commercial payloads, in the late 1970s McDonnell Douglas began to explore new ways to economize on the Delta when it became apparent that Government use of all ELVS was to be phased out after the Space Shuttle became operational. McDonnell Douglas funded (with RCA) the development of upgraded Castor IV strap-on solid rockets, which increased Delta payload capacity 50 percent, and also found ways to economize on launch operations procedures. Although each individual step has been small, over time, such steps have made the entire set of procedures more cost effective.

SOURCE: McDonnell Douglas Astronautics Corporation.

Table 2-2.—Approaches to Low"Cost Launch Design

- **Include all segments of the launch team (including managers) in the design of a new launch system**
- **Reduce launch system complexity**
- **Increase maintainability**
  - **—Increase subsystem accessibility**
  - **—Design for modularity**
  - **—Include autonomous, high-reliability flight control and guidance systems**
  - **—Build in testing procedures, for mechanical and fluid systems, as well as for electronic systems**
- **Make payloads independent of launcher, with standardized interfaces**

SOURCE: Office of Technology Assessment, 19SS.

Through its Office of Aeronautics and Space Technology, NASA has funded a Civil Space Technology Initiative (CSTI), which is pursuing research on a number of technologies, including autonomous systems and robotics~that could im~prove some launch procedures and might even lead to cost savings (table 2-3).

As part of the CSTI, all the NASA centers are involved to some extent in the Systems Autonomy Technology Program, which has been designed to develop and demonstrate the feasibility of using "intelligent autonomous systems" in the U.S. civilian space program, and to enhance NASA's in-house capabilities in designing and applying autonomous systems. Some of these systems, if successful, will have direct applications for launch and mission operations. For example, the Systems Autonomy Technology Program is developing an online expert system to assist flight controllers in monitoring and managing Space Shuttle communications. It is also developing the hardware and software for autonomous diagnostics and control for the KSC Launch Processing

System. Both systems would increase the reliability and capability of mission and launch operations and could eventually lead to reductions in the number of personnel necessary for these tasks.

The CSTI is designed to demonstrate the feasibility of selected technologies. However, without a clear and focused plan for choosing which technologies are needed for launch and mission operations, and inserting them into existing procedures, they may not be applied effectively. The NASA Office of Space Flight is planning an Advanced Operations Effectiveness Initiative, to begin in fiscal year 1989, that would provide plans for inserting new technology into launch and mission operations. Though funded at only $5 million per year, this initiative should play an important role in improving operations procedures, because it can verify, validate, and demonstrate technologies developed under the CSTI. In the long run, it could also lead to lower operations costs. Congress could consider funding this program at a higher level.

Through the Focused Technology Program, funded within the Advanced Launch System program, NASA and the Air Force are working together on research crucial to reducing operations costs. Some of these technologies may also contribute to improving the efficiencies of existing systems (table 2-4).

The National Aeronautics and Space Act of 1958 gave NASA the responsibility of "the preservation of the role of the United States as a leader in aeronautical and space science and technology.[15] Its role as a research and development (R&D) organization is firmly imbedded in its institutional culture. The Air Force is mission oriented; its launch systems organization is therefore organized to respond to the special transportation needs of the DoD payload community. Both organizations have developed different institutional cultures applying different operational approaches, which occasionally lead to costly friction in programs of mutual interest. For example, in the area of launch vehicle R&D development, the two organizations continue to compete for funding and for program lead. Yet, especially in this era of budget stringency, the Air Force and NASA must work together more effectively on research to improve existing systems and develop the next-generation launch systems.

15 Natjona] Aeronautics and Space Act, Sec. 102(5), 24 U.S.C. 2451.

Table 2-3.—Civil Space Technology Initiative Funding (in miiiions)

Program area	FY 88	FY 89 (requested)
● Automation and robotics ...	$25.1	$25.9
Propulsion	23.8	46.7
Vehicle (aeroassist flight experiment).	15.0	28.0
‘Information technology	16.5	17.1
Large structures and control.	22.0	25.1
Power	12.8	14.0
Total	$1 15.2	$156.8

"Technologies of importance to launch and mission operations.

SOURCE: National Aeronautics and Space Administration.

ISSUE C: What Factors Impede the Introduction of New Technologies and Management Strategies in Launch and Mission Operations?

Existing launch and mission operations are extremely complicated, and have unique requirements for technology, facilities, and management. For example, operations procedures may necessitate airplane runways; test facilities for a wide variety of equipment; massive, environmentally controlled buildings for launcher assembly and checkout; and fixed and mobile launch pads. Logistics, including the provisions of parts and supplies, contributes its own complexities. Each facility adds additional complexity and distinctive management requirements. In addition, the Government is both financially and institutionally invested in existing operations procedures. The following factors make it difficult to reduce operations costs significantly for existing launch systems:

Investment in Existing Infrastructure.—The United States has already invested billions of dollars in facilities at Kennedy Space Center (KSC), Johnson Space Center (JSC), Cape Canaveral, and Vandenberg.

From a near-term budget perspective, it is easier to justify refurbishing old facilities than to build totally new ones because the short term costs are often lower. However, existing facilities that were built for earlier launch programs require continued modernization and repair, and the resulting inefficiencies become part of the work flow

Table 2-4.—Advanced Launch System Focused Technology Program (in millions of 1988 dollars)

	Year				
	1987188	1989	1990	1991	1992
Propulsion:					
Engine definition/demonstration	$ 12.00	$ 6.00	$ 16.50	$30.10	$ 31.40
LOX/LH2 engine	17.60	26.80	45.60	18.20	9.60
LOX/LHc engine	32.90	16.30	32.90	28.60	11.50
Propulsion subsystems	0.50	1.40	4.50	5.60	4.00
Solid rocket booster	7.00	12.00	15.00	15.50	17.50
Propulsion facilities	24.00	34.00	20.00	7.00	2.00
Total	94.00	96.50	134.50	105.00	76.00
Avionics/Software:					
● Adaptive guidance, navigation and control	6.10	6.40	7.00	4.00	5.00
● Multi-path redundant avionics	10.30	0.00	0.00	0.00	0.00
● Expert systems	3.50	0.00	0,00	0.00	0.00
● Electromechanical actuators	6.50	0.00	0.00	0.00	0.00
Flight simulation lab	2.00	2.50	3.00	3.00	3.00
Total	28.40	8.90	10.00	7.00	8.00
Structures/Materiais:					
Cryogenic tank(s)	14.00	15.00	15.00	19.00	12.00
Booster	3.00	6.00	6.00	8.00	11.00
NDE for SRB	1.00	2.00	4,00	4.00	2.00
Structural certification	8.00	5.70	10.00	3.00	1.00
Total	26.00	28.70	35.00	34.00	26.00
Aerothermodynamics/Fiight mechanics:					
● Precision recovery	2.50	4.00	5.00	5.00	2.00
Multi-body ascent CFD	0.50	0,00	0.00	0.00	0.00
Aero data base	0.50	0.00	0.00	0.00	0.00
Base heating codes	0.50	0.00	0.00	0.00	0.00
Total	4.00	4.00	5.00	5.00	2.00
Groundandfiight operations/Manufacturing:					
● Ground operations	14.10	7.00	13.00	12.00	7.00
● Health monitoring demo	4.00	4.63	5.16	4.63	3.58
● ManTech	4.50	5.20	7.22	5.70	4.03
Total	22.60	16.83	25.38	22.33	14.61
Grand total	$175.00	$154.93	$209.88	$173.33	$126.61

"Technologiesof importance in launch and mwslon operations

SOURCE: U.S. Alr Force.

and extend throughout the life of theprogram.[16] For example, because the Vehicle Assembly Building, used for attaching the Shuttle orbiter to the external tank and solid rocket boosters, was originally built for the Saturn 5 program, it does not have the optimum size and shape for the Shuttle, which leads to longer and more complicated vehicle assembly. Thus, the long-term costs maybe greater than if a new, more appropriate, facility were built.[17]

[16] National Aeronautics and Space Administration, "Shuttle Ground Operations Efficiencies/Technology Study, " KSC Report NAS1O-11344, Boeing Aerospace Operations Co., May 4, 1987, p. 4.

[17] In addition, many replacement parts required for certain Shuttle test or training systems are no longer being manufactured and must be custom built or refurbished by NASA.

On the other hand, any investments in new facilities, such as a new launch complex, must also be weighed against the expected savings to be gained over the expected life of the launch system. If the up-front costs are great enough, they could outweigh the total operational costs for current systems, even if some reductions in operations costs are achieved. However, because facilities become obsolete and equipment wears out over time, and must be replaced, opportunities will arise for making program changes in the course of replacing outdated facilities. Program changes that require either major alterations, or replacement of otherwise usable launch facilities, may lead to greater life-cycle costs. Because they involve projects requiring considerable manpower, the construction and geographical placement of new facilities may also face political constraints that affect life-cycle costs.

Old **Systems That** Need Upgrading.—Because the United States decided in the early 1980s to phase out ELVS and depend solely on the Shuttle for launch services, needed improvements to the efficiencies of ELV launch fleets and facilities were not made. Many of these improvements, including performance upgrades, lighter and more capable avionics packages, and higher performance, safer solid rocket motors, are being made today as part of the Air Force's competitive ELV purchases.

Because certain parts of the Shuttle system are now more than a decade old, they need to be upgraded as well. For example, both the Shuttle's flight computers and the Shuttle processing system computers are being replaced. These changes are unlikely to lead to cheaper operations, though they will increase the capability of the Shuttle system and may contribute to greater reliability.

Excessive Documentation, Oversight, and Paperwork.—As one workshop participant charged, "it is the Government's excessive oversight and documentation that have kept the cost of space launch management and operations outrageously high. " Both the Government and the contractor incur high costs from extra oversight personnel and from reporting requirements such as the Cost and Schedule Reporting System (C/SCSC). Although this system can provide useful information for reducing costs, "it must be tailored to the program and its true cost to administer must be carefully weighed against its advantages. "[18]

Excessive Government oversight and reporting requirements generally develop incrementally as a response to real problems of quality control, a concern for safety, and the desire to complete high cost projects successfully. Over time these small increments of personnel or paper build to the point that they impede efficient operations, limit contractor flexibility, and add unnecessary costs.

Chapter 4 discusses several technological options for reducing the paperwork burden through installation of automated systems. It also examines the inefficiencies introduced by excessive oversight of contractors during the launch process.

Uniqueness of Launch Pad and Other Facilities.—Current U.S. facilities are often unique to a given launch system, and therefore different facilities cannot be shared. It may be possible to design future launch pads to accommodate several different launch vehicles in order to save on facilities costs. For example, the Aerospace Corporation has explored the potential of using a universal launch complex, which would be designed with a universal launch stand, a universal mobile launch platform, and a modular assembly integration building.[19] A modular integration building, in which a variety of vehicle designs can be assembled and integrated, is particularly important. However, such designs would represent a major change in the way the United States manages its launch operations and would require strong interaction between launch vehicle designers and facilities planners. These changes in operations procedures would also mark a step toward establishing launch operations that functioned more like airline operations.

Lack of Sufficient Incentives for Lowering Costs.—The current institutional and management structure provides few incentives for reducing costs of launching the Shuttle or ELVS for Government payloads. "The system does not have incentives built in for achieving low-cost, successful launches," observed one workshop participant. "There is the incentive not to fail, but not the incentive to lower costs. " Several participants noted that NASA lacked the administrative structure for tracking funds and responsibilities by item to reward managers directly for reducing costs and increasing efficiency. Participants also pointed to the fact that although it is possible to fashion incentives for top-level management, it is difficult to make suitable incentives "transfer down to the guys who do the work" on the launch pad.

A recent study echoed these points and found that contractors generally have little incentive to reduce costs because "their profit/cash flow is

[18] *Space Systems and Operations Cost Reduction and Cost Credibility Workshop: Executive Summary* (Washington, DC: National Security Industrial Association, January 1987), p. 2-5.

[19] U.S. Air Force, "Strategic Defense Initiative Launch Site Considerations," Report No. TOR-0084A(5460-04)-1 (Los Angeles, CA: Air Force Space Division, July 1985).

reduced when they perform under budget." In addition, the program officers "do not have an incentive to reduce spending below the program budgeted amount."[20]

ISSUE D: What Impediments To Reducing Operations Costs Are Unique to the Space Shuttle?

The complexity of Shuttle and payload processing, and crew training, require substantial annual investment in personnel and facilities. The following points illustrate the most important impediments to reducing the costs of Shuttle launch and mission operations:

- Shuttle still in development. —Although NASA declared the Shuttle system operational after the fourth flight, it has as yet not achieved true operational status.[21] Because the Shuttle is still undergoing major design changes, it requires a larger launch operations staff than an "operational"[22] system. For example, NASA employs about *5000* engineers at KSC, Marshall Space Flight Center, and JSC who work on Shuttle systems. They have strong incentives to implement changes for increasing safety and performance, many of which increase the time and cost of preparing Shuttle for flight. On the other hand, there are few incentives for increasing operations efficiency and reducing costs.
- *Safety requirements.* —Because the Shuttle carries human crews, and because it is a highly visible symbol of American technological prowess, safety issues receive unusually great attention. As a result of the investigation of Shuttle subsystems following the loss of Challenger and its crew in January, 1986, the Shuttle system is now undergoing many major safety-related changes,[23] which have led to considerable system redesign. These changes have also increased the time and complexity of launch operations. Prior to the loss of Challenger, NASA had reduced the turnaround time necessary to prepare the Shuttle orbiter for flight to about 55 workdays (three shifts a day).[24] NASA expects orbiter turnaround for the first few flights to equal about 150 workdays, decreasing to an average 75 workdays only after 4 years of additional experience.[25] However, judging from the experience in preparing Discovery for the first reflight of the Shuttle since the Challenger explosion, this sort of turnaround may be extremely difficult to achieve.
- *Lack of spares; cannibalization of orbiter parts.* —The Shuttle program has had a continuing problem maintaining a sufficient stock of major spare parts and subsystems. For example, 45 out of 300 replacement parts needed for Challenger on mission 51-L had to be removed from Discovery.[26] This has significantly impeded the ability of launch crews to refurbish and test Shuttle orbiters between flights. Each time a part must be taken from one orbiter to substitute for a defective part in another, the amount of labor required more than doubles (table 2-5). In addition, the process increases the chances of damaging either the part or the subsystem from which it is removed. Although NASA has improved its stock of spares for the Shuttle, the budget allocated for spares continues to be a target for reductions. NASA runs a continuing risk of having to cannibalize parts from one orbiter to process another.
- *Complexity of the Shuttle* systems.—The Shuttle was a revolutionary step in launch systems, and was not designed for operational simplicity. As with experimental aircraft, many of its systems are highly complex, and made up of a multitude of parts

[20] ***Space Systems and Operations Cost Reduction and Cost Credibility Workshop: Executive Summary*** (Washington, DC: National Security Industrial Association, January 1987), p. 2-2.

[21] George E. Mueller, Panel discussion, ***Space Systems Productivity and Manufacturing Conference IV*** (El Segundo, CA: Aerospace Corp., August 1987), pp. 232-235.

[22] The term "operational" implies that the vehicle in question is capable of being launched routinely on a well-defined schedule with a minimum of unplanned delays.

[23] Major alterations include improvements to the SRBs, modifications of the SSMEs, and installation of an escape hatch in the orbiter.

[24] This does not include time the orbiter spends in the Vehicle Assembly Building and on the launch pad.

[25] Charles R. Gunn, "Space Shuttle Operations Experience," paper presented at the 38th Congress of the International Astronautical Federation, Oct. 10-17, 1987.

[26] Report of the presidential Commission on the Space Shuttle Challenger Accident (Washington, DC: U.S. Government Printing Office, 1986).

Table 2-5.—Steps in the Changeout of Defective Parts in the Shuttle Orbiter When Replacement Spares Are Unavailable

A part is needed for orbiter A. It is not in the parts inventory, but is available in orbiter B, which is not scheduled to fly for several months. The following steps are necessa~:

+ Document steps of part% removal from orbiter B.
+ Remove part from orbiter B. (It takes longer to remove a part from an orbiter than to take it from storage.)
  Document installation in orbiter A.
  install the part in orbiter A.
  Test part in orbiter A.
+ Document installation of replacement part in orbiter B.
+ instaii replacement part in orbiter B.
+ Test replacement part in orbiter B.

+ = Addition to standard procedure.

SOURCE: Office of Technology Assessment, 198S.

that need to be inspected or repaired.[27] For example, each of the solid rocket boosters (SRBS), one of the simpler Shuttle elements, contains about 75,000 parts and components. Of these, about 5,000 are removed, inspected, and replaced or refurbished after each Shuttle flight. A design that required inspecting and handling of fewer parts would require fewer launch personnel. However, the costs of redesign, testing, and acceptance of such a simplified design must be taken into account.

The thermal protection system, composed of over 31,000 fragile tiles, requires careful inspection and repair, an extremely labor intensive operation. Although only about so tiles now need replacing because of damage after each flight, all of them must be inspected.[28] Not only must they be inspected for damage, they must also be tested for adherence to the vehicle, and the gaps between tiles carefully measured to assure sufficient space for thermal expansion upon reentry. (See ch. 4, box 4-A for a description of a semi-automated system for inspecting and replacing the TPS.)

Finally, the Shuttle orbiter has about *250,000* electrical connections which must be tested for continuity. Each time one of the 8,000 connectors is disconnected or removed, there is a chance that one or more pins will be damaged or will otherwise fail to reconnect properly.

ISSUE E: What Can the Operational Experience of the Airlines Contribute to Space Operations?

Although the technical and managerial constraints on airlines operations are quite different than for launch vehicles, certain of their methods used in logistics, maintenance, task scheduling, and other ground operations categories may provide a useful model for making launch operations more efficient and cost-effective. Because of the extreme volatility of launch propellants and a relatively low launch rate, other airlines methods may not be applicable to launch or mission operations. Chapter 4 discusses the specific applications of airline operations practices to space operations. Many of these lessons are being applied in the Advanced Launch System program (see ch. 4). The airlines:

- *. . . begin cost containment program at planning stage.*[29] New aircraft design takes into account operational requirements such as support equipment, logistics flow, and facility design, as well as payload characteristics and route structure, in the early planning stages.
- *. . . involve operations personnel in design changes.* As one workshop participant observed, “the chief objective of the airlines is to move a seat from A to B as quickly and efficiently as possible. Safety is a primary goal, but increased efficiency is a basic requirement for making any design change.” Increases in efficiency must outweigh any shortcomings brought about by incorporating such a design change in the entire system.

[27] George E. Mueller, “Panel on Productivity Issues for Space and Launch Systems, ” *Space Systems Productivity and Manufacturing Conference IV* (El Segundo, CA: The Aerospace Corporation, 1987), pp. 232-35.

[28] Only a few tiles are interchangeable; most are unique three dimensional shapes that are fitted to the curved surfaces of the orbiter. Charles R. Gunn, “Space Shuttle Operations Experience, ” paper presented at the 38th Congress of the International Astronautical Federation, Oct. 10-17, 1987, p. 2.

“’’Space Systems and Operations Cost Reduction and Cost Credibility Workshop,” Executive Summary (Washington, DC: National Security Industrial Association, January 1987), pp. 2-18-2-19.

- . . . *have developed detailed cost estimating relationships for operations.* When an aircraft manufacturer suggests improved equipment for an aircraft subsystem, the airline can generally estimate the recurring and nonrecurring costs and any potential savings to be gained. The airlines also have an extensive historical database to assist them in testing the accuracy of their own cost estimation models.
- . . . *stand down to trace and repair failures only when the evidence points to a generic* failure. Generally the airlines continue flying when one aircraft has crashed unless there is clear initial evidence of a generic fault in the aircraft model. For example, in the November, 1987 crash of a DC9 in a Denver snowstorm, other DC9s continued to fly. However, in the 1979 crash of a DC1O in Chicago, the entire DC1O fleet was grounded because there was early evidence that the wing mounting of one of the engines had failed, and safety officials were concerned that generic structural faults might have caused the failure.
- . . . *insist on aircraft designed for fault tolerance.* Commercial aircraft are designed to be robust enough to fly even when they have known faults. Airlines, with thousands of flights per day, have developed a minimum-equipment list—a list of vital operations equipment that is absolutely mandatory for flight; if any of this equipment malfunctions on pre-flight check-out, the plane is grounded until the problem is fixed. The existence of such a list means that an aircraft can fly with known faults as long as they are not on the minimum equipment list.
- . . *design aircraft for maintainability.* Commercial airliners are designed to be inspected periodically and to have certain parts and subsystems pulled and inspected after a given number of hours of flight. The airlines call this practice “reliability-centered maintenance.”
- . . . *encourage competitive pricing.* For the manufacturers of aircraft and aircraft subsystems, the ability to purchase competitive systems from several suppliers acts as an incentive not only to reduce costs, but to improve reliability.
- . . . *maintain strong training programs.* In the airlines, at all times some 10 percent of the operations crews are in training. Training includes all aspects of the operations procedures. Extensive training contributes to flight safety as well as to lowering costs.
- . . . *use automatic built-in checkout of subsystems between flights.* Many aircraft subsystems can be checked from the cockpit or from mobile ground units between flights, and in some cases, even in-flight with the aid of ground-based data links. Because they involve minimum operator interaction, these procedures tend to be more accurate than non-automated systems.

ISSUE F: Does the United States Possess Adequate Techniques To Judge the Relative Benefit **of Improvements in Launch and Mission Operations Procedures?**

When debating the relative merits of either improving current launch systems or developing a major new one, the principal question for Congress is: will the investment in a new system be worth it? In other words, will spending more money now yield greater savings later in the life cycle of a system? Answering this straightforward question is impossible without adequate models for estimating costs. OTA workshop participants generally agreed the United States has not developed adequate cost estimating models for launch and mission operations procedures.

Workshop participants noted that estimating costs of new or improved systems requires data from existing systems. Commercial airlines use extensive historical data to help them create accurate models for estimating costs, but launch operations do not have a comparable database to draw upon. In addition, NASA and the Air Force have made no focused effort to collect such information. For example, there are no detailed historical records tracing the number and cost of personnel for different components of space operations. One reason is that this information, where gathered, often rests with the contractors, who regard it as proprietary, In addition, for systems in development, the technologies tend to be more fluid, and therefore operations data that could be collected are poor predictors of the applicable costs for later routine launches. A deeper reason is that the funding required to gather and analyze such historical data is often the first thing to be eliminated from a program to save money —"but what is being eliminated is the future capability to learn from mistakes," stated one workshop participant. Today we do not have sufficient data on which to base a more meaningful cost estimation model.

STAS contractors focused some effort on cost modeling, but their work was hampered by inadequate historical data. In addition, the accuracy of cost models developed by the contractors awaits validation. The ALS Phase 1 study teams have continued work on developing better cost models.

What is often unclear in policy debates over the choice of a new space transportation system is that estimating the costs of ground operations is necessarily uncertain and partially subjective. Program managers often fail to calculate and present to policymakers the uncertainties in estimated costs. New cost models will reduce the uncertainty and subjectivity of cost estimation but not eliminate them. If such uncertainties and subjective judgments were made more explicit, it would be possible to give policy makers a clearer sense of the economic risks of alternatives.[30]

Appendix A contains a brief summary of current cost estimation methods that illustrates the uncertainty and subjectivity involved. Methods used in the Space Transportation Architecture Study (STAS) are typical and are used as examples.

ISSUE G: Are **the Near-Term Launch Systems Under Study by NASA and the Air Force Likely To Generate Major Reductions of Launch Operations Costs?**

The goal of the Advanced Launch System (ALS) program is to design a low cost, heavy lift launch system to serve U.S needs at the turn of the century.[31] Chapter 4 examines many of the operations technologies under study in the ALS program. However, because an ALS would require some technologies not fully developed at this time, and because NASA and the Air Force would like to be prepared to meet any additional demand for launch services in the mid 1990s, they are also considering options for new, interim, high capacity launch systems based on current technology.[32]

The following paragraphs discuss the launch operations requirements of two options, one based on Shuttle technology, the other based on a variety of other technologies, and explores whether they would lead to reduced operational costs. OTA's analysis of these proposed systems leads to the general conclusion that although careful design, which took into account the operational requirements of such systems, could indeed reduce operating costs, the investment cost of adding the necessary operations infrastructure and its attendant recurring costs might offset such gains, especially if launch demand remains low. Policy makers should carefully scrutinize estimated life-cycle costs of any new system.

Shuttle-C (Cargo Vehicle)

NASA's version of a heavy-lift launch vehicle is the Shuttle-C, which in several respects competes with Air Force heavy-lift concepts. The Shuttle-C[33] would be an unpiloted cargo vehicle based primarily on Shuttle technology. It would use the solid rocket boosters, the external tank, and the main engines (SSMES) from the Shuttle system. A large cargo canister, capable of transporting some 85,000 to 100,000 Ibs. of payload to low-Earth orbit, would take the place of the current Shuttle orbiter.[34] If Shuttle-C is used to ship major subassemblies of the space station to orbit, one Shuttle-C flight would replace two or three Shuttle missions. These could reduce

[30] T. Mullin, "Experts' Estimation of Uncertain Quantities and Its Implications for Knowledge Acquisition," *IEEE Transactions on Systems, Man, and Cybernetics* [to be published].

[31] The program's original goal was to design a heavy-lift launch system that would serve U.S. needs at the turn of the century, resulting in a so-called "objective" system, with an "interim" system based on existing technologies for the mid 1990s. However, congressional resistance to funding a system capable of launching a space-based ballistic missile defense system caused Congress to forbid expenditures for studies of an interim ALS system.

[32] 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), ch. 4,

[33] Ibid.

[34] STAS also considered in-line Shuttle-derived vehicles, but these are considered to require too much development to be considered as a low-cost alternative at the present time.

the need to fly all of NASA's planned shuttle missions.

Shuttle-C would have the advantage of using much of the same technology and many of the same parts that have already proved successful in 24 flights. To keep fixed costs down, it would use the same launch pads, vertical integration facilities, and launch support crews now used for the Shuttle. It carries the disadvantage that a stand down of the Shuttle might well result in delaying Shuttle-C flights for the same reasons.

However, the following considerations would affect the costs of launch operations for the Shuttle-C:

- Not having to process a Shuttle orbiter would likely speed up launch operations and therefore reduce total operations costs compared to the Shuttle.[35] However, it would still be necessary to assemble, integrate, and test the Shuttle-C before flight. In addition, some Shuttle-C designs call for employing a reusable engine/avionics package that would need to be refurbished after each flight. If the Shuttle-C were not specifically designed for simplicity and ease of operation, its operational costs could grow to become a significant fraction of the cost of preparing the Shuttle orbiter.
- Shuttle-C will affect the processing flow of the Shuttle orbiter. Because the Shuttle-C would be the same overall size and configuration as the Shuttle, it could be processed in the same facilities as" the Shuttle, and inserted into the Shuttle flow, if the Shuttle launch schedule permits. This raises several cost-related issues.

  First, because NASA intends to use Shuttle-C for transporting major components of the space station to orbit, which are likely to be of substantially greater value than the vehicle, NASA would have considerable incentive to process the Shuttle-C as carefully as it processes the Shuttle, and with the same crews and procedures.[36]

  Second, the Shuttle facilities themselves, including the launch pads, may constrain NASA's ability to reach the 12-14 launches per year projected for a 4-orbiter fleet, and simultaneously launch Shuttle-C two or three times a year. Launching both vehicles requires either shifting some payloads, such as space science missions, to the Shuttle-C and flying fewer orbiter missions, or building new facilities to accommodate Shuttle-C. New or upgraded facilities might include increased engine shop facilities, an engine/avionics processing facility, and a mobile launch platform. Any necessary new facilities should be taken into account when costing the Shuttle-C system.[37]

  Inserting Shuttle-C into the Shuttle processing flow could actually increase costs for launching the orbiter because of the risk of slipping Shuttle-C schedules. Experience has shown that nonstandard tasks, such as engineering modifications or special instrumentation, imposed on the Shuttle processing flow can contribute as much as 50 percent to an orbiter's turnaround time.[38] Because, except for the orbiter, Shuttle-C hardware would be quite similar to Shuttle hardware, we should expect Shuttle-C to experience similar delays for several years after being introduced into NASA's fleet. Modifications to non-orbiter Shuttle subsystems would have to be made on the Shuttle-C as well.

  Finally, because Shuttle-C would share many parts with the Shuttle, delays may occur in one or the other launch system should the parts supply system become choked. On the other hand, because parts become cheaper when purchased in quantity, the existence of a Shuttle-C might reduce the costs of some parts.
- Mission Operations would be simpler and therefore less costly than for the Shuttle orbiter. Because the Shuttle-C would not carry humans, mission operations would consist

[35] Because it takes longer than any other single ground operations procedure, processing of the Shuttle orbiter effectively sets the Shuttle launch rate.

[36] It might even cost more to develop independent launch processes for Shuttle-C because NASA would then have to train additional launch *crews.*

[37] Recent NASA estimates for the cost of additional facilities at KSC range from $60 to $3oO million depending on the number of projected Shuttle and Shuttle-C flights.

[38] Charles R. Gunn, "Space Shuttle Operations Experience," paper presented at the 38th Congress of the International Astronautical Federation, Oct. 10-17, 1987.

primarily of control, navigation, and guidance, and releasing the payloads at the proper time and in the proper orbit.

- Payload manifesting. For non-monolithic payloads, the costs of payload manifesting and integration are likely to be comparable to the Shuttle. NASA's experience on the orbiter has shown that payloads may interact in unforeseen ways, and require considerably more testing. If payloads were required to be self-contained, as suggested for the Advanced Launch System, it might be possible to reduce some of these costs. However, because the payloads would be required to provide services normally provided by the launcher, such payloads would likely weigh much more. (See ch. 4 for a discussion of this point.)

Air Force Near-Term Launch Systems

The Air Force is considering building larger capacity vehicles to carry spacecraft designed for ongoing Air Force programs, which are slowly but steadily growing in payload mass and size as they grow more capable. Modifications to existing vehicles to increase payload capacity offer no great operations savings .39

A new high capacity interim launch vehicle specifically designed for rapid ground operations might reduce launch operations costs sufficiently to pay for the necessary R&D. However, this would also require high demand for launch services.[40] If high demand for cargo launch failed to materialize during 1992-1997, it would not be prudent to invest in a high capacity launch system designed to respond to high launch rate.[41] Developing a new system, even from existing technology, also incurs substantial risk that the new vehicles could not be processed for launch as quickly as planned, whether for technical or "cultural" reasons. In fact, OTA workshop participants were extremely skeptical that launch processing times could be dramatically accelerated in the near term. They argued that only if radical changes were made in the methods of launching space vehicles and the institutional culture surrounding launch processing could costs be brought down significantly.

ISSUE H: How Do Concerns for Launch System Reliability Affect Launch Operations?

The reliability of a launch vehicle (see app. C) has always been of concern to payload managers, because the cost of a payload may amount to two to eight times the cost of launch services. Although some commercial communications satellites are relatively inexpensive compared to research or national security spacecraft, companies may stand to lose potential revenue amounting to hundreds of millions of dollars if their spacecraft fail to reach orbit. Payload owners regard the incremental costs of additional procedures to increase launcher reliability, even for unpiloted vehicles, as worth the cost. The built-in conflict between the desire to reduce launch operations costs and the desire to increase the success of launching spacecraft typically results in increased attention to detail and a consequent increase in costs.

For the high visibility Shuttle, national prestige and leadership as well as safety and reliability are at stake. Losing an orbiter, or even encountering non-catastrophic failures, are blows to national prestige. Nevertheless, in the view of some launch managers, launch operations currently assume more than their share of the cost burden for improvements in the reliability of an operational system. Launch operations tend to be complex and time consuming because vehicles have been designed to achieve high performance rather than rapid, inexpensive launch turnaround, and because launch managers perceive they can improve the chances of launch success by repeatedly testing every possible subsystem before launch. Their confidence in the reliability of a launch system is generally lower than the calculated engineering estimates .42

[39] The Aerospace Corp., Space Transportation Development Directorate, ***Air Force-Focused Space Transportation Architecture Study*** (El Segundo, CA: The Aerospace Corp., Report TOR-O086A(2460-01)-2, August 1987).

[40] The only program currently under consideration that could require this sort of payload demand is the deployment of space-based ballistic missile defenses (SDI).

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

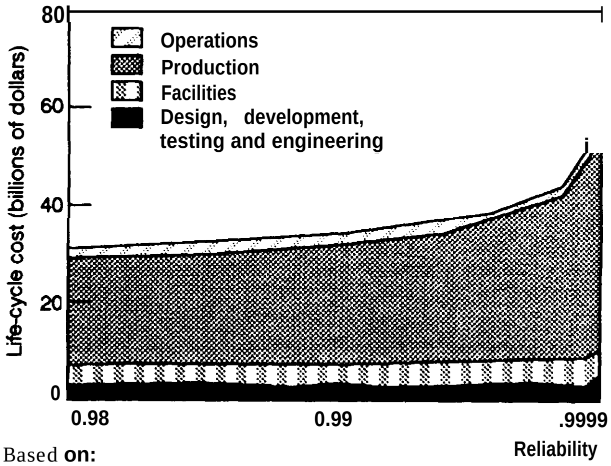
[42] Ibid., p. 85.

Some experts argue that it may not be possible to lower overall launch costs (including the vehicle, payload, and other subsystems) significantly without increasing system reliability because the costs of losing launch vehicles and payloads are too high. A reusable system, especially, depends upon successful recovery and easy refurbishment of expensive components. On the other hand, the experience with recent improvements to the Shuttle system demonstrates how expensive it can be to improve a launch system's reliability. Although experts disagree about the estimated reliability of the Shuttle with these improvements, they do agree that instituting and carrying out a test program capable of substantially improving confidence in the reliability of the Shuttle is likely to be costly. Figure 2-4 illustrates the expected rapid rise in costs as engineers attempt to design vehicles for reliabilities above the 99 percent level.

Because of Titan and Shuttle launch failures in 1985 and 1986, the time it now takes to assemble, integrate, check out and launch these vehicles is much greater than before the failures. Increased emphasis on safety and subsystem testing and quality control to catch potential failures contribute most of such increases. Managers now know much more about the vehicles, though they can seldom point to a specific example of a fault that would likely have led to a launch failure unless repaired.[43]

[43] OTA staff were told at a briefing at Vandenberg Air Force Base in July 1987 that the non-destructive testing of Titan solid rocket motors instituted after the 1986 Titan launch failure had revealed a number of imperfections in the propellant of solid rocket motors segments, which had been stored for some time. These were reworked to eliminate such imperfections. However, it is not at all clear that they would have caused a launch failure if they had gone undiscovered.

Figure 2-4.—Cost of Achieving Extremely High Reliability



Based on:
- Expendable vehicle, 20 years of flight, 1 launch site
- 5M lb to LEO, 125K capability
- 40 flights per year, 100% load factor

SOURCE: Martin Marietta