EELV Reliability: Building on Experience

The National Space Transportation Policy, signed by President Clinton on August 5, 1994, gave the National Aeronautics and Space Administration (NASA) responsibility for reusable launch vehicle development, while tasking the Department of Defense (DoD) with improving expendable launch vehicles (ELV) and the nation's existing launch infrastructure. This goal resulted in the initiation of the Evolved Expendable Launch Vehicle (EELV) program. Under this program DoD was to partner with industry to develop a national launch capability to satisfy both government and commercial payload requirements and reduce the cost of space access by at least 25 percent. Four companies initially competed for DoD contracts to develop these vehicles and ultimately, Lockheed Martin Corporation and The Boeing Company were awarded EELV production and service contracts for their respective Atlas 5 and Delta 4 vehicles.

With a focus on the Atlas and Delta families, the Fourth Quarter 2001 Quarterly Launch Report special report addressed the process by which launch vehicles become more reliable and capable over time. The present report augments the prior one, examining in greater depth the EELV program's effort to produce highly reliable vehicles in a relatively short period of time. The first part of this report shows that vehicle reliability tends to increase with testing and flight experience, and that later variants within a launch vehicle family tend to be more reliable than earlier ones. The second part of the report describes the approaches, many of which were taken to improve earlier vehicles' reliability that Boeing and Lockheed Martin are now using to bolster reliability and reduce technical risk of their respective EELVs. The report suggests that if past is prologue, the Atlas 5 and Delta 4 EELVs are on track to exceed the initial reliability of their predecessors in the short term, with a good chance of achieving superior reliability over the long term.

LAUNCH VEHICLE RELIABILITY AND THE IMPACT OF EXPERIENCE

Launch vehicles are complex devices, and like any complex device, it takes time to refine them. The ideal way to "wring out" a design's flaws and thus bolster a vehicle's reliability is to follow a thorough testing process. Vehicle developers routinely conduct ground tests of vehicle components and systems before a complete vehicle ever flies. While these tests certainly are critical to increasing a vehicle's chances of flight success, they do not guarantee that a vehicle will fly flawlessly. Optimally, ground tests would be followed by many dedicated test flights of the vehicle carrying a mass simulator or dummy payload. Repeat numbers of test flights would allow vehicle engineers to analyze the vehicle's performance, make modifications to enhance performance, and fly the vehicle to test the performance with design alterations.

For early ballistic missiles, the testing process did involve a large number of flights: the Atlas Intercontinental Ballistic Missile (ICBM), for

Vehicle	Number of Test Flights
Ariane 1	1
Ariane 2	0
Ariane 3	0
Ariane 4	1
Ariane 5	3
Space Shuttle	4
Atlas 1 & 2	0
Delta 3	1
Zenit 3SL	1

Table 1: Numbers of Test Launches for Launch Vehicles

one, made 82 test flights between 1957 and 1962, while the Titan ICBM made around 100 test flights. In contrast to missiles, launch vehicles generally make far fewer test flights (see Table 1). While this, in part, is because many launch vehicles are based on ballistic missiles and benefit from the testing carried out on the missiles, it is also because numerous test flights can be cost- and schedule-prohibitive for vehicle manufacturers. As a result, it is not uncommon for the first flight of a launch vehicle to carry a functional payload, as opposed to a mass simulator or test equipment. Regardless of whether or not a vehicle is formally in test status, however, continuous operations, analysis of performance, and subsequent design improvements are key to raising a design's reliability[1].

Moreover, constant monitoring of vehicle performance is necessary to maintain a high degree of reliability once it has been achieved: even proven systems may lose reliability as a result of changes in manufacturing or operating procedures. For example, both the Pratt and Whitney RL-10 engine, used on the Delta 3 and the Centaur upper stage, and the Proton's NPO Energomash 11D58M have caused launch failures because changes in manufacturing procedures resulted in flawed engines. Once these failures occurred, the problems were identified and corrected, but these cases serve to illustrate that launch vehicles require constant attention to keep them reliable.

THE CASES OF ARIANE, ATLAS, AND PROTON

To explore the development of vehicle reliability over time, this report considers members of three vehicle families: Ariane 1-4, pre-Atlas-3 Atlas vehicles, and pre-Proton-M Proton vehicles (Proton M and Atlas 3 vehicles differ too much from there respective predecessors to make their inclusion meaningful). These vehicles were chosen to compare the development histories of three representative vehicles of major spacefaring nations. Although other vehicles, such as the Delta and Soyuz, also have lengthy development histories, the three vehicles chosen are all similar in mass class and compete for the same basic market.

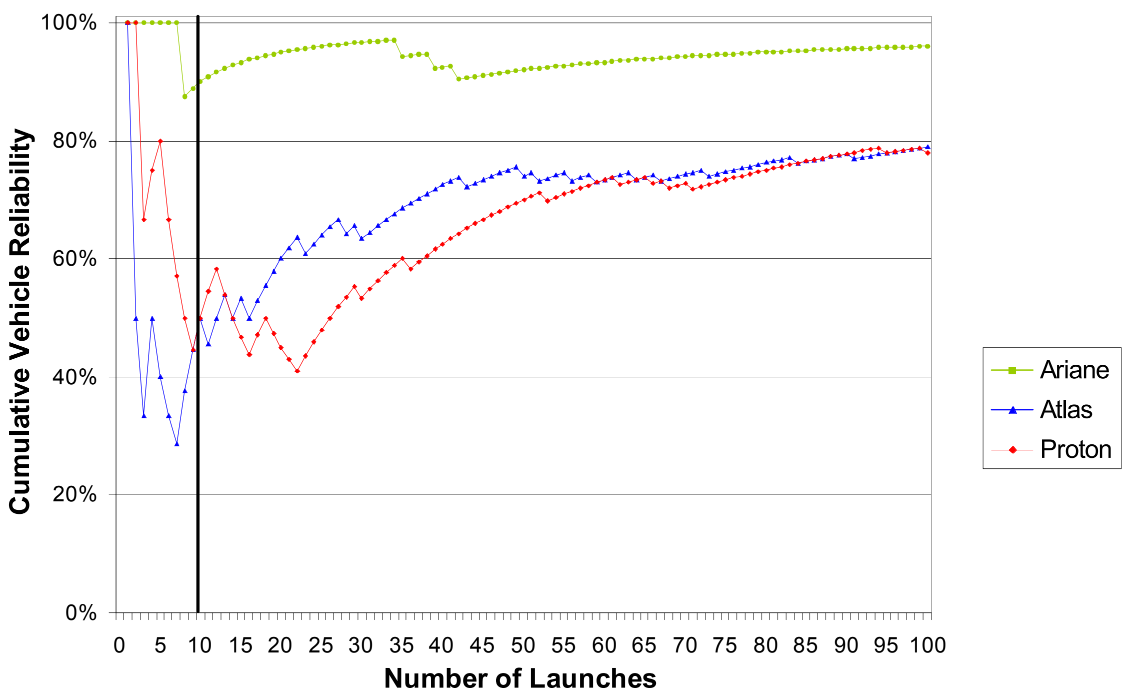

Figure 1: Cumulative Vehicle Reliability for the First 100 Launches

	Ariane 1-4			Atlas			Proton		
	Launch Number	Success Rate (for Interval)	Change	Launch Number	Success Rate (for Interval)	Change	Launch Number	Success Rate (for Interval)	Change
1	1-50	88%	N/A	1-50	74%	N/A	1-50	70%	N/A
2	51-100	94%	6%	51-100	84%	10%	51-100	86%	16%
3	101-136	100%	6%	101-150	88%	4%	101-150	96%	10%
4				151-200	90%	2%	151-200	96%	0%
5				201-250	88%	-2%	201-250	92%	-4%
6				251-300	100%	12%	251-284	94%	2%
7				301-306	100%	0%			

Table 2: Vehicle Reliability by Chronological Intervals of Fifty

As can be seen in Figure 1, a vehicle's first ten launches are generally the most problematic. For both Ariane and Atlas, the worst cumulative reliability occurred during the first ten launches. The Russian Proton deviates from this pattern, having made 22 flights before its reliability began to improve. This late turning point reflects the Russian design methodology, which calls for flight testing earlier in the design process than would be considered appropriate by a Western designer. Despite this testing process, the Proton still begins to improve early in its lifetime. By the 100^{th} launch, Atlas and Proton achieved nearly identical cumulative reliabilities.

In order to portray early reliability gains in a different light, Table 2 and Figure 2 show vehicle success rates by increments of 50. The success rate of each set of 50 launches is based on the experience in that set of launches; it is not cumulative. As such, Table 2 and Figure 2 provide vehicle reliability data for distinct 50-launch increments and illustrate differences in reliability among different periods (for instance, the difference between the reliability of launches 1 through 50 as compared to launches 51 through 100). Note that the size of the final interval varies among the vehicles, as none of them have been launched an even multiple of fifty times.

Table 2 and Figure 2 show that these vehicles continue to improve for at least the first 100 to 150 launches, with reliability reaching the 90- to 100-percent range. As long as a vehicle's reliability is under 100 percent, however, there is the possibility of further improvement. This

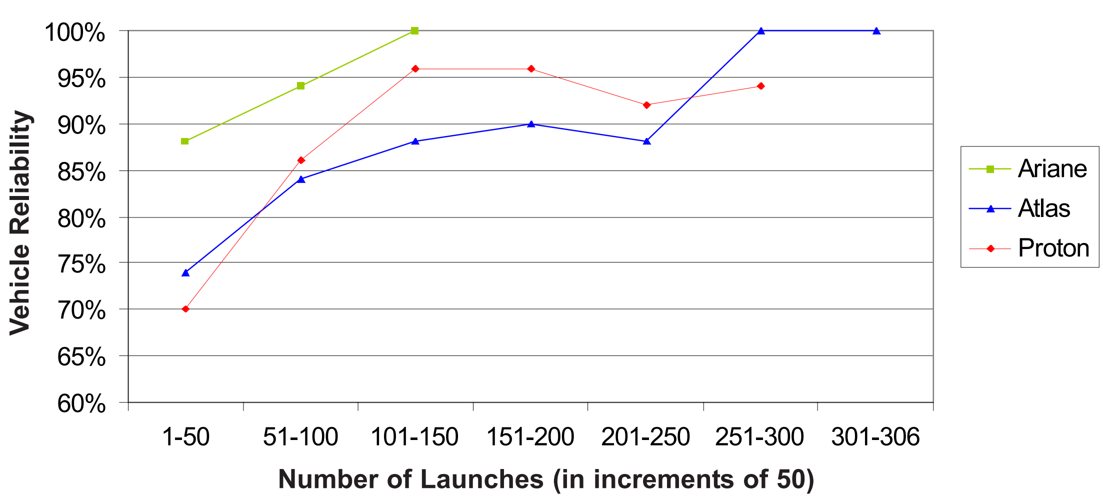

Figure 2: Vehicle Reliability by Chronological Intervals of Fifty

is demonstrated by the improvement shown by the Atlas vehicle in its final two increments (flights 251 through 306).

For Ariane, reliability improvement ceased when it achieved a perfect record in its last interval of 36 launches. This achievement is even more striking considering that the actual number of successful consecutive Ariane launches was 65, from 1995 to the present. As of the first quarter of 2002, Ariane vehicles (excluding the Ariane 5) have cumulative reliability of 94 percent.

Proton improved throughout its first 150 launches, then showed no improvement during its fourth increment and declined by two percent in its fifth increment. The sixth set of launches is promising, returning to the third and fourth increments' 96 percent success rate. Improvement in Proton's reliability already may be occurring, but this will not be clear for another 20 or 30 launches. Proton's lifetime cumulative reliability is 89 percent.

The Atlas reliability development pattern shows similarities to the histories of both Ariane and Proton. Atlas vehicle reliability improved up through the third 50-launch increment, then declined slightly, and then leveled off for the next three periods. In the sixth period, Atlas had a perfect record, which has continued into the first nine launches of the seventh 50-launch period. The total number of consecutive successful launches for Atlas is now 60, for a cumulative reliability of 88 percent.

This analysis intends not to determine which vehicle is superior, but instead to outline the developmental patterns of launch vehicles gained over many launches. Judging from the sample vehicles, it appears that most launch vehicles experience the greatest improvements in reliability over their first 150 launches. Improvement may continue to occur, but the technical innovations resulting in the greatest immediate increases in reliability will have already been made; thus, reliability gains will be harder to achieve.

There is also the possibility that a vehicle may manifest new problems and suffer a decrease in reliability as it ages. In some cases, this occurs because components become obsolete or unavailable, forcing changes in a vehicle that may cause failures. In other cases, design or manufacturing changes in proven components and systems may result in new bugs to replace the old ones that had been carefully removed from the launch vehicle system. Still, even in cases where reliability does decline, the vehicle's reliability remains better than during its initial period of operation: single or even multiple, failures later in a vehicle's life have less of an impact as the number of successful launches grows.

In effect, when launches are successful, reliability improves. When a failure occurs, reliability declines; in correcting the problems revealed by the failure, however, the vehicle becomes more reliable in the long term. Figure 2 shows that both Atlas and Proton have endured declines in reliability. Although it is not possible to go into the details of every launch failure of Ariane, Atlas, and Proton some failures can be chosen for closer examination because they exemplify the process by which launch vehicle reliability improves.

In Proton's last 34 launches, there have been two launch failures (flights 263 and 266). These failures were similar and were caused by the same problem: debris left inside their second-stage engines during assembly at the Voronezh Mechanical Plant in Russia. Design changes have been made in current production engines, and controls have been developed to prevent such problems in the future. These controls include better quality control processes during manufacturing and special examinations of all flight motors. Following these changes and increased scrutiny of older engines, there have been no more Proton launch failures.

There have only been three failures of the Atlas launch vehicle since its commercialization following the Challenger disaster. All three of these failures occurred in Atlas' fifth launch increment (launch numbers 236, 246, and 247). These failures are further examples of why even well-proven vehicles fail. Flight numbers 236 and 246 failed when their Centaur upper stages' engines malfunctioned. Investigations of both failures revealed that the Centaur engines could be frozen during a chill-down procedure used prior to liftoff to ensure proper liquid oxygen (LOX) flow. In order to mitigate this flaw in the Atlas vehicle, General Dynamics (who then produced the Atlas launch vehicle) introduced hardware and launch procedure changes that have prevented the recurrence of this problem.

Atlas' flight number 247 was lost because an improperly tightened set-screw caused the vehicle's first stage to produce only two thirds of its nominal thrust. This shortfall caused the payload to be deployed into an improper orbit. Once this problem was identified and it was determined not to be a design or hardware problem, launches quickly resumed. The problem has not recurred.

Even when a failure is not fully understood useful information can be gained from it. In the case of the most recent failure of an Ariane 4 launch vehicle (an Ariane 42P), the vehicle achieved only 70 percent of its nominal third-stage thrust and failed to place its payload into a proper geostationary transfer orbit. The investigating board concluded that insufficient amounts of LOX had reached the turbopump gas generator. Two causes seemed likely. One was a partial blockage of one of the supplier components by a foreign particle or ice; the other was a leak in the LOX feed, possibly due to a bad seal. Simulations indicated that an obstruction was the most likely cause of the accident.

Despite the uncertainty concerning the cause of the failure, the board recommended a series of steps to improve the Ariane 4's reliability. Six of the board's 13 recommendations covered contamination risks, while five related to improved testing and leak prevention, while the final two concerned the study of overall failure options. Even though the exact cause of the failure was not proven, the chances of a similar failure were reduced and the Ariane 4 has since flown without a failure.

The discussion of vehicle reliability thus far has largely revolved around the accumulation of experience with, and a growing understanding of, launch vehicles by their builders and operators. As can be seen in the previous examples, failures occur for many reasons. Some of these are as simple as an inadequately-torqued screw while others can be traced back to the drawing board. The important point is that failures not caused by wholly random events (for instance, a lightning strike) can generally be prevented once the hardware or procedural flaw that caused them is discovered. With each such discovery-many of which are discovered without the loss of a vehicle-the vehicle grows more reliable. The availability of and desire to conserve this knowledge base is why launch vehicle manufacturers prefer to make improvements in an incremental fashion as opposed to creating new systems from scratch.

Because the knowledge gained through the experiences with one variant is imparted in the next, a new variant within a given vehicle family starts higher on the learning curve than an entirely new vehicle. Table 3 shows the development of the Ariane 1-4 family. It can be seen that the earliest two Ariane variants, Ariane 1 and Ariane 3, have the lowest reliability records of all of the variants considered here. These two variants have the lowest initial reliabilities as well as the lowest lifetime reliabilities. Note that both initial and lifetime reliabilities generally increased as new Ariane variants were introduced.

Vehicle Variant	Introduction Year	First Ten Launches			All Launches		
		Success	Failure	Reliability	Success	Failure	Reliability
Ariane 1 (all)	1979	8	2	80%	9	2	82%
Ariane 3 (all)	1984	8	2	80%	9	2	82%
Ariane 2 (all)	1986	5	1	83%	5	1	83%
Ariane 44LP	1988	9	1	90%	25	1	96%
Ariane 44L	1989	9	1	90%	32	1	97%
Ariane 40	1990	7	0	100%	7	0	100%
Ariane 42P	1990	9	1	90%	13	1	93%
Ariane 44P	1991	10	0	100%	17	0	100%
Ariane 42L	1993	9	1	90%	10	1	91%
Totals		74	9		127	9	

Table 3: Ariane 1-4 Variant Launch Reliability

Unfortunately, an analysis of the reliability differences among variants in a family cannot be applied to Proton or Atlas. The major distinction among various Proton vehicles is the upper stage; Proton vehicles do not vary in the same way as Ariane vehicles, whose variants use different combinations of strap-on boosters and were introduced at different times. The large number of Atlas variants, many of which have made only two or three launches, prevents the Atlas from being useful as an example of the effects of variation on launch vehicle reliability. Nonetheless, the analyses in this section suggest that, in general, the most reliable launch vehicle is one whose history is extensive and replete with incremental developments.

EELV RELIABILITY

The products of the EELV program, the Lockheed Martin Atlas 5 and the Boeing Delta 4, represent an effort to create new vehicles that achieve high reliabilities but with fewer launches than the vehicles discussed above. The EELV manufacturers hope their vehicles will not undergo the initial failures of their predecessors and will capture many of the reliability improvements developed during their predecessor's operational lifetimes. The manufacturers hope to achieve high reliability using a combination of their predecessors' heritage and experience, incremental innovation, and simplification of various systems.

Despite embracing quite different design choices, the developers of both the Delta 4 and the Atlas 5 are using the same approach to maintain the experience gained by previous launch vehicles. Both Delta 4 and Atlas 5 have been preceded by intermediate vehicles serving as transitions between them and their proven ancestors. These "bridge" vehicles are the Atlas 3 and the Delta 3, both of which have a large degree of commonality with the older Delta and Atlas designs while pioneering various innovations for the follow-on Delta 4 and Atlas 5.

The Atlas 3 is an initial effort to reduce vehicle complexity while increasing vehicle performance. It uses improved first-stage fuel tank construction and simplified components, while replacing the original Atlas's stage-and-a-half staging concept with a more conventional single stage. It also replaces the original design's three Rocketdyne engines with a single, more powerful, NPO Energomash/Pratt & Whitney RD-180 engine. As a result, the Atlas 3's first-stage thrust section undergoes only one staging event and has only seven fluid interfaces, as opposed to previous Atlas models with six staging events and 17 fluid interfaces.

Figure 3: Atlas Vehicle Lineage

The Atlas 3 family also introduces two improved versions of the Centaur upper stage: the Atlas 3A uses a single-engine Centaur, removing one RL10A-4-1 engine and centering the other along the Centaur's axis, while the Atlas 3B uses a lengthened version of the improved Centaur with two RL10A-4-2 engines. The improved Centaur engines include upgrades, such as chiller modifications and a health monitoring system designed to increase reliability and operational standards. Both the single- and dual-engine Centaurs will continue to be used on the Atlas 5 series after the Atlas 3 is retired (see Figure 3 for the Atlas lineage).

Unlike the Atlas 3 program, Boeing did not improve the Delta 3's engines for use on the Delta 4, but it does introduce a number of new features that will be used on the Delta 4. The upper stage introduced on the Delta 3 will be used in an expanded form (using the same RL10B-2 engine as the previous version with larger fuel and oxidizer tanks) on the Delta 4, along with the Redundant Inertial Flight Control Assembly avionics system that debuted on the Delta 3.

By introducing a limited number of new components to the EELVs, and doing so as much as possible through transitional vehicles, Boeing and Lockheed Martin are attempting to increase EELV reliability while reducing their development risk. Lockheed Martin is confident, for instance, that the success of the Atlas 3 has proven 80 percent of Atlas 5's technologies.[2]

In addition to reducing risk and thereby improving reliability by incrementally introducing new systems and better designs, both the Atlas 5 and Delta 4 are designed with

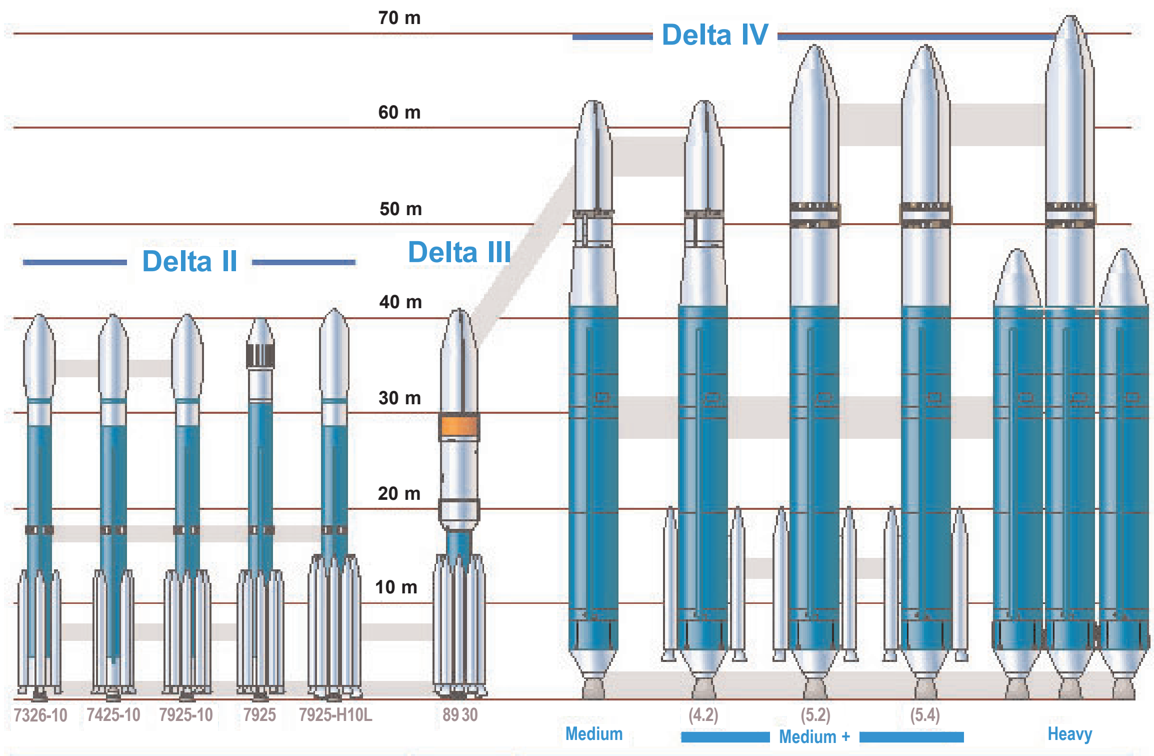

Figure 4: Delta Vehicle Lineage

fewer possible failure modes than their predecessors. The Atlas 5, for example, is estimated to have approximately 125 potential single-point failures as opposed to over 250 for the Atlas 2AS.[3] Lockheed Martin will also replace the pressure-stabilized fuel tanks used on all previous Atlas vehicles with structurally-stable propellant tanks. These tanks will support the weight of the vehicle's payload without being fueled, in contrast to previous Atlas vehicles, which required the pressure of the fuel in their tanks to bear the weight of their payloads. The new Atlas 5 Common Core Booster™ (CCB) will be much more robust than its pressure-stabilized predecessor, while still using many systems proven on the Atlas 3.

The Delta 4 involves further improvements on the components pioneered by the Delta 3. It introduces a new first-stage common booster core (CBC), which will use the Rocketdyne RS-68 engine developed specifically for the Delta 4. This engine has 95 percent fewer parts than the comparable Space Shuttle Main Engine (SSME) and requires only 8,000 hours of touch labor, compared with 171,000 hours for the SSME.[4]

The heavy version of the Delta 4 will use three CBC stages in parallel. It will resemble the current Titan 4 in appearance, but instead of using two entirely different engine systems (a liquid-fueled core stage and strap-on solid fuel boosters) it will have a single design repeated three times. Only after the CBC has been tested in single core launches will it be used in this triplex arrangement-an approach aimed at reducing the risk of vehicle failure (see the Delta vehicle lineage in Figure 4).

CONCLUSION

If the strategies of using incremental innovation and simplified components and systems are successful, the overall reliability of the Boeing and Lockheed Martin EELVs should be higher than that of earlier variants in their respective vehicle lineages at a corresponding point in their development. As the name *Evolved* Expendable Launch Vehicle suggests, these vehicles are intended to build on success and limit new risk, while introducing capabilities equivalent to those of a new vehicle. If experience provides any guidance, to the extent that launch vehicle development is successfully managed, the EELVs will have higher initial reliabilities than those of a clean-slate design. Such a success will improve U.S. launch assets while maintaining current capabilities.

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1 It should be noted that every launch of an expendable launch vehicle (ELV) is actually an inaugural flight of that particular vehicle (if not that particular design). ELV reliability is thus not easily or fairly comparable with that, for example, of a certified commercial aircraft.

2 http://www.ilslaunch.com/missionplanner

3 Ibid.

4 http://lean.mit.edu/Events/workshops/files_public/EBRT_eelv.pdf