RELIABILITY AND COST CONSIDERATIONS IN LAUNCH VEHICLES

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Abstract

Most of the discussion of new launch systems is focused on reduced cost of access to orbit. For the past twenty years it has been alleged that the cost of access to orbit is the primary impediment to the exploitation of space. The inherent reliability - or lack of it - in the launch system is, in many circumstances, more significant than the nominal cost.

Assured access to space can be provided in a number of ways. Maintaining multiple launch systems may not be the most cost-effective plan for all considerations. Product improvement that enhances the inherent reliability may be the most economical approach in at least some instances. At some point, the limitations of the technology currently used in systems must be acknowledged and new technology developed; the lack of a systematic research, technology, and advanced development propulsion effort for the past twenty years limits near-term options.

Introduction

In every launch there are significant assets at risk. There are important relationships between the value of the payload assets at risk, the cost of the launch, and the reliability of the launch system. When the payload cost is a fraction of the cost of the launch, then the cost of the launch becomes important. When the launch vehicle has a reliability in the low nineties, then the best strategy is to limit the value of the payload to the cost of the launch. When the assets at risk are many times the cost of the launch, then the reliability of the launch is more important than the cost of launch.

The original specification for the target reliability of the Space Transportation System was .995. The reliability demonstrated to date is .967. If the reliability cannot be improved significantly, then the cost to execute any given portfolio of missions will be several times greater than if the target reliability were achieved.

Improvements in inherent reliability are more cost-effective than supporting alternative systems.

Alternate systems may be necessary when continuity of operations is required and the inherent reliability is not adequate to assure launch availability.

One the most effective ways to reduce operations costs is to improve the reliability of the system at every level. An improvement in the inherent reliability of components and subsystems reduces the need for extensive checkout and provides longer, fault-free performance. Each incremental improvement provides additional opportunity to improve reliability in other areas.

Continued experience with any system offers opportunities for improvement, but reusable systems have more opportunities to "learn" from the hardware and the flight experience. Such learning has been the key to improvements in aircraft reliability and offers the promise of attaining significant improvements in launch vehicle reliability. Another paper at this conference by Dr. Cohen outlines the US NSTS approach to assured launch capability.

Finally, the direct address to reliability improvement is essential if we are to undertake the initiatives that will be required to fully explore the solar system.

Current Launch System Experience

During the last thirty years, trends have been for the costs of launch vehicles to remain generally constant but for the lift capability to grow, so unit mass-to-orbit has declined in cost. There has been a general trend also for the reliability of launch systems to improve.

Characteristically, there is a significant number of failures in the early flights as design flaws are revealed; then failure rates are lower and largely attributable to process errors, equipment aging, or other, more diverse causes. The effect has been that the demonstrated reliability has improved from the mid-80's to the mid-90's. No system has been able to sustain a demonstrated reliability above .97 for any protracted period.

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Figure 1 illustrates the lifetime reliabilities for a number of systems. When early development flights are excluded, all the figures improve slightly. Titan completed a series of 68 flights between failures and Delta had a run of 43 flights between failures; no other launch vehicles have yet demonstrated such extended runs. It is noteworthy that the Space Shuttle has the best record to date, since most systems experience a substantial number of their failures early in their history. It is also noteworthy that none of the systems has attained a reliability above .97.

The figure also indicates the time the system was down after the last failure. The down-time is a significant factor because of its implication in the back-log of commitments that accrue before the system resumes flight. Resiliency is a concept that relates reliability, downtime, surge (i.e., the ability to launch at more frequent intervals), and back-log to develop a figure of merit; the ability of a system to recover from failure and meet its accrued requirements before the next failure is expected. Resiliency can be achieved by having a very high reliability, short downtime, and sufficient operations margins to work off the backlog rapidly. An alternate strategy might be to have two launch systems to meet a requirement so no backlog accrues during the downtime of the primary system. Obviously, there are many potential strategies, and the "best" solution for one set of commitments may not be appropriate for a different set of requirements.

Spacecraft Evolution

The long-term trend has been for spacecraft to grow in size and complexity and for the cost per kilogram of the spacecraft to increase substantially. This trend has been true not only for commercial communication satellites but is even more identified with scientific and military observation satellites.

Figure 2 illustrates the effect of the reliability of the launch system on the life cycle costs of a given program as a function of the cost of the assets at risk and the reliability of the launch system. The life-cycle cost is strongly influenced by each of the factors. Launch reliability, in effect, defines the wastage to be expected. Cost per kilogram defines the expected value of the loss; assets at risk is the terminology used to provide for the assessment when there are reusable components in the system such as the Space Shuttle Orbiter. Spacecraft costs range in U.S. dollars from $53,000/kg to $188,000/kg, and the replacement cost of an orbiter and its engines is approximately $28,000/kg. It is clear that the cost for any particular scenario is a function of the values of the payloads; if the payloads are costly one-of-a-kind units such as the Hubble Space Telescope, the slope of the line would be much greater.

The Cost of Failure

The costs of failure are a function not only of the event itself but are strongly influenced by the

Launch System	Launches			Last Failure Downtime (Months)	Failure in Last 20 Flights	
	Successes	Total	R		No.	Avg. Downtime (Months)
STS	29	30	.967	32	1	32
Titan	135	141	.957	19	2	10
Ariane	29	33	.878	16	2	11
Atlas Centaur	56	67	.848	19	2	11
Delta	175	187	.936	4	1	4
Scout	98	112	.875	6	1	6
TOTAL	522	569	---	---	9	---
AVERAGE	---	---	.917	15	---	12

Fig. 1 Reliability experience of current launch systems.

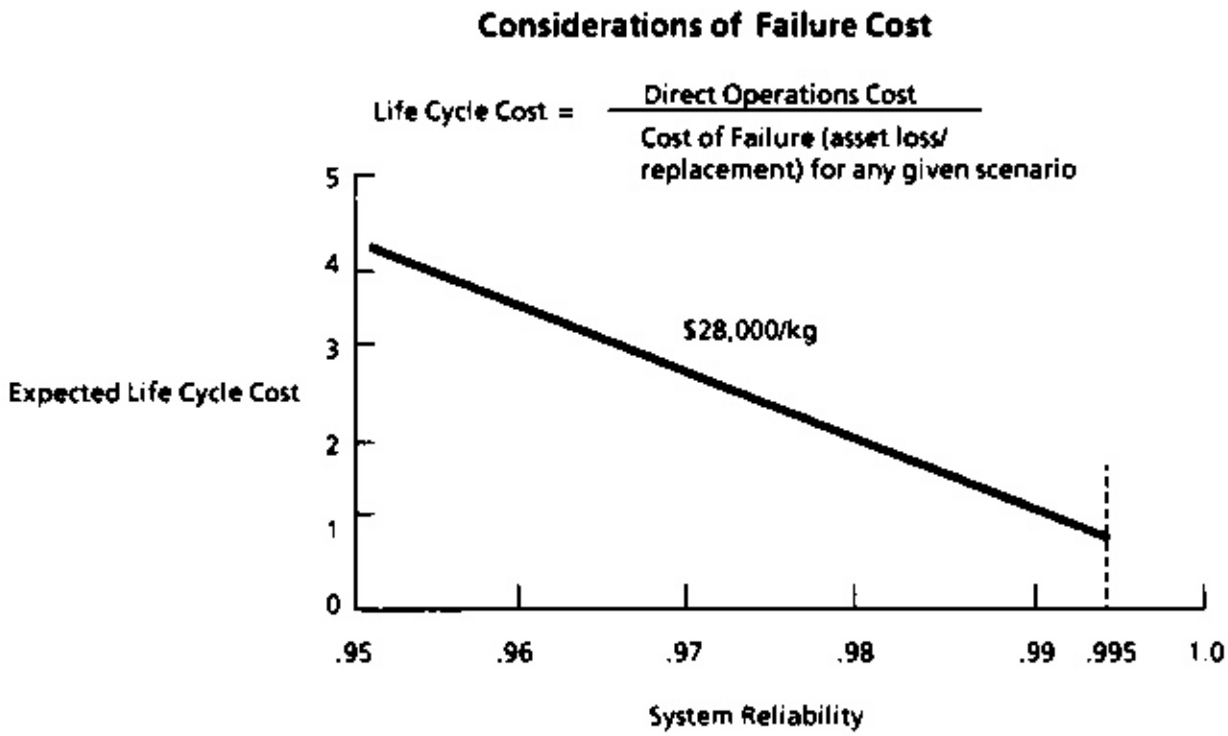


Fig. 2 Reliability of the launch system, and life cycle cost sensitivity to the value of the payload and reusable assets at risk.

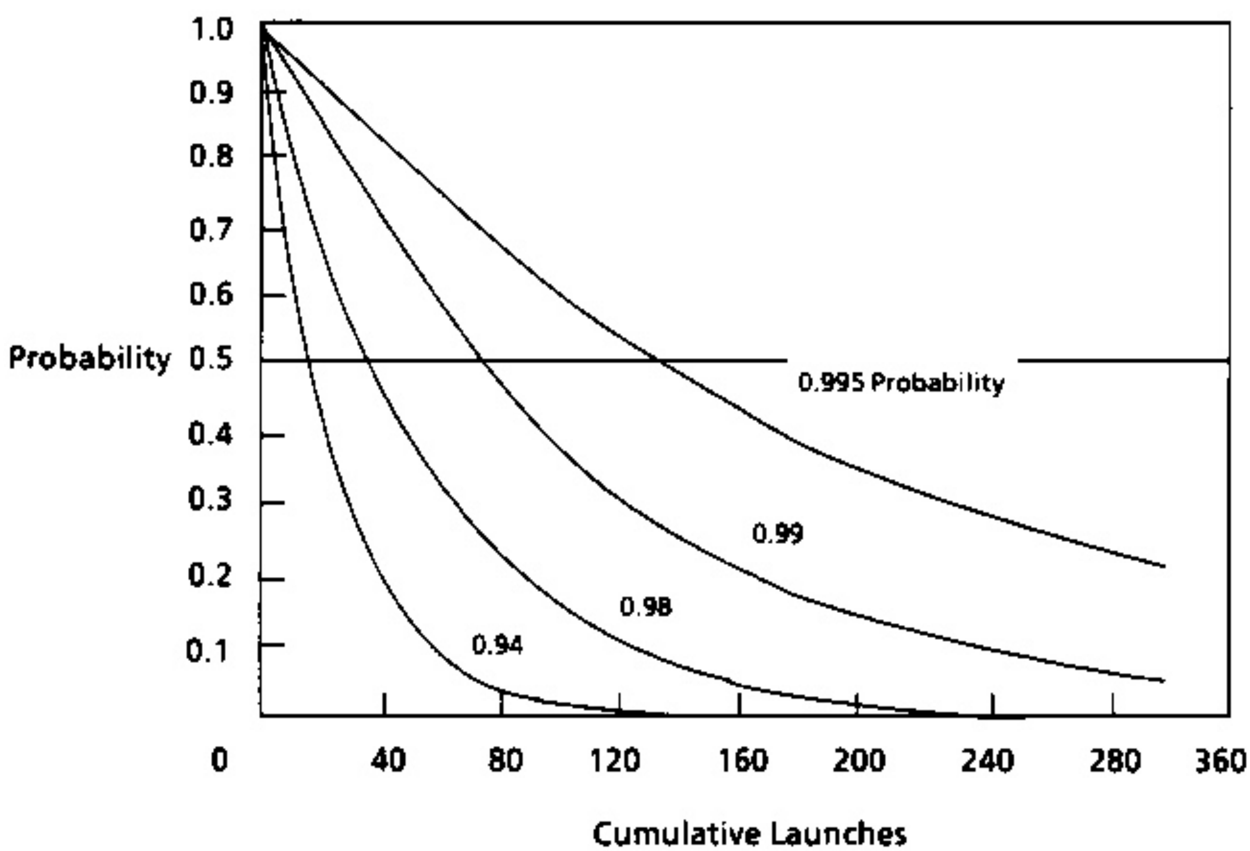


Fig. 3 The probability of no loss as a function of inherent reliability and the cumulative number of launches.

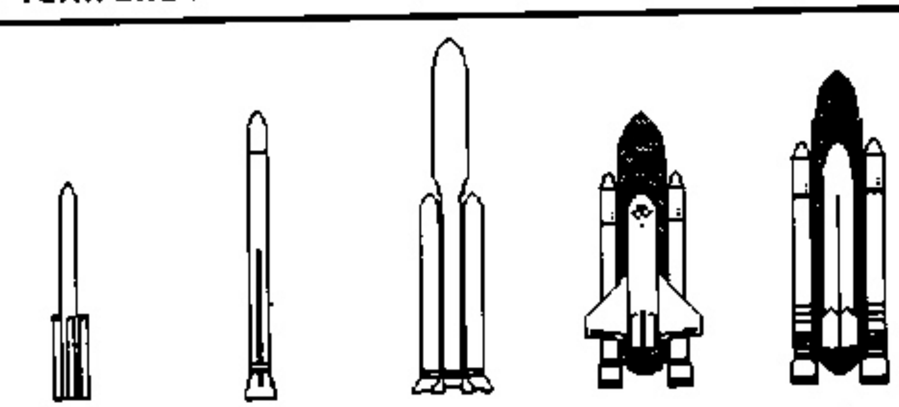
posture of expectancy in preparation for the event. The impact of the Challenger loss would have been greater had there not been structural spares on hand, and it would have been somewhat less had there been sustained orbiter production. Figure 3 illustrates the probability of a loss as a function of the inherent reliability of the system and the exposure to risk indicated by the cumulative number of launches conducted. It is clear that in any scenario in which continuity of operation is to be sustained, continuity of production of reusable assets must be provided to assure launch availability without prolonged lack of capability or substantially reduced capacity.

It is not readily illustrated, but it is equally important to be psychologically prepared for a loss as well as having suitable physical assets and production capability. When a system has performed successfully for a significant period and then experiences a failure, it is important to "contain" the fix lest it (1) destroy the heritage developed and (2) introduce new elements that may induce future failures.

Launch Capability for the Nineties

Figure 4 illustrates the launch systems available to the U.S. through the next decade. Since the Delta, Atlas, and Titan systems are all derivatives of the systems that have flown during the last several decades, it is expected that their reliability will be no worse than the past record and will likely be somewhat better. In each case, the lift performance

Near-Term and Mid-Term Launch Vehicles



	Delta II	Atlas II	Titan IV NUS	STS	Shuttle-C
Performance Capability (lb)					
100 NM East	11,100	14,500	39,100	50,200	113,000-156,000
100 NM Polar	N/A	N/A	31,000	N/A	84,000-127,000
GEO	1,950	3,300	N/A	5,200	10,000*
Launches per year	3-6	1-3	1-4	10-14	2-4 Nominal
Hardware and launch cost (Millions.of FY96 dollars)	30	60	142	115**	200 (AVE)
Cost per pound	3,400	4,100	3,600	2,300	1,500-2,500

* Using Centaur G' ** Based on DOD/NASA Cost of $115M/Flight N/A = Not Available
NUS = No Upper Stage

Fig. 4 Launch systems available in the U.S. for the next decade.

of the vehicle is improved relative to earlier configurations, which reduces delivery cost per kilogram. Cost per unit is roughly proportional to the mass lift capability of the vehicle but is sensitive to the annual flight rate. The costs cited are internally consistent but do not represent "prices" as they would be quoted to users. They are useful for comparative purposes between systems but not outside of this context.

Reliability and Resiliency

The objective in maintaining multiple systems is to assure launch availability. As figure 5 illustrates, the effectiveness of such a strategy is a function of the basic reliability of each of the systems. Two parametric cases are illustrated: a primary and backup system, each with a reliability of .96; and a primary system with a reliability of .99 and a backup with a .96 reliability. Resiliency or assured availability as a function of annual flight rate is shown.

It is clear that there is a significant difference in capacity for the higher reliability system. At flight rates above twelve per year, it is more likely to be available than either of two systems of .96. It is also clear that the better the base system, the less it is helped by a backup system of lower reliability.

The obvious question is the relative cost of the two cases. Unfortunately, there is no simple parametric way to do a cost comparison. There are, however, some observations that can be made to illustrate the cost considerations. For spacecraft systems that require a constellation of similar spacecraft, as in the case of the GPS (Global Positioning System) where the relatively large number of units required and lot buys significantly reduce unit cost and are comparable to the cost of the launch, then dual compatibility with two launch vehicles in the .96 reliability range may be a good trade. One could also infer that when the value or cost of the payload is high relative to the cost of the launch, it is preferable to use the higher reliability system

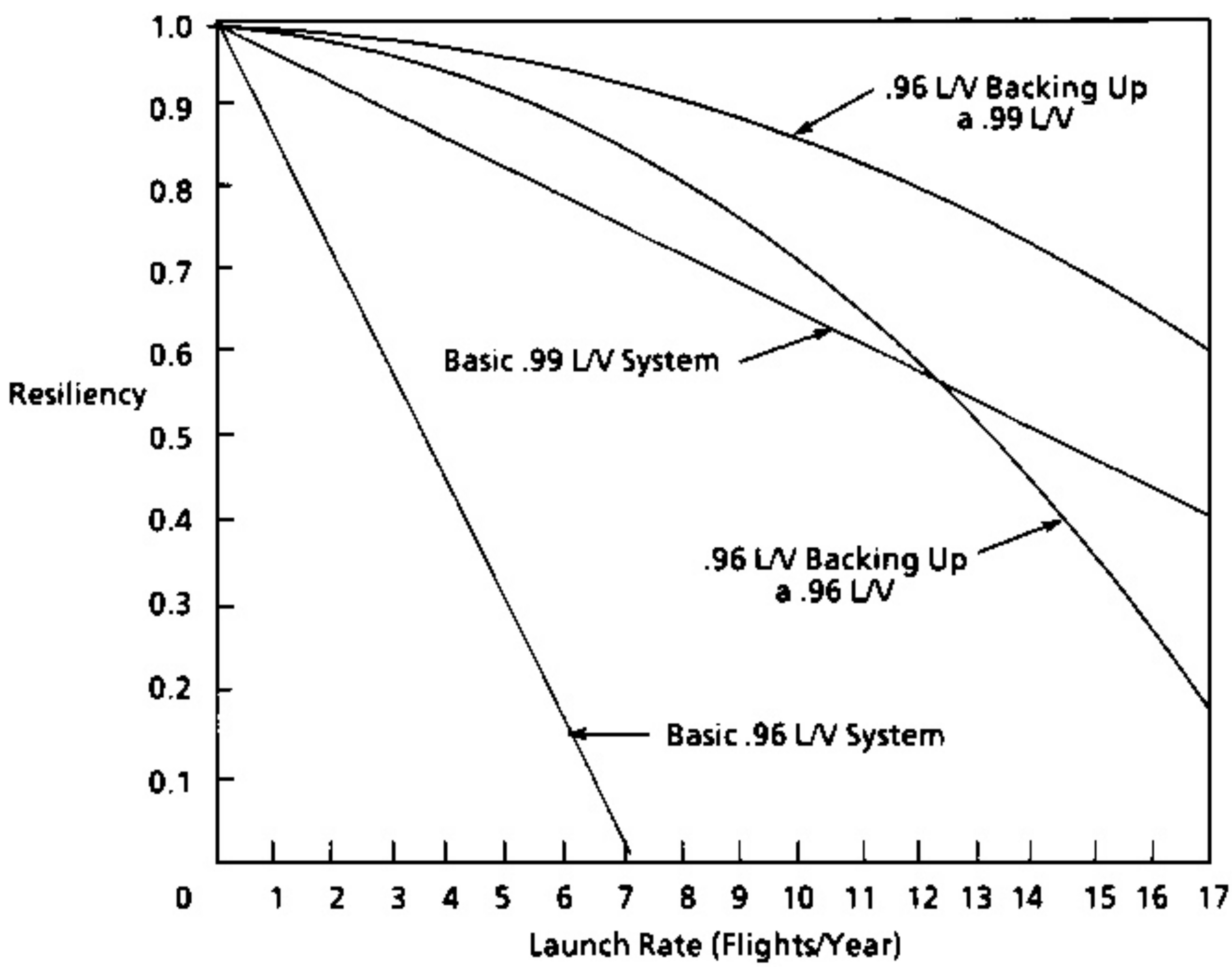


Fig. 5 Resiliency or probability of having available launch capability as a function of the reliability of the prime and backup launch systems.

because the expense of loss will be dominated by the replacement of the payload.

Technology Base

All the systems in operation in the U.S. are based on technology development programs of the 1960's. The only new engine in the U.S. launch fleet is the SSME (Space Shuttle Main Engine). No program existed to develop new engines or propulsion systems until the recent initiatives of the ALS (Advanced Launch System) Program. The initiative to develop new sea level booster and second-stage engines is long overdue. The propulsion system is the primary cause of unreliability in current vehicles and can only be enhanced by systematic development testing. The limitations on our current capability will persist until the necessary development has been conducted.

The fundamental source of reliability is comprehensive understanding of the designs and processes with which we work. That can be obtained only through continuous testing of our systems and our understanding of them. Because of the nature of the enterprises we want to undertake in a manned Mars expedition, success can only be achieved by developing greater inherent reliability. There may be some hard choices to be made between assurance in the near term by replication of launch systems, which is expensive, and the investment in reliability enhancement which requires comparable resources but, in the end, provides a much higher payoff.

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