Chapter 4

Technologies and Management Strategies

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Chapter 4

Technologies and Management Strategies

INTRODUCTION

Launch and mission operations could be made more efficient and less expensive by employing emerging technologies in the three major components of the launch system—ground support facilities, mission control facilities, and launch vehicles. These technologies must be put to work in an institutional structure and culture that facilitates, rather than hinders, their use. Therefore, efficient management strategies must also receive consideration.

The first section of this chapter, Technologies *for Ground and Mission Operations*, introduces operations technologies that could be used in an advanced launch system specifically designed for low cost. They are consonant with technologies for the Advanced Launch System (ALS) currently under consideration by the Air Force and NASA. Many of them would also be appropriate either for enhancing existing launch systems or for inclusion in new launch systems built with existing technologies.

The next section, *T'echnologies for Launch Vehicles*, introduces launch design principles and explores technologies that could be inserted into vehicles to reduce the costs of launch and mission operations. The section on *Management Str-ategies* examines some methods of organizing and managing launch systems to achieve low cost operations. Finally, *Assessing Technological Options and Costs* discusses the principal trade-offs to consider in designing new facilities and a new launch operations strategy, and explores how these concepts and techniques may affect the design, costs, and processing of vehicles and payloads.

TECHNOLOGIES FOR GROUND AND MISSION OPERATIONS

Because of considerable overlap in the technologies that could be employed in launch and mission operations, this section discusses them together. Some of these technologies exist in one form or another today, but would need to be modified for specific space applications; others require additional research and development. Table 4-1 lists some major categories of technologies or applications. Those marked with an asterisk are described and discussed briefly in the text.

Table 4-1.—Technologies for Operations

Automated data management system*
Automated test & inspection*
Automated launch vehicle and payload handling
Database management systems
Computer-aided software development •
Ex~ert systems*

• Discussed in text.

SOURCE: Office of Technology Assessment, 19S8

Automated Data Management System

Computer work stations linked through a network that provides a common database can assist the speed and accuracy of information transfer and make it possible to speed up sign-off procedures. Such automated data management systems are in common use in manufacturing and service industries.

"One of the highest cost items, if you look at the Shuttle program today, is the operations cost associated with all the data processing systems involved, " observed one OTA workshop participant. On-board systems, flight-design-and-preparation, training, launch processing, and mission control systems have all evolved over the years. They are complex, written in different computer languages, and sometimes poorly documented. Each uses different, unlinked databases. Participants further explained that individual program elements have their own autonomous mission planning jobs and their own manner of sending information among the subsystems; people use "bulky paper, communications, phone calls, " and group meetings, and use no integrated approach to transferring the data to all elements, even though they are all interdependent. As a result, although the flow of information within NASA during the launch sequence is excellent, during the months leading up to launch, information flow is very poor. The events before the failure of the Challenger provide an unfortunate example of how constrained the flow of information can be in the months prior to launch.[1]

An automated data management system should be incorporated into any future launch systems. Workshop participants urged planners of future systems to: standardize the architecture of on-board and ground systems, standardize the code used, and minimize custom hardware and software by using commercially available products where possible. One participant estimated that an integrated paperless information-management system could reduce the time spent in launch operations by one-half. The space station project plans an integrated, paperless information system to assist in managing space station operations. Many of the lessons learned in that effort could be applied to launch and mission operations.

Automated Test and Inspection

Automating certain test and inspection procedures could also reduce costs. However, before automating current procedures, they should be carefully examined to see which ones are necessary, and whether some steps can be simplified or even eliminated. "It makes no sense to automate nonsense, " asserted one workshop participant. Certain kinds of automation such as the assembly and test of electrical and electronics systems may be technically straightforward, but difficult to incorporate because workers understand current procedures well and are reluctant to change. Workers require incentives and additional training to smooth the transition to new procedures.

Automating the assembly and test of mechanical, pneumatic, and fluid systems is a major challenge. Today, mechanical and fluid systems create the most operations delays and verification problems, whereas electrical and electronic systems are already well-instrumented and tend to be reliable. For example, on the Delta launch vehicle, more time is spent in mating the strap-on solid- fuel rocket motors to the liquid rocket, fitting the cork insulation, and doing the leak check on the pneumatic hydraulic systems than in checking out the entire electronic system. On the Atlas, part of the leak check test calls for looking for bubbles or listening for leaks—something very difficult to automate.

Box 4-A presents an example of a semi-automated system for inspecting the thermal protection tiles on the Shuttle orbiter. The system, developed by NASA, Stanford University, and Lockheed Space Operations Company, promises to make tile inspection more reliable and may lower its cost.

Computer-Aided Software Development

Traditional methods of developing software and writing the necessary computer code are highly labor-intensive and require skilled programmers. However, new techniques promise to improve the speed and accuracy of software development.

Computer-aided software development options range in power and complexity from commercially-available, so-called software engineering environments,[2] which are program libraries, editors, and program debuggers, to automatic programming.[3]

The benefits of using computer-aided software development include reliability, economy, and responsiveness, a key aspect of operational flexibility. Proponents of computer-aided software development suggest that it will be applicable to both mission control and ground operations.

[1]*Report of the Presidential Commission on the Space Shuttle Challenger Accident* (Washington, DC: U.S. Government Printing Office, 1986), ch. 5.

[2]For example, SmallTalk: Adele Goldberg, *Smalltalk-80* (Reading, MA: Addison-Wesley, 1983).

[3]Skeptics contend that "automatic programming has always been a euphemism for programming with a higher-level language than was presently available to the programmer. "-D. L. Parnas, "Software Aspects of Strategic Defense Systems, " ***American Scientist***, November 1985.

Box 4-A.—Shuttle Tile Automation System

Inspecting the some 31,000 thermal protection system (TPS) tiles on the Shuttle orbiters and repairing damaged ones is highly labor intensive. Automating the inspection procedures could reduce overall labor costs, and increase inspection speed and accuracy. In 1986 NASA began the Space Systems Integration and Operations Research Applications (SIORA) Program as a co-operative applications research venture among NASA-KSC, Stanford University, and Lockheed Space Operations Company. One of its initial tasks is to apply automation and robotics technology to all aspects of the Shuttle tile processing and inspection system.

The team is developing an automated work authorization document system (AWADS) that will enable technicians to document the condition of each tile, determine any necessary repairs or replacement, and generate work instructions. With the automated system, the computer, which is programmed to recognize each technician's voice, prompts the technician to find the correct tile, enter its number, and report on its condition in a systematic way. The TPS quality control technician first inspects the tiles after each flight and enters the part number, location, and condition of each tile into a computer base by voice. The computer's central database automatically generates a problem report in electronic format, which a TPS engineer uses to identify and recommend proper repair procedures for the tile. The problem report proceeds through an electronic signature loop until final approval for the repair. Finally, the TPS technician uses the voice data entry method to indicate tile status as repair procedures are completed.

The AWADS system and other automated systems developed in the SIORA program use the Ada programing language,[1] the software environment that will be used in the space station, and other large NASA programs in the future. It offers the advantages of excellent portability from one hardware system to another, a rich set of programming functions and tools, and a uniform code documentation. The tile automation system is expected to be operational by January 1989.

[1]Ada was originally developed for use by the armed services. It has become the DoD software standard,

When used in the appropriate application, "it will minimize programming time and effort . . . and improve the probability of mission success. "[4]

Expert Systems

Some systems attempt to capture experts' problem-solving knowledge in a computer program. So-called "expert systems" could provide considerable assistance in automating complex launch and mission operations procedures, such as fuel loading and gantry disconnect, where the experts' knowledge can be codified. Expert systems can also be applied to maintenance checks and fault isolation procedures which are currently performed manually. In their most mature form, expert systems are used as diagnostic assistants. Knowledge engineers and programmers have developed expert systems for a diversity of disciplines, including medicine, geology, chemistry, military science, electronics, education, agriculture, and law.

Expert systems solve problems arising in a particular discipline using the same rules of thumb that humans employ in decisionmaking. A typical expert system has two parts:

- A knowledge base: typically including descriptions of relationships among objects or a set of rules describing actions. These rules take the form, "if the power is turned off, then the system won't work. "
- An inference engine: typically including a rule base (in this case, a set of rules of thumb to be used for problem-solving) and meta-rules (instructions that determine the order in which to use the rules in the rule base when solving a problem).

Each knowledge base is specific to a particular domain of knowledge and must be appropriate for the type of problem to be solved. The inference engine, on the other hand, is generic; it is developed by programmers trained in the methods of artificial intelligence and, once developed,

[4]USAF Space Division, ***Launch Systems for the Strategic Defense Initiative–Data Book*** (Los Angeles Air Force Station, CA: Headquarters, U.S. Air Force Systems Command Space Division, December 1986), p. 6-93.

can be used with appropriate knowledge bases to solve a variety of problems.[5] At present, knowledge engineers act as intermediaries in the process. The knowledge engineers and programmers are now aided, and may eventually be replaced, by computer programs that help translate the experts' rules of thumb into formats the inference engine can interpret.[6] Box 4-B discusses three expert systems that could be used for launch operations.

'Cf. critiques by F.P. Brooks, Jr., "No silver bullet—essence and accidents of software engineering, " *Computer,* April 1987, pp. 10-19; and F. Flores and T. Winograd, ***Understanding Computers and Cognition: A New Foundation for Design*** (Norwood, NJ: Ablex, *19~6).*

[6]W. B. Gevarter, "The nature and evaluation of commercial expert system building tools, " ***Computer,*** May ***1987,*** pp. 24-41.

Box 4-B.—Expert Systems for Launch Operations

Expert systems that are potentially useful in space transportation systems include LES (LOX Expert System), KATE (Knowledge-Based Automatic Test Equipment), and ISIS (Intelligent Scheduler and Information Systems).[1]

LES is a quasi-expert system built to demonstrate monitoring and troubleshooting of the portion of the Shuttle Launch Processing System that performs liquid oxygen (LOX) loading of the Shuttle at KSC.[2] Sensors at numerous points in the LOX loading system report the temperature, pressure, and operating status of various subsystems to the Shuttle Launch Processing System. LES was designed to:

1. identify abnormal sensor readings immediately;
2. deduce whether an abnormal reading indicates a problem in the loading procedure or merely failed instrumentation; and
3. override reactions to apparent system failures, such as the safing operation, countdown hold, or launch abort, if it identifies failed instrumentation as the cause.

LES produces reports in the format of an Interim Problem Report, a paper form used at KSC for many years (figure 4-I). LES can also display and print schematic diagrams of the wiring and plumbing it monitors.

In developing prototype expert systems for use in launch operations, NASA engineers chose to apply an expert system to the LOX loading system because a complete functional description of the Shuttle Launch Processing System was available. This improved LES'S performance but made LES a questionable model for other expert systems that must reason about domains about which they have only fragmented and sometimes inconsistent descriptions. An upgraded version of LES (KATE-see below) subsequently demonstrated an ability to diagnose problems even when it had only limited information about the domain, by producing a list of "suspect" faults.

LES'S developers also chose to use algorithmic reasoning rather than than applying "rules of thumb" gained by experience. In other words, LES follows programmed instructions to achieve full logical consistency of its diagnoses. In this respect LES is not a true expert system. It also cannot understand systems with feedback or diagnose multiple failures.

Nevertheless, LES'S developers are enthusiastic about its potential for use on other KSC fluids systems. They suggest that "the cost of . . . software would plummet while the reliability and safety of the control software would rise dramatically. "[3]

KATE is an expert system developed to demonstrate monitoring, diagnosis, and control of systems with electrical, mechanical, hydraulic, and pneumatic components.[4] The present KATE system is being

'For other examples, see NASA Advanced Technology Advisory Committee, Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, NASA TM-87566, v. II, March 1985, and NASA Ames Research Center, "Systems Autonomy Technology-Program Plan," briefing slides, 1987.

'J. R. Jamieson, et al., "A knowledge-based expert system for propellant system monitoring at the Kennedy Space Center, " ***Proceedings of the 22d Space Congress, Cocoa Beach, Florida,*** **1985, pp. 1-9; E.A. Scarl, et al., "A fault detection and isolation method applied to liquid oxygen loading for the Space Shuttle,"** ***Proceedings of the Ninth International Joint Conference on Artificial Intelligence,*** **1985, pp. 414-416.**

[3]Jamieson, et al., op. cit., pp. 1-9.

[4]E.A. Scarl, et al., "Diagnosis and sensor validation through knowledge of structure and function, " ***IEEE Transactions on Systems, Man, and Cybernetics,*** **vol. SMC-17, No. 3, May/June 1987, pp. 360-368; M. Cornell, "Knowledge-Based Automatic Test Equipment, "** *Proc. ROBEXS* **86, NASA JSC, June 1986.**

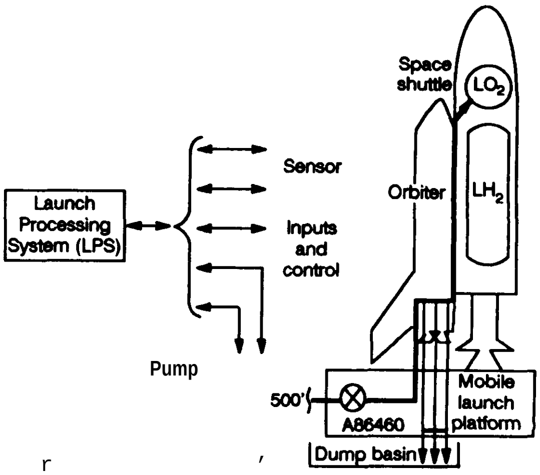
Figure 4=1

I N T E Ft I tl F' R O E! L E M R E P O R T it*it**itit********
tlonday the twenty-fifth of llarch, 1985; 3:38:23 pm
REPORTED FJY: LES the Lox Expert System

PROBLEM lIESCi?IPTION:
GLOX3043E the replenish valve open measurement ne. **2 is not reading correctly.**
It now reads: OFF ,but should read: ON .

ANALYSIS & **TROUBLESHOOTING STEPS:**
1) GLOP2045R the replenish valve signal pressure measurement detects the current state of A3370&, because if A33706 was failed to ON, then EiLOP2045fi would have to be reading between -0.5 and 0.5.
2) GLOP2045A the replenish valve signal pressure measurement detects the current state of A3370EI, because if A33708 was failed to ON, then GLOP2045A would have to be reading between -0.5 and 0.5.
3) GLOP20450 the replenish valve signal pressure measurement detects the current state of A33709, because
if h33709 was failed to ON, then GLOP2045fi would **have to be** reading between -0.5 and 0.5.
however, GLOP204511 is reading 15, thus clearing:
20-PSI-PR1, A33784, A33709, A33706, K105, and A33708.
Suspects now are: A86460, 64019452, 6602111-F2, +22D180B, and GLOX3043E.
41 GLOX2043E the replenish valve open measurement no. 1 is NOT **reading correctly** thus clearing: GLOX3043E.
Suspects now are A86460, 6401A452, 6602G1-F2, and +22D180B.
5) GLOH30449 the replenish valve position indicator no. 2 detects the current state of /!86460, because if A86460 was **between 0.0 and 93, then GLOH3044A would have to be reading between -5.0 and 98.**
however, GLOH3044A is reading 99, thus clearing:
A864LI0.
Suspects now are: 6401A452, 6602AI-F2, and +221)180B.
61 GLOX2035E replenish valve secondary pressures okay measurements detects the current state of +22D180)3! because if +22D180)3 was failed to **OFF, then FLOX2035E would have to be reading OFF.**
however, GLOX2035E is reading ON, thus clearing:
6602A1-F2 and +22D180B.
Suspects now are: 6401A452.
Monday the twenty-fifth of March, 1985:
3:38:42 p m
At this point It appears that the most likely single point failure is 6401A452 the replenish valve **open** limit switch. The rest of the measurements will **be searched** for conflicting evidence.
7) The balance of the RELATED MEASUREMENTS have been examined, and cannot add additional information to the above analysis.
CONCLUSION:

It is determined that the most likely single **point failure is 6401~452 the replenish valve** open llmit switch
Thank VOU----LES
Monday'the twenty-fifth of March, 1985:
3:38:44 pm



aouRcE:wlonal&~ and~Mminhtration

demonstrated on a laboratory air purge system. Like LES, KATE is neither designed to understand systems with feedback nor to diagnose multiple failures.

KATE was developed from LES by modifying the program so that it could not only diagnosis faults in a monitored system but could also control the system. For example, it can turn valves and motors on and off in an attempt to keep sensor measurements within specified limits. LES diagnoses faults by: 1) hypothesizing faults that might cause sensors to report the undesirable measurements observed; and then 2) deducing whether they would cause the undesirable measurements. KATE's developers realized that the same method could be used to hypothesize commands that might cause sensors to report acceptable measurements and then deducing whether they would cause all sensors to report acceptable measurements.

KATE's developers added an ability to learn about its domain by experimentation. KATE's Learning System enables KATE to construct a partial knowledge base, or a complete knowledge base of a simple system, by observing the performance of a system to which it is connected. KATE "issues combinations of inputs, each time looking for measurement reactions and filing the results in a table. When all combinations have been tried, the table is evaluated to produce frames[5] representing the tested system. "b KATE has produced complete knowledge bases about simple digital circuits by experimenting with them. KATE's approach may be inappropriate for learning about complicated real systems because experimenting with all combinations of inputs would take time and might even cause failures in some systems.

1S1S[7] is a job scheduler. It is designed to solve "work flow" problems such as:

> We want to produce Tethered Upper Stage Knobs (TUSKs)[8] at the maximum rate possible without buying new tools. Each TUSK requires casting for five hours, milling for two hours, grinding for three hours, two different half-hour inspections, and five different one-hour tests. We have two molds, one milling machine, two grinding machines, one inspector qualified to perform each inspection, and one test cell for each required test. The casting must precede the milling, which must precede the grinding. Any tests and inspections, which are the last stages of TUSK manufacture, can be done in either order, although it has proven economical to inspect before testing. The time required to transfer an unfinished TUSK from one work cell to another depends upon the origin and the destination; these times have been measured and tabulated. By what path or paths should unfinished TUSKS be routed among the operations?

If only one TUSK were to be produced, this scheduling problem would be a "traveling salesman problem" with additional constraints upon the routes the "salesman" [unfinished TUSK] can take through the "cities" [operations] he must visit. The additional constraints can be used to simplify the search for the shortest route, but the resulting simplified problem is still of the traveling-salesman type. The computational effort required to solve such problems by the fastest published methods[9] grows exponentially (in the worst case) as the number of operations increases. The scheduling problem in the example above, although far simpler than an actual one, is even more complicated than a traveling salesman problem; it is analogous to the problem of coordinating the itineraries of a succession of traveling salesmen—one departing each day—so that the average trip duration is minimized, subject to the condition that no two can be in the same city on the same day.

At KSC, Shuttle processing operations are now scheduled manually by individuals who maintain charts showing durations of individual operations as horizontal bars; these Gantt charts cover several walls. Portions of the charts are photographed, printed, and distributed daily and weekly. When schedule interruptions, delays, or speed-ups occur, schedulers modify the charts; they must determine a new schedule which satisfies all constraints, for example, on the order in which operations can be performed. Except fortuitously, such a procedure will not result in the most efficient schedule for the workforce. Although schedulers also try to minimize processing time, they find it impossible to determine and compare all possible schedules satisfying all constraints resulting in the most efficient schedule.l" How much vehicle processing time could be reduced and costs saved by more efficient computer scheduling has not been explored.

5 A "frame" is a list of statements about an object's properties and relations (e. g., connections) to other objects.

6 M. Cornell, op. cit.

7 Mark S. Fox and Stephen F. Smith, "ISIS-a knowledge-based system for factory scheduling, " *Expert Systems,* vol. 1, No. 1, July 1984, pp. 25-49.

8 For illustration only. Any resemblance to acronyms in current or previous use is purely coincidental.

9 S. Kirkpatrick, et al., "Optimization by simulated annealing, " *Science,* vol. 220, No. 4598, May 13, 1983, pp. 671-680.

10 Critical path methods are used to monitor payload integration schedules at KSC but cannot be used to schedule processing operations; these methods can identify the sequence of operations that will take the longest to perform (the "critical path") but cannot rearrange the sequences to save time.

TECHNOLOGIES FOR LAUNCH VEHICLES

Vehicle Design Principles

As experience with the Space Shuttle illustrates, vehicle design significantly affects launch and mission operations and plays a crucial part in the ability to reduce costs. Many Shuttle subsystems are extremely difficult and time consuming to maintain or repair because Shuttle designers focused on attaining optimum performance and high safety, often at the expense of ease of ground operations, maintenance, or mission control.[7] In order to determine which technologies might reduce costs most, launch system designers should consider certain design principles.

Include all segments of the launch operations team (including logistics personnel) in the design of any new launch system.

When plaming and designing a new launch system, it is essential to consider the entire system as an interactive entity, including the operations infrastructure, and operations management. This enables system designers to anticipate potential operations and maintenance problems and provide for them before the system is built.

Reduce number and complexity of tasks requiring human intervention.

Complexity of documentation, maintenance, and interfaces among subsystems generally lead to higher system costs. ‘Therefore, reductions in the number and variety of tasks necessary for launch preparation, especially those that require human involvement, could assist in reducing launch costs.[8] However, vehicle subsystems themselves can be complex, if they are designed to simplify each procedural step. For example, including self-testing electronics in an avionic subsystem makes that subsystem complex, but reduces the number of tasks required of launch personnel. ESA achieved simplicity in the Ariane by using a high degree of commonality in the design of different vehicle stages, and evolutionary design from one vehicle to the next. In addition, Arianespace has simplified the payload/launcher interfaces that are required for Ariane.

Increase maintainability.

Launcher designers have paid relatively little attention to providing the ease and simplicity of assembling or maintaining vehicles. As one OTA workshop participant observed, “One problem with the Shuttle is that the systems on board are not designed for changeout. You can pull a box, but you have to do copper path testing to get it back up there. And on the Shuttle, there area lot of boxes to fail. ” Even with ELVS, the amount of testing that is done on the pad requires greater attention to the principles of maintainability. The following would contribute to launch system maintainability:

Increase *subsystem accessibility*. It would be highly desirable to design subsystems that are more accessible to repair and changeout. One way to assure more accessible subsystems is to include operations people in the design process.

Such involvement might avoid situations in which some subsystems later turn out to require a lot of detailed inspection and changing, such as the Shuttle main engines, or even the air filters in the Shuttle crew cabins, which collect unanticipated amounts of hair, blue-suit lint, washers, and screws. These subsystems are difficult to access and repair. Even where frequent maintenance has been anticipated, such as in the avionics packages, pulling and replacing electronics boxes requires time-consuming retesting to ensure the integrity of hundreds or even thousands of electrical connections.

Workshop participants noted that fluid and mechanical systems particularly need more accessible design and an improved capability for making internal tests. A future reusable system might also take a lesson from aircraft design: airliners are designed to have certain parts and subsystems pulled and in-

‘George E. Mueller, Panel discussion, ***Space Systems Productivity and Manufacturing Conference IV*** (El Segundo, CA: Aerospace Corp., August **1987), pp. 233-35.**

‘1-I. S. Congress, Office of Technology Assessment, ***Low-Cost, Low-Technology Space Transportation Options,*** staff paper, in preparation.

spected after a given number of hours of flight. On the Shuttle, however, most subsystems require disassembly, reassembly, and retest after each flight.

- *Design for modularity.* Workshop participants also suggested that as much as possible, components should be modular, standardized and interchangeable. To achieve design modularity means deciding which functions must be handled separately from others and how they must be connected, and even what standards (such as electrostatic discharge protection) must be used. Having standardized interfaces would improve the chances for achieving modularity. This practice is widely used in the design of both military and commercial aircraft. Thus a considerable base of experience already exists.

  Arianespace has attempted to assure that the Titan 3 and the Ariane 4 use similar payload interfaces, because it is in the customers' best interests to have alternative launch vehicles to turn to. In the opinion of one participant, "an absolute mistake on the Shuttle was marrying the payload to the vehicle, " which results in major software changes for each flight and complicates the task of remanifesting payloads for other vehicles. Standardized interfaces do, however, exact a marginal cost in performance. Hence they require that payloads be designed slightly lighter and smaller than the vehicle's theoretical maximum capacity. Moreover, it may not be possible to design standardized interfaces across all types of vehicles and missions because the mission requirements for, say, launching into geosynchronous orbit are very different than for low-Earth orbit.
- *Include autonomous, high-reliability flight control and guidance systems.* This technology has yet to be fully developed for space systems, and will be very expensive.
- *Build-in testing procedures, especally for mechanical and fluid systems, as well as for electronic systems.* As noted in a later section, designers already know how to incorporate test procedures in the electronic systems. The biggest hurdle is in the mechanical and fluid systems, which are difficult to test.

Make payloads independent of launcher.

Payload integration constitutes a major fraction of the cost of launch operations. In the Shuttle, payload integration has turned out to be a "long, complex, and arduous task, compared to integrating a payload on an expendable launch vehicle. "[9] In large part this complexity results from the potential influence of multiple payloads on each other as well as the interaction of the payloads' weight distribution and electrical systems with launcher subsystems. In the case of the Shuttle, payload customers must also take part in planning and training for deployment or operation of their payloads. Prior to the loss of Challenger, payload integration for the Shuttle typically required about 24 months.[10]

Workshop participants agreed that payloads should be designed to be as independent as possible of the launch vehicle. From the standpoint of the launch system managers, the payload-vehicle interfaces should be standard and incorporate automated checkout procedures, off-line processing, and testing prior to delivery at the launch site. However, such an approach finds few adherents among payload designers, who generally find themselves pushed by the payload performance requirements and weight limitations.

Several workshop participants warned that nothing is gained in reducing overall costs by changes in procedure or technology that merely send problems elsewhere. Many of the ALS and STAS concepts for improved launch operations tend to shift costs from operations to other stages in the launch services process, such as payload processing. For example, requiring payloads to provide their own internal power, rather than relying on a source in the launcher, may reduce ground operations costs, but may also increase the cost of preparing payloads. On the other hand, if launch costs per pound were sufficiently cheap, it might be possible to construct less costly payloads (box 4-C).

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

[10] This too is likely to increase with the new safety requirements for the orbiter.

Box 4-C.—Vehicle-Payload Interfaces on the Advanced Launch System

One of the recommendations of the Space Transportation Architecture Study[1] was to eliminate or sharply reduce the burden of supplying special services from the launch vehicle to the payload. This strategy would assist in reducing vehicle turnaround on the pad, which in turn reduces the launch operations costs. ALS study managers have accepted that recommendation and adopted the philosophy that the ALS will provide minimum services to the payload.

Because the payload designers have been severely constrained by the total weight launchers could carry to orbit, their previous practice has been to consider the launch vehicle as almost an extension of the payload, and to expect it to provide a variety of special fittings, upper launch stages, and services such as power, cooling, and fueling. Not only does such an approach lead to extra costs for the launch vehicle itself, it dramatically raises the costs of integrating and launching the payloads. ALS managers also maintain that payloads could be much cheaper to build if the payload designers were less severely constrained by weight capacity of the launch vehicle.

They have asked the payload community to consider the ALS as a transportation system capable of launching high mass payloads safely and on time, but which will provide only standard interfaces and limited services (table 4-2). As one Air Force manager put it, "This won't sit well [with the payload designers] because it's new and it won't be the same way we're doing business now." He went on to say, "We mean to force a revolution in the design of launch vehicles. An evolutionary approach won't reach cost reductions of a factor of ten. It just won't do it."

Participants at two Air Force ALS workshops[2] on the launcher/payload interface were asked to consider and analyze payload designs based on minimum services from the vehicle, and to identify any services they considered essential. In addition, they were asked to consider the effects on payload design of delivering payloads to a ballistic trajectory, just short of orbit. Such a plan would make the launch vehicle much simpler because it would avoid adding rockets to the core vehicle to send it into the ocean after delivering its cargo. However, the payload designers would be required to provide their own boost to operational orbit. In return, they could count on vastly reduced costs per pound to reach space.

Considerably more design work will be necessary to determine whether these stratagems could reduce total launch costs dramatically, and consequently lead to cheaper payload designs. If successful, they could ease many of the current payload design restrictions. For example, with a ten-fold reduction in cost-per-pound to orbit, the weight of the payload and its upper stage could grow by a factor of two and still result in reductions of a factor of five in cost per payload to orbit. In addition, if designers do not have to find innovative but costly ways to shave weight, payloads could be much cheaper to design and build. However, if these tactics lead primarily to shifting most launch costs to the payload accounts, the exercise will prove moot. In addition, if payload weights continue to grow to meet or exceed launch vehicle capacity, costs cannot be reduced. At present, the payload community, especially the designers of highly complicated national security spacecraft, have met the suggestions with profound skepticism (table 4-3).

[1]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.

[2]Held at Aerospace Corp., Los Angeles, CA, November 1987, and January 1988.

SOURCE Office of Technology Assessment, 1988

Use less toxic propellants.

Storable high-performance propellants such as nitrogen tetroxide or monomethylhydrazine offer significant advantages where the size of the propellant tanks is an issue, or where propellants must be stored for long periods of time, especially on orbit. These propellants can be used in relatively simple engines and are frequently used for spacecraft as well as for launch vehicles because engines using such propellants can be started and stopped easily.

Although such propellants will continue to have an important role in space transportation, they are also toxic and corrosive, giving rise to human health risks and maintenance problems. Launch personnel must be protected by special suits from

Table 4-2.—ALS Launch Operations Specifications

- Separate launcher preparation from payload preparation
- Place payloads in standard cannisters
- Provide no access to payloads when vehicle is on the pad
- Provide no flight power and communications interfaces

SOURCE: Air Force Space Division, 1987.

Table 4=3.—Launch Vehicle/Payload Interface Issues

- How beneficial is standardization of launch vehicle/payload interface?
- How will needed payload sewices be provided if minimize sewices provided by launch vehicle?
- Are total system costs lowered as launch vehicle costs are lowered and vehicle availability enhanced by keeping launch vehicle-provided sewices at a minimum?
- Can generalized ALS mission analyses provide timely loads and environment analysis to payload?
- Can payload requirements still be met if launch vehicle design is insensitive to payload type?

SOURCE: Air Force Space Division, 1987.

exposure to carcinogenic or corrosive materials. When propellant technicians work with these fluids, other launch personnel must evacuate the area. Toxic propellants also tend to destroy seals and metal containers and create internal leaks. Solving these problems could eliminate a significant amount of ground processing—especially for reusable systems, which require post-flight handling. Developing better materials for storage vessels would help in this effort.

Cryogenic propellants offer lower production costs and higher energy density per pound of propellant. However, cryogenic rocket engines and logistical support are generally more complex and expensive than storables.

Vehicle Technologies

The particular technologies used in a launch vehicle may enhance or hinder ground and mission operations. Table 4-4 provides a list of several advanced technologies that could lower launch operations costs when incorporated in a vehicle.

Table 4-4.-Vehicle Technologies To Facilitate Ground Operations

Built-in test equipment (BITE)
Thermal protection system (TPS)
Fault-tolerant Computers
Autonomous and adaptive guidance, navigation, & control (GNC) system

SOURCE: Office of Technology Assessment, 1988.

Built-in Test Equipment (BITE)

Future launch vehicles are likely to incorporate built-in test equipment and software to detect faults and reconfigure redundant systems; this would thereby reduce ground operations labor and cost. It could also increase vehicle reliability and autonomy during flight, easing mission control requirements. Technology for built-in test of avionics, especially computers, is most mature.

Technology for built-in test of mechanical and fluid systems, especially sensors, will require more development. More reliable sensors could reduce false alarms, and software similar to the expert system KATE (see box 4-B) could diagnose sensor faults.

Thermal Protection System

Reusable vehicles, such as the Space Shuttle, require a thermal system to protect the vehicle upon reentry. As noted in chapter 3, the Shuttle thermal protection system, which was the first reusable system to be developed, has proven expensive to maintain. A more robust thermal protection system would reduce the complexity of inspection and repair and dramatically reduce the costs of refurbishment. Advanced materials, such as carbon-carbon composites and titanium-aluminum alloy, which are being developed for the X-30 program,[11] promise much greater tolerance to the heating and buffeting experienced on atmospheric reentry than do the current Shuttle thermal protection tiles.

[11] U.S. Congress, General Accounting Office, *National Aero-Space Plane: A Technology Development and Demonstration Program to Build the* X-30, GAO/NSIAD-88-122 (Washington, DC: U.S. Government Printing Office, 1988), pp. 37-38. For a detailed discussion of new structural materials and composites, see U.S. Congress, Office of Technology Assessment, ***Advanced Materials By Design, OTA-E-351*** (Washington, DC: U.S. Government Printing Office, June *1988).*

Fault-Tolerant Computers

The on-board computers of future launch vehicles could consist of identical computer modules "mass-produced" for economy and connected by optical fibers for reduced susceptibility to electromagnetic interference. These modules could hold software that allows several of them to perform each calculation, compare results, and vote to ignore modules that report "dissenting" results. This approach, now used on the Shuttle in an early version employing less sophisticated computers,[12] would enable the launch vehicle to tolerate failures in one or more computer modules. Computers with a high degree of fault-tolerance would allow the launch of a vehicle with a known fault rather than holding the launch to replace a failed module and retest the system.

The full potential of fault-tolerant computers to reduce maintenance, turn around times, and cost may not be realized until space transportation managers gain sufficient confidence to accept the small risks inherent in launching vehicles with certain known faults. For example, the Shuttle has a quintuple-redundant primary computer system and dual-redundant software for these computers. Shuttle avionics also have triple- and quadruple-redundant sensors. Four of its five computers could fail during flight, or before launch, without causing mission failure. Yet, NASA's highly conservative launch criteria now require all these systems to be operational before the Shuttle can be launched. This increases safety and the probability of mission success, possibly at the expense of economy, resiliency, and access probability. In contrast, airlines will fly aircraft with faulty or failed equipment, as long as the equipment is not vital to safety, or has sufficient redundancy for safe operations.

Autonomous and Adaptive Guidance, Navigation, and Control

Current launch vehicle avionics that perform navigation, guidance, and control must be updated before launch with data such as payload masses and positions within the vehicle, launch time, and predicted winds aloft. Launch delays or changes in weather or payload configuration can require additional updates.

Advanced avionics and software could make the mission software less sensitive to payload configuration and weather, by monitoring a vehicle's response to commands during the early flight stages. For example, an adaptive guidance and control system could estimate payload mass distribution and use the estimate to calculate guidance and control for the remainder of the flight. Similarly, wind could be measured by its effects on vehicle acceleration, trajectory, and structural strain, and control surfaces could be moved not only to steer the vehicle, but also to alleviate structural stresses. A vehicle with these capabilities would not only require less detailed programming before launch, it could also be lighter because it would "know" when to "give" under unanticipated stress. Some current military and civilian aircraft use such systems.[13]

Computer-Aided Design and Computer-Integrated Manufacturing

Computer-aided design and computer-integrated manufacturing can make vehicle design and production faster and probably reduce life-cycle cost even at low launch rates. Computer-aided design techniques can speed vehicle development by automating the distribution, retrieval, and utilization of design information. Computer-integrated manufacturing techniques can reduce production costs by automating selected manufacturing operations. '4 This will require specifically designing systems to facilitate their manufacture by computer integrated methods.

12A Spector and D. Gifford, "The Shuttle primary Computer Systern, " *Communications of the Association for Computing Machinery,* vol. 27, No. 9, September 1984, pp. 874-901.

'3 E.g., Airbus Industries A320; tested on the B-52 and F-4.

14 For example, Hercules Corporation has used automation to increase the speed and safety of its manufacture of solid rocket motors for the Titan IV.

MANAGEMENT STRATEGIES

Without appropriate management strategies, the ability of launch and mission operations managers to utilize new technologies efficiently is likely to be limited. In addition, management strategies that lead to improvements in the ways existing technologies are used could result in cost reductions.[15] This section examines several management strategies that experts have suggested would increase the efficiency of operations and decrease costs.

Facilities

Use an integrate/transfer/launch (ITL) approach.

The ITL method of launch operations (figure 2-9), in which each individual component in the launch process has its own dedicated set of facilities, is essential for achieving high launch rates. Separating the different launch operations functions in this way means that parallel processes, such as payload checkout and vehicle assembly, can proceed at the same time. However, ITL necessarily requires substantial investment in facilities. Further, ITL requires mobile platforms and other facilities for moving launch vehicles along the steps of the process.

Shuttle operations at Kennedy Space Center (KSC) and Titan operations at Cape Canaveral were originally designed to use the ITL approach. By contrast, the launch complexes at Vandenberg Air Force Base require assembly and integration on the pad. Payloads must also be tested and integrated with the vehicle on the pad. Such procedures necessarily limit the rate at which Vandenberg can launch. However, even at KSC and Cape Canaveral, the launch rate for existing vehicles is highly limited, in part because the available facilities are too few and overscheduled to allow the ITL method to be fully realized.

Future launch complexes might be designed to accept several different launch vehicles in the same general size class (figure 4-2).[16] As Arianespace has demonstrated in a limited way, the same launch pad can be used for different launch systems with a minimum of alterations to the launch complex.

Locate manufacturing facilities near launch complex.

Placing the launcher manufacturing facilities near the launch complex would shorten and simplify the launch vehicle supply lines, and eliminate the need for most acceptance testing at the launch complex. However, unless the launch rate was expected to be extremely high, such a strategy might not pay for itself, because it would require substantial capital investment in facilities. In addition, it would require the manufacturing workforce to relocate near the launch complexes.

Use off-shore launch pads.

New locations for launching space vehicles may be needed if demand for launch services increases significantly. Because of restraints caused by lack of suitable real estate and cultural and environmental restrictions, the Air Force and its ALS contractors am studying several off-shore launch concepts, including offshore drilling rigs, small offshore islands, or even mid-Pacific islands. In addition to easing many of the restrictions of coastal launch pads, such options have potential for launching toward all azimuths.

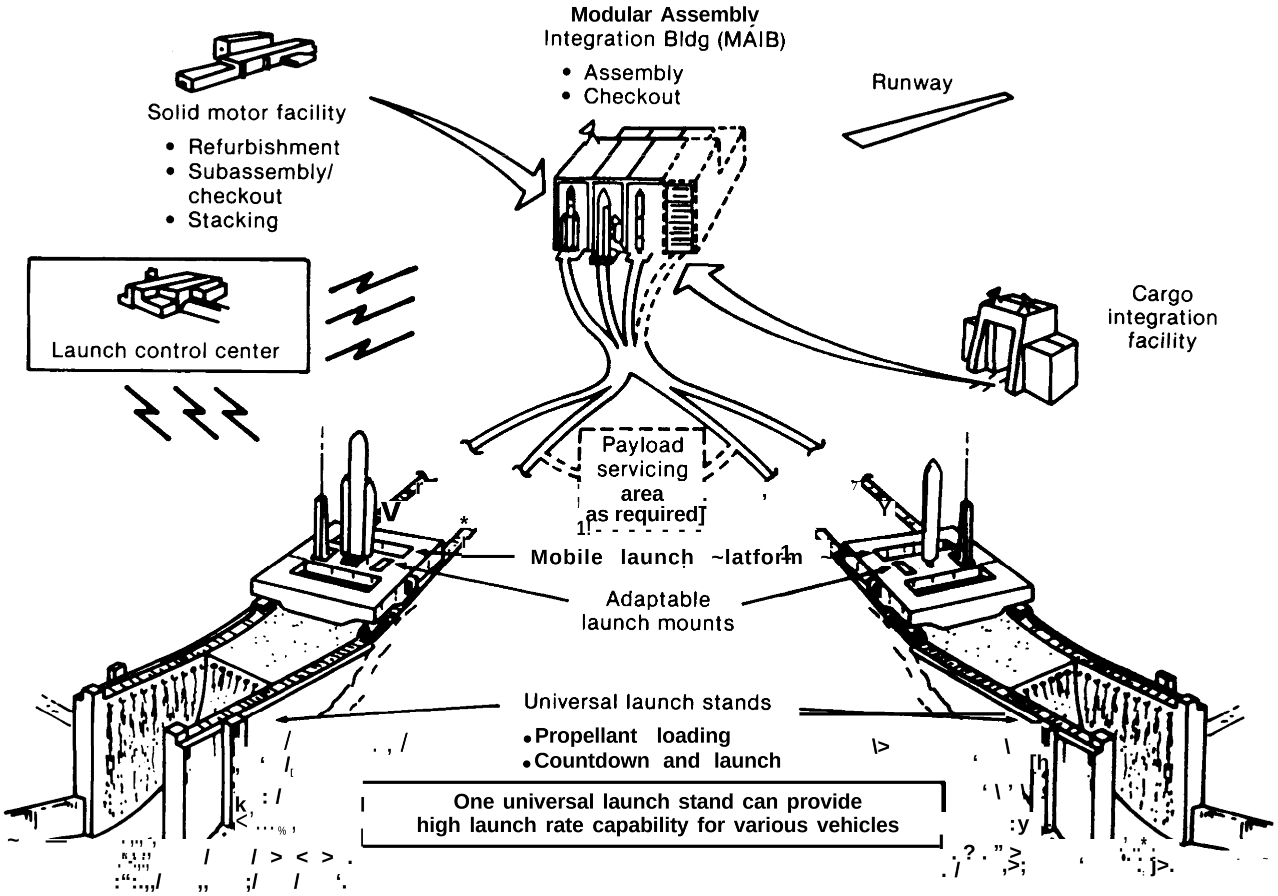
The Air Force is taking a preliminary look at the potential for using offshore drill rigs, because they seem to present greater opportunity for operational flexibility than an island. It is exploring launch pad designs similar to floating oil drilling rigs that could be loaded with a rocket, towed to an offshore site, and, in a matter of hours, turned into a stable launch platform.[17] For this and other offshore possibilities, technical feasibility (especially safe handling of toxic and cryogenic fuels),

[15] "Space Systems and Operations Cost Reduction and Cost Credibility Workshop," Executive Summary (Washington, DC: National Security Industrial Association, January 1987), p. 2-1,2.

[16] Peter L. Portanova and Harold S. Smith, "Strategic Defense Initiative Launch Site Considerations," Aerospace Corporation Report No. TOR-0084A(5460-04)-1.

[17] "USAF Studies Concept for Launching Heavy-Lift Rockets from Offshore Rig," *Aviation Week and Space Technology,* Feb. 1, 1988, p. 42.

Figure 4-2.—Universal Launch Complex



Main principles

- New operational philosophy (enhanced ITL)
- Simplified launch stand sized for largest vehicle
- Minimum time on launch stand
- Containerized cargo
- Rapid recovery capability
- Integrated manufacturing/operations processing on or near launch site
- Adaptable launch mounts (support beams adjustable for vehicle size)

SOURCE: Air Force Space Division

cost, logistics, and onshore facility and harbor requirements will all need considerable study.

Operations Management

Create incentives for achieving low cost, successful launches.

The current institutional structure tends to penalize launch failure, but is poorly structured to lower launch costs or increase launch rate. Although commercial launch service offerors now have the incentive of competition to encourage them to drive down operations costs, similar incentives are not apparent for Government launches.

Centralize facilities, management, mission control.

One way to lower the overall costs of launch and mission control is to centralize the facilities and personnel. For example, because responsibility for Shuttle launch operations and mission control is divided among KSC, Johnson Space Center, and Marshall Space Flight Center, NASA must duplicate some facilities and personnel, and provide appropriate coordination among centers.

Develop and use computerized management information systems.

Although computer systems play a major part in all parts of mission preparation, launch, and control, they are seldom used for scheduling launch vehicle preparation and keeping track of the status of launch vehicle and payload systems. For the Shuttle at KSC, for example, Shuttle orbiter refurbishment, system status reports, and subsystem alterations are all handled by paper documents. Not only is a paper system more cumbersome and subject to error, it requires considerably more time.

The fundamental difficulty in changing over to a computerized system is that not only would it require the development and installation of a large computer system, it would lead to substantial alterations of the ways in which managers interact with each other. In other words, it would require fundamental changes in the institutional culture of NASA and the Air Force. The computer screen would replace the "in-box. "

Increase autonomous operations.

Many operations procedures now carried out by humans, especially routine ones, can be automated to reduce the "standing army" of human operators. Automation could also reduce the time spent in preparing for launch and mission operations, and increase system reliability. However, to be automated, operations procedures must also be standardized.

In fiscal year 1989, NASA's Office of Space Flight will start an Advanced Operations Effectiveness Initiative to focus on automating portions of launch and mission operations (table 4-s). Its goals are to:

- improve the efficiency and productivity of STS operations;
- develop an integrated software strategy;
- develop an autonomous space flight operations software test bed for:
  - —determining enabling technologies for "fully" autonomous operations;
  - —performing hardware/software trade-offs among operational systems;
  - —characterizing flight operations procedures/techniques
- organize existing autonomous capabilities in~o an integrated system.[a]

NASA's program will serve as a test bed for inserting automated procedures into space transportation operations. It should also assist in making automation more acceptable to launch managers, if it is successful in demonstrating the applicability and safety of autonomous operations.

[18]NASA JSC Mission planning and Analysis Division, "Autonomous Spaceflight Operations, " briefing to OTA staff, Aug. 5, 1987.

Table 4-5.-NASA'S Advanced Operations Effectiveness Initiative

Kennedy Space Center
• Prelaunch processing/preparation
• Launch operations
Johnson Space Center
• Flight planning/preparation
• Flight control
• On-orbit operations
• Postflight analysis

SOURCE: National Aeronautics and Space Administration, 19S7.

ASSESSING TECHNOLOGICAL OPTIONS

Although launch system operations could be improved in a variety of ways, any proposed improvement must meet the test of several measures of merit. Do the intended changes improve efficiency, reduce costs, and/or enhance reliability? Do they contribute to other desired ends, such as improving U.S. economic or political competitiveness? Do they help or hurt the morale of the work force? The primary criteria for judging space transportation system performance and economy include cost, reliability, access to space, and operational flexibility.[19] Proposed changes in launch system operations can be evaluated on the basis of their effects on these criteria.

Economic Criteria

Space transportation analysts have used several economic criteria (box 4-D) to judge space transportation system economy. The decisions about which economic criteria to use to evaluate a particular technology for a new system, or for improvements to an existing system, will affect the choice of technology and even of launch system design. For example, selecting new launch systems on the basis of the lowest non-recurring cost generally favors existing technologies and may penalize designs chosen for highest maintainability. The Nixon Administration apparently considered low non-recurring cost as paramount in the initial budgeting for the Space Shuttle,[20] which led in part to a vehicle design that is difficult and expensive to prepare for launch.

On the other hand, selecting minimum recurring cost as the sole criterion may favor technol-

[19] STAS Joint Task Team, *National Space Transportation and Support Study,* Annex C, May 1987; p. 12, Table 2-3: "Space Transportation Architecture Screening Criteria."

[20] National Aeronautics and Space Administration, "Shuttle Ground Operations Efficiencies/Technologies Study," (Boeing Aerospace Operations Company), (Kennedy Space Flight Center, NAS10-11344), vol. 1, p. 2.

Box 4-D.—Economic Criteria

nonrecurring costs include costs of vehicle design, development, test, and evaluation (DDT&E), and construction or improvement of facilities for manufacturing vehicles, processing and integrating vehicles and payloads, and mission control. The costs of facilities and equipment existing at the beginning of the accounting period are considered to be "sunk" and are not included in most calculations of net benefit for new systems. Costs of developing technologies should be fully included unless they are being developed for other purposes.

recurring costs include costs of flight hardware (expendable or reusable) and costs of operations and support (e.g., wages). Some recurring costs (e.g., ELV purchases) increase roughly in proportion to the number of launches; Recurring costs such as salaries are moderately insensitive to launch rate.

life cycle cost (LCC) is the sum of the nonrecurring costs and the recurring costs paid to operate a space transportation system for a specified period to transport specified payloads to their operational orbits. Unless otherwise indicated, LCC generally refers to the undiscounted life cycle cost, i.e., the total dollars spent regardless of the year in which they were spent.

present value (PV) LCC discounted at a specified rate to reflect the benefit of not investing for a deferred return. Depending on the goals they wish to achieve, experts differ concerning which discount rate should be used. A 5 percent discount rate (often used in STAS) is considered a reasonable "real" discount rate for use as an adjustment for risk and time preference for government investment but should be increased to adjust for inflation. A 10 percent discount rate was sometimes used in STAS and could be considered the sum of a 5 percent "real" discount rate and a 5 percent inflation rate.

cost risk was defined in STAS as the percentage increase in the present value (of life-cycle cost discounted at 5 percent per annum) which would be exceeded with a subjectively estimated probability of only **0.3.**

net benefit is the decrease in present value of life cycle cost that could be obtained by an improvement in a space transportation system, for example, by applying new technology to vehicles, building new support facilities, or changing management methods. The calculated net benefit of an improvement will depend upon the discount rate assumed.

cost **leverage:** is the net benefit of an improvement divided by the present value of the cost of implementing it. The calculated cost leverage of an improvement will depend upon the discount rate assumed.

internal rate of return (IRR) is the discount rate at which the net benefit of an improvement would be zero.

'**Robert C. Lind,** *Discounting for Time and Risk in Energy Policy* **(Washington, DC: Resources for the Future, 1982).**

ogy development with little regard for its cost, if system life expectancy is assumed to be long. The language of the act appropriating fiscal year 1987 supplemental funding for the Advanced Launch System requires NASA and the Air Force to obligate and expend funds "only for ALS variants which embody advanced technologies with a design goal of reducing the cost to launch payloads to low-Earth orbit by a factor of ten compared with current space boosters . . . "[21] Because launch operations account for a substantial percentage of overall launch costs, the agencies would therefore have to reduce these recurring costs significantly.

Present value of life-cycle cost is a flexible criterion that can be made to resemble either nonrecurring cost (by using a high or variable discount rate) or recurring cost (by using a low discount rate). STAS analysts used present value of life-cycle cost discounted at a rate of five percent per annum as the fundamental economic criterion; they also used discount rates of zero percent and 10 percent.

The criteria of net benefit, cost leverage, and internal rate of return (IRR) have been used to identify technologies that could be applied beneficially in a space transportation system. All three criteria have been used for evaluating options for technology development, system design, and management. However, they are not equivalent; options may be ranked differently when evaluated by different criteria. An option may even be judged an improvement according to one criterion and undesirable according to another; an option with a positive IRR would have negative net benefit and cost leverage at discount rates greater than its IRR. For example, Boeing Aerospace Co. estimated that automating the handling and transfer of components for a proposed cargo vehicle would yield an IRR of three or four percent and save $55 million in an SDI deployment scenario, but would have a negative net benefit ($17 million) at a discount rate of five percent, increasing the present value of life-cycle cost by $17 million .22

[21] Fiscal Year 1987 Supplemental Appropriations Act: Public Law 100-71.

[22] USAF Space Division, ***Launch Systems for the Strategic Defense Initiative–Data Book*** (Los Angeles Air Force Station, CA: Headquarters, U.S. Air Force Systems Command Space Division, December **1986),** pp. *7-22* and C-9.

Noneconomic Criteria

Several non-economic criteria have been used to rate space transportation system performance (table 4-6 and app. B).[23] In addition, other non-economic criteria, such as international technological, political, or economic leadership, are often employed in choosing among competing paths.

Because both ground operations and mission operations are integral parts of the launch system, they play significant roles in meeting the non-economic, as well as the economic criteria. For example, the Titan 34D fleet had low operational availability for 1986 and most of 1987 as the result of the failure of a liquid fuel pump and a solid rocket motor respectively, and of standdown policy. During the standdown of the Titan, the Air Force developed non-destructive testing methods to test the rocket motors prior to assembly. These methods are now in use at Vandenberg and at Cape Canaveral.

The example of non-destructive testing illustrates the tradeoff among economic and non-economic criteria. Although developing and installing these methods of testing were relatively expensive and will increase the costs of preparing a Titan for launch, the perceived improvement

[23] Other criteria used in STAS are defined in Joint Task Team, ***National Space Transportation and Support Study 1995-2010,*** Annex E ("DoD Functional/Operational Requirements"), May 1986, p. 5, and Annex C ("Space Transportation Architecture"), p. 12, Table 2-3 ("Space Transportation Architecture Screening Criteria").

Table 4-6.—Non-economic Criteria for Judging Space Transportation System Performance

- **Capacity—maximum annual launch rate or payload tonnage to given orbits.**
- ***Flexibility*—ability of a launch system to meet alterations of schedule, payload, and situation, and to satisfy missions in more than one way.**
- ***Reliability*—the probability with which a system will perform an intended function successfully.**
- ***Resiliency*—the ability of a space transportation system to adhere to launch schedules despite failures—to "spring back" after failure.**
- ***Operational Availability*—the probability that a fleet, or a multi-fleet system, will be operating (i.e., not standing down).**
- *Access Probability—the* **probability that a launch system can launch a payload on schedule and that the payload will reach its operational orbit intact.**

SOURCE: Office of Technology Assessment, 1988.

in access probability was considered to outweigh the costs incurred.

Economic Benefits

Several contractors participating in the Space Transportation Architecture Study estimated the economic benefits[24] to U.S. space transportation of developing or applying technologies to facilitate ground operations. Table 4-7 illustrates one set of estimated benefits.[25] The technologies assessed include some that would be used in launch vehicles (e.g., built-in test equipment) and others that would be used in ground support equipment or facilities (e.g., automated data management system). The technologies of table 4-7 are considered "enhancing" technologies—they reduce costs in the assumed demand scenario but are not required to build or operate the chosen mix of launch vehicles and facilities.[26]

The benefits of each technology are estimated in terms of three criteria: internal rate of return, undiscounted net benefit, and net benefit discounted at 5 percent per annum. The technologies are listed here in order of their estimated internal rates of return. As the table illustrates, if they were ranked according to undiscounted or discounted net benefit, the order would differ. For example, "expert systems" rank highest in undiscounted net benefit but tenth in internal rate of return. The benefits are sensitive to changes in mission model, discount rate, or mix of launch vehicles.

Similar estimates by other contractors differ in detail but generally predict that development of these technologies would be beneficial. Table 4-8 compares internal rates of return estimated by Boeing Aerospace Co.[27] with estimates by the Space Systems Division of General Dynamics.[28] Comparison of the two sets of estimates is complicated because the two companies defined technology categories differently. For example, Boeing defined a category it called built-in test equipment (BITE), while General Dynamics included BITE used for pre-flight testing in a category it called automated ground operations and BITE used for in-flight testing in a category it called flight management systems. The flight management systems and automated ground operations categories included equipment other than BITE. For example, flight management systems

[24] These estimates apply only to U.S. space transportation expenditures. Benefits of technology transfer to other sectors is difficult to estimate even a posteriori; see NASA Advanced Technology Advisory Committee, ***Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, NASA-TM87566,*** March 1985, vol. II, p. 104. It would be very difficult to forecast spin-off benefits from the technologies described above, and OTA knows of no such forecast.

[25] Boeing Aerospace Company; from ***Space Transportation Architecture Study, In-Progress Review Number 5*** (Seattle, WA: Boeing Aerospace Company, Apr. 7, 1987), p. 209.

[26] The mix assumed in table 4-7 features a new piloted orbiter, a flyback booster, and a cargo vehicle core stage with a recoverable propulsion/avionics module,

[27] Boeing Aerospace Company, op. cit.

[28] General Dynamics Space Systems Division, ***Space Transportation Architecture Study, Special Report—Interim Study Results,*** report GDSS-STAS-87-001 (San Diego, CA: General Dynamics Space Systems Division, May 12, 1987), vol. 2, book 3, pp. 7-90-7-91.

Table 4-7.—Estimated Economic Benefits of Developing Technologies to Facilitate Ground Operations ("Normal Growth" mission model)

Technology	Internal rate of return	Net benefit (undiscounted)	Net benefit (discounted 5% pa.)
Built-in test equipment	140.0?40	$2,617M	$911 M
Automated data management system	115.0	1,898M	709M
Automated test and inspection	61.0	1,454M	498M
Accelerated load calculations	19.5	247M	48M
Thermal protection system	16.0	218M	59M
Fault-tolerant computers	15.5	106M	30M
Automated launch vehicle and payload handling	15.0	830M	227M
Database management system	13.5	5,413M	1,472M
Computer-aided software development	12.5	2,225M	552M
Expert systems	11.5	5,775M	1,372M
Autonomous and adaptive guidance, navigation, and control system	6.0	716M	43M

NOTE: Not endorsed by OTA; sensitive to architecture and mission model.

SOURCE: Boeing Aerospace Co.

Table 4-8.—Technology Development Benefits: A Comparison of Estimates by Two STAS Contractors
(“Normal Growth” mission model)

Boeing Aerospace Co. proposed vehicles		General Dynamics proposed vehicles	
Technology	IRR	IRR	Technology
Fault-tolerant computers	15.50/0	43.40/0	Flight management systems
Built-in test equipment	140.00/0	9.1 0/0	Automated ground operations
Automated test and inspection	61 .t)"/o		
Automated component handling	15.00!0		
Automated data management system[b]	115.OYO	17.8°10	Advanced information processing
Database management system[c]	13.50/0		
Expert systems	11 .50/0	30.50/0	Expert systems
Accelerated load calculations	19.50/0		
Computer-aided software development	12.59’o	21.8°\o	Automated software generation and validation
Thermal protection system	16.0°\o	21 .7"!0	Reusable cryogen tankage
Autonomous, adaptive guidance, navigation, and control system	6.00/0	31.1 0/0	Adaptive guidance, navigation, and control
Kerosene engine	NA[d]	4.1 0/0	Liquid oxygen/hydrocarbon engine
Actuators	NA[d]	1.9?40	Precision recovery
Hang gliders	NA[d]		

%eneral Dynamics included built-in test equipment et al. in two categories: flight management systems and automated ground operations,
bF$_{or}$ ground operations.
[c]For mission control.
d N$_o$t assessed: Boeing assumed this technology to be enabling—i.e. necessary for its recommended architecture–and assessed its net benefit but not its IRR.
e N$_o$t assessed: General Dynamics assumed this technology to be enabling—i.e. necessary for its recommended architecture—and did not assess its IRR.

SOURCES: Boeing Aerospace Co. and General Dynamics Space Systems Division

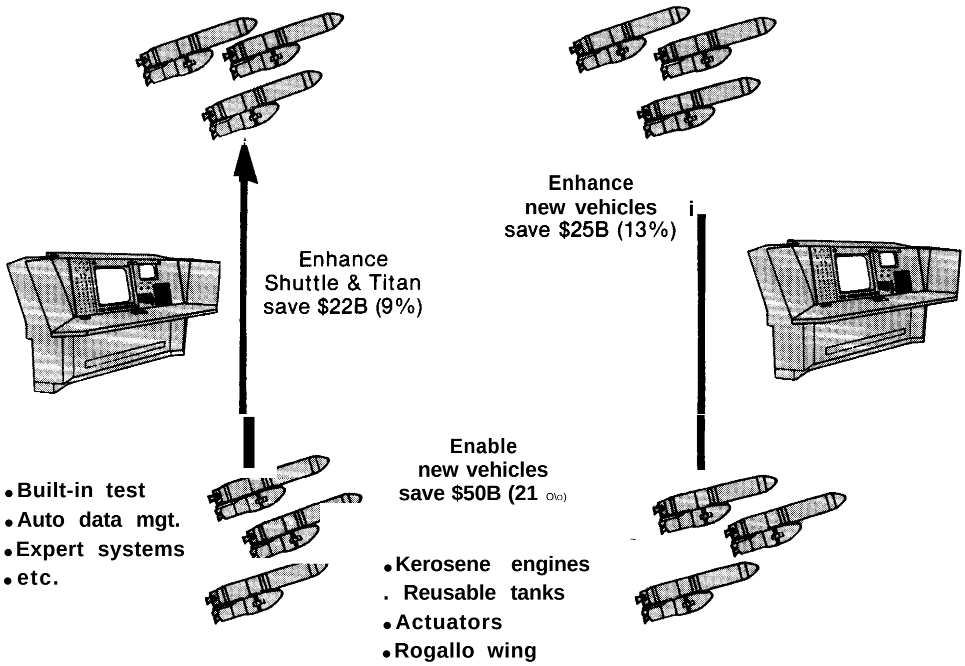
included fault-tolerant computers, which Boeing defined as a separate category.

In table 4-8, OTA attempted to group overlapping technology categories. For example, the first group of rows includes four categories defined by Boeing and two, covering the same applications, defined by General Dynamics. The second group of rows includes the Boeing categories “automated data management system” (for ground operations) and “database management systems” (for mission control) and the General Dynamics category “advanced information processing” (for both ground operations and mission control). The third group of rows includes the Boeing categories “expert systems,” and “accelerated load calculations” and the General Dynamics category “expert systems, ” which would include expert systems for load calculations. For those technologies that can be compared (e.g. “computer-aided software development” versus “automated software generation and validation”), the estimated internal rates of return differ because of differing vehicle concepts, technology application concepts, estimation techniques, databases, and judgments.

The economic benefits of so-called “enabling” technologies, which are required in order to build a given mix of launch systems, can also be estimated. For example, figure 4-3 displays estimates of the undiscounted net benefits of four technologies that, if developed, would enable the Nation to develop a mixed fleet of advanced vehicles proposed by Boeing Aerospace Co.[29] Boeing estimated the undiscounted life-cycle cost of the reference launch system mix (featuring the Shuttle for manned flights and Titan IV for cargo) to be $248 billion in the STAS “normal growth” scenario. Developing kerosene-burning rocket engines, reusable liquid hydrogen tanks, actuators for the control surfaces of reusable vehicles, and Rogallo wings and control systems (“hang gliders”) to return propulsion/avionics modules to the launch area, would enable the United States to build new kinds of vehicles that could carry the assumed traffic for $197 billion-about $50 billion (21 percent) less than the reference mix would cost.

[29]This vehicle mix features a new piloted orbiter, flyback booster, and cargo vehicle core stage with recoverable propulsion/avionics module.

Figure 4-3.—Economic Benefits of Emerging Technologies



SOURCE: Office of Technology Assessment. Based on estimates by Boeing Aerospace Co.

The figure also displays Boeing's estimates of the undiscounted net benefits of applying ground-operations technologies and other technologies[30] to enhance a launch system. Enhancing the reference launch system would save $22 billion, or 9 percent of $248 billion. Using the same technologies to enhance operations of advanced vehicles embodying the chosen enabling technologies would save $25 billion, or 13 percent of $197 billion. The total savings afforded by enabling new vehicles to be built and then enhancing their operations is estimated to be $76 billion or about 70 percent of the undiscounted life-cycle cost of the reference Shuttle-Titan IV launch system. The enhancing technologies would save $3 billion more if applied to the new launch system (as Boeing recommended) than if applied to the reference launch system, an example of synergism between the enabling and enhancing technologies.

[30]The enhancing technologies include some (e.g., expendable aluminum-lithium tankage), which would not significantly affect ground operations but which could reduce life-cycle costs in other ways.