The Evolution of Commercial Launch Vehicles

INTRODUCTION

On February 14, 1963, a Delta launch vehicle placed the Syncom 1 communications satellite into geosynchronous orbit (GEO). Thirty-five years later, another Delta launched the Bonum 1 communications satellite to GEO. Both launches originated from Launch Complex 17, Pad B, at Cape Canaveral Air Force Station in Florida. Bonum 1 weighed 21 times as much as the earlier Syncom 1 and the Delta launch vehicle that carried it had a maximum geosynchronous transfer orbit (GTO) capacity 26.5 times greater than that of the earlier vehicle.

Launch vehicle performance continues to constantly improve, in large part to meet the demands of an increasing number of larger satellites. Current vehicles are very likely to be changed from last year's versions and are certainly not the same as ones from five years ago. In many cases this is true even though the commonly used name for a vehicle has not changed.

This report will detail vehicle performance improvements over the last four decades. Evolutionary paths will be traced for the Atlas and Delta launch vehicles. Patterns of growth and reliability of these vehicles are also examined.

Atlas and Delta vehicles, in particular, have been chosen because they were part of the original generation of U.S. launch vehicles and exhibit increased capacity with only moderate technical change from one generation to the next. Later vehicles, designed from the beginning as launch vehicles, (for instance the European Ariane series, or the Russian Proton) have not undergone the same degree of evolution and, hence, are less interesting for this study.

LAUNCH VEHICLE ORIGINS

The initial development of launch vehicles was an arduous and expensive process that occurred simultaneously with military weapons programs; launch vehicle and missile developers shared a large portion of the expenses and technology. The initial generation of operational launch vehicles in both the United States and the Soviet Union was derived and developed from the operating country's military ballistic missile programs. The Russian Soyuz launch vehicle is a derivative of the first Soviet intercontinental ballistic missile (ICBM) and the NATO-designated SS-6 Sapwood. The United States' Atlas and Titan launch vehicles were developed from U.S. Air Force's first two ICBMs of the same names, while the initial Delta (referred to in its earliest versions as Thor Delta) was developed from the Thor intermediate range ballistic missile (IRBM) coupled with the upper stages of the unsuccessful Vanguard launch vehicle (the first launch vehicle developed as a launch vehicle from the start).

This evolution followed the pattern set by the development of the atmospheric sounding rocket, the use of which was pioneered when the U.S. Army launched German-built V-2s after World War II. In this program, scientists were offered the chance to place scientific instruments in V-2s that were to be launched for weapons development reasons. As the explosive warheads had been removed from the missiles, increased room and lifting capacity allowed for scientific and weapons research on the same flights.

LAUNCH VEHICLES VS. BALLISTIC MISSILES

The most basic difference between launch vehicles and ballistic missiles is that launch vehicles have the ability to modify their trajectories once they achieve orbital velocities. While a ballistic missile may have the ability to achieve an orbital velocity, it cannot change its path to circle the Earth instead of following a parabola that returns it (regardless of its speed) to the Earth because it does not have the additional propulsion capacity to change its path once it reaches orbital speed and altitude (see Figure 1 for a visual depiction of the difference).

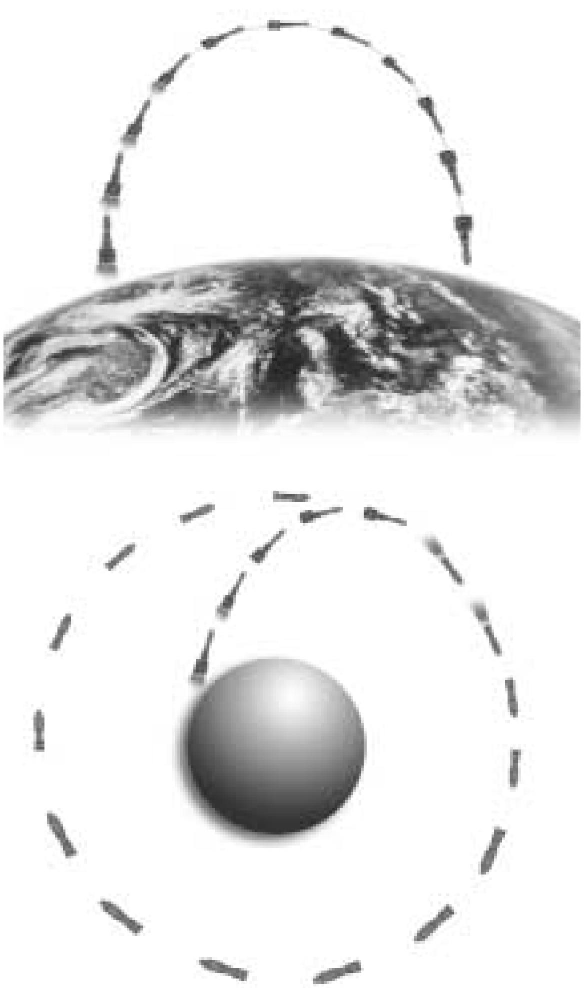

Figure 1. Ballistic Missile Parabola (top) vs. Launch Vehicle Orbital Path (bottom)

Due to these considerations, the first step in modifying a ballistic missile to fill a launch vehicle role is to give it an upper-stage maneuvering capability. In the case of the Thor Delta, this was achieved by the addition of the Vanguard launch vehicle's upper stages to the Thor IRBM that served as the Thor Delta launch vehicle's first stage. In the case of the Atlas, new hardware was developed to allow the payload to achieve a stable orbit (although the Atlas Able also used Vanguard stages).

These early launch vehicles had the capacity to lift a payload to low Earth orbit (LEO). As time progressed, however, the desire to place satellites into higher orbits such as GEO became more prevalent. Additional systems to increase capacity from that of a ballistic missile or a LEO-capable launcher became necessary. Launch vehicles were soon given an extra upper stage to place payloads into GEO orbits.

ATLAS VEHICLE EVOLUTION

As described in the previous section, the first step in the evolution of launch vehicles was the addition of stages that allowed missiles to perform a launch vehicle role. Following this basic modification, a continuing series of major and minor modifications occurred that increasingly optimized the vehicle for its role as a launch vehicle. First government and then industry (after the Challenger accident) incrementally increased the launch capacity of the Atlas launch vehicle (Figure 2 and Table 1show the evolution of Atlas GEO capable vehicles).

For the Atlas launch vehicle, the first major change following its introduction in 1958 (an Atlas B carrying the world's first communications satellite for Project SCORE) was the ability to release its payload. The initial SCORE payload remained attached to the launch vehicle while the Mercury capsule that was the Atlas' next payload was able to detach from the launch vehicle upon reaching orbit. The use of the Atlas as a crew-rated vehicle also involved structural enhancements to the Atlas D ICBM-based launch vehicle. The first Atlas capable of launches to GEO was the 1959 Atlas Able, which married the Atlas ICBM with an upper stage based on Vanguard's second stage. This combination was not a success, however, failing in four out of four launch attempts.

The Atlas D ICBM was the basis of almost all early Atlas launch vehicles. In its space launch version, the Atlas D was referred to as the Atlas LV-3 (standing for launch vehicle 3). The LV-3A was an Atlas D with an Agena upper stage, the LV-3B carried the Mercury spacecraft, and the LV-3C used the Centaur upper stage. Unfortunately, as each launch vehicle was individually converted from an ICBM, the LV-3 was not an optimal vehicle. Large-scale missile production was cheap but converting ICBMs to launch vehicles was a lengthy and cumbersome process. As a result, in 1962 the Air Force awarded General Dynamics a contract to resolve this problem and develop a standardized Atlas D-based launch vehicle. The SLV-3 (standardized launch vehicle, as this vehicle was designated) was a more reliable, standardized version of the Atlas D ICBM with three Rocketdyne MA-3 engines (with a total of 1725 kN thrust), replacing the original three Rocketdyne MA-2 engines (with a total of 1630 kN thrust).

In 1965 General Dynamics received a further Air Force contract to improve the Atlas SLV-3 by lengthening the vehicle to increase its fuel load, reducing overall vehicle weight, and replacing the engines with Rocketdyne MA-5 engines (1950 kN total thrust). This program resulted in the SLV-3A and SLV-3C. These versions differed in the method of engine cut-off and choice of upper stage. The Atlas SLV-3A used a radio-controlled engine cut-off and an Agena upper stage. The Atlas SLV-3C used a Centaur upper stage with engine cut-off caused by fuel depletion.

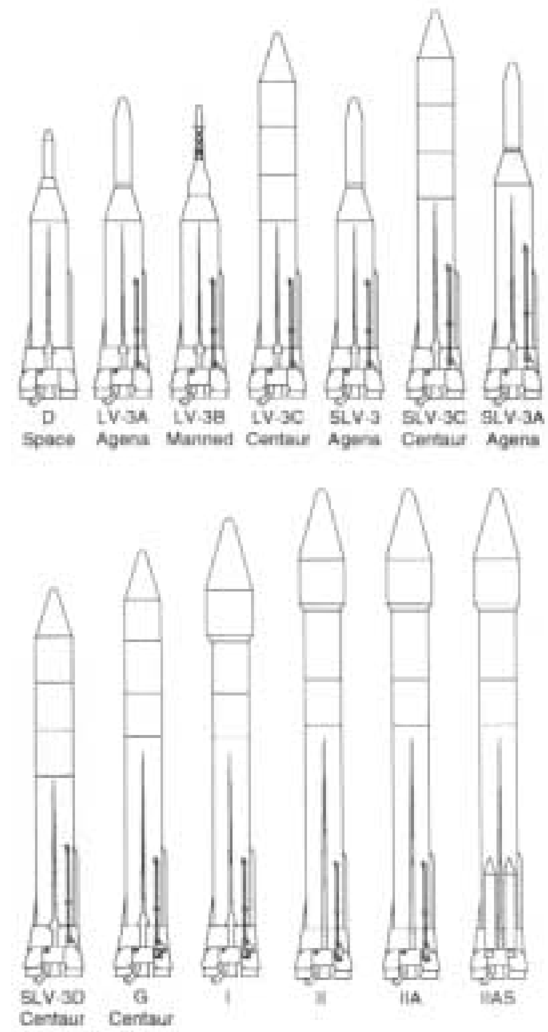

Figure 2. Atlas Launch Vehicle Evolution

The Agena upper stage's development ended with the SLV-3A, but the success of the SLV-3C with its Centaur upper stage led to an evolution into the SLV-3D. This vehicle used the Centaur's autopilot and guidance systems to control the entire vehicle unlike previous vehicles, which used Atlas-based control systems for the initial part of the launch and then transferred control to the Centaur upper stage to complete the mission.

The final government-initiated version of the Atlas was the Atlas G, which was first launched in 1984. As with the previous SLV-

3D, the Atlas was once again lengthened to increase fuel capacity and received improved versions of the MA-5 engines.

The Atlas G led directly to the commercial Atlas vehicle program initiated by General Dynamics in 1987 after the destruction of the Space Shuttle Challenger, previous to which government-funded production had been canceled. For the first time, Atlas vehicles were built with no assured government customer. These first commercial Atlas launch vehicles (dubbed Atlas 1) were very similar to the Atlas G but offered two new payload fairings and were entirely funded by General Dynamics. The first Atlas 1 was launched in 1990.

The Atlas 1 was followed in 1991 by the Atlas 2, which was originally developed to launch Air Force Defense Satellite Communications System satellites under the Medium Launch Vehicle (MLV) 2 contract. The Atlas 2 uses upgraded Rocketdyne MA-5A engines (2155 kN thrust), a lengthened booster for greater fuel capacity, improved structures, a new stabilization system, and a lengthened Centaur upper stage to provide more fuel and hence better upper-stage performance.

The final versions of the Atlas 2 series, the Atlas 2A (1992) and the Atlas 2AS (1993), differ from the Atlas 2 by having more powerful Pratt & Whitney RL-10 engines in the Centaur upper stage. In the case of the 2AS, four Thiokol Castor 4A solid rocket motors add an additional 173.6 kN of thrust to the first stage of the vehicle. Following these modifications, Lockheed Martin (the current owner of the Atlas line) replaced the three Rocketdyne engines with a single, more powerful, NPO Energomash / Pratt & Whitney RD-180 engine.

With the Atlas 3, the slow incremental process that characterized the development of previous Atlas vehicles was replaced by a more revolutionary approach. The Atlas 3 represents an initial effort to reduce vehicle complexity while increasing performance. This model uses improved first-stage fuel tank construction, contains less-complicated components and increases overall launch vehicle performance. As an example, the Atlas 3's first stage thrust section undergoes only one staging event and the engine is supplied by only seven fluid interfaces. By contrast, previous Atlas models had up to six staging events and 17 fluid interfaces.

New and improved versions of the Centaur Upper Stage were also introduced on the Atlas 3 series. The Centaur Upper Stage used by the Atlas 3A uses a single engine. The removal of one RL10A-4-1 engine and the centering of the remaining engine along the Centaur's axis differentiate it from earlier Centaur versions. The upper stage for the Atlas 3B is a lengthened version of the Centaur outfitted with two RL10A-4-2 engines. These engines include upgrades (such as chiller modifications and a health monitoring system) designed to increase reliability and operational standards. Both the single-engine Centaur and the lengthened Centaur with dual RL10A-4-2 engines will be used on the Atlas 3 series as well as on the Atlas 5 series.

Built under the U.S. Air Force’s Evolved Expendable Launch Vehicle (EELV) program with funding from both the Air Force and Lockheed Martin, the Atlas 5 will continue the trend of radical change toward bigger, more capable launch vehicles initiated with the Atlas 3. The Atlas 3 will provide valuable experience needed for Atlas 5 production and operation and, once the Atlas 5 is operational, the Atlas 3 will be phased out. More than twice the weight of Atlas 3, Atlas 5 will be able to carry twice the payload mass. The Atlas 5 will have approximately 125 potential single point failures, as opposed to over 250 for the Atlas 2AS, will be able to launch in higher wind conditions,

Vehicle	Intro Year	Vehicle Weight (kg)	GTO Performance (kg)
Atlas B	1958	110740	N/A
Atlas Able	1959	120051	250
Atlas D	1959	117730	N/A
Atlas LV-3B Mercury	1959	116100	N/A
Atlas LV-3A/Agena	1960	123990	800
Atlas LV-3C/Centaur	1962	136124	1800
Atlas SLV-3/Agena	1964	N/A	N/A
Atlas SLV-3C/Centaur	1967	148404	1800
Atlas SLV-3A/Agena	1968	N/A	700
Atlas SLV-3D/Centaur	1972	148404	1900
Atlas G/Centaur	1984	166140	2255
Atlas 1	1990	164300	2255
Atlas 2	1991	187600	2810
Atlas 2A	1992	185427	3039
Atlas 2AS	1993	233750	3630
Atlas 3A	2000	220672	4055
Atlas 3B	2001	225392	4500
Atlas 5 (551)	2002	540340	8200

Table 1: Evolution of Atlas Mass and GTO Payload Capacity

and will dispense with the pressure-stabilized fuel tanks used on all previous Atlas vehicles. Unlike its predecessors, the Atlas 5 will be able to stand under the weight of its payload without being fully fueled because it will have structurally-stable booster propellant tanks. By contrast, previous Atlas vehicles used the pressure of the fuel in their tanks to bear part of the load of the payload.

DELTA VEHICLE EVOLUTION

The Delta launch vehicle was initially adapted from an IRBM by Douglas Aircraft Company for the U.S. Air Force. In April 1959, NASA's Goddard Space Flight Center contracted with Douglas to create a civilian launch vehicle based on the Air Force's Thor-Able vehicle. Douglas (later as McDonnell Douglas) continued to produce Delta vehicles for the U.S. Government until production was ended in 1984 due to the U.S. policy decision to launch all payloads on the Space Shuttle. Following the Challenger accident, production was restarted as a commercial venture with the vehicle called the Delta 2. McDonnell Douglas captured the U.S. Air Force's MLV-1 contract with this vehicle in 1987 and then offered the Delta 2 on the commercial market.

Between Delta's first flight in 1960 and today's Delta 2 vehicles the Delta launch vehicle has gone through a set of evolutions similar to that of the Atlas vehicle. Extensive changes have been made that have resulted in substantially greater capacity (see Figure 3 and Table 2). During this period, the Delta's first stage has received five different engines and has been lengthened twice to increase propellant mass. The second stage has had five different engines and has also been lengthened twice to increase propellant mass. The third stage has seen seven engine changes and overall, the Delta vehicle has received two avionics upgrades, four increasingly large fairings, and two sets of strap-on solid rocket motors.

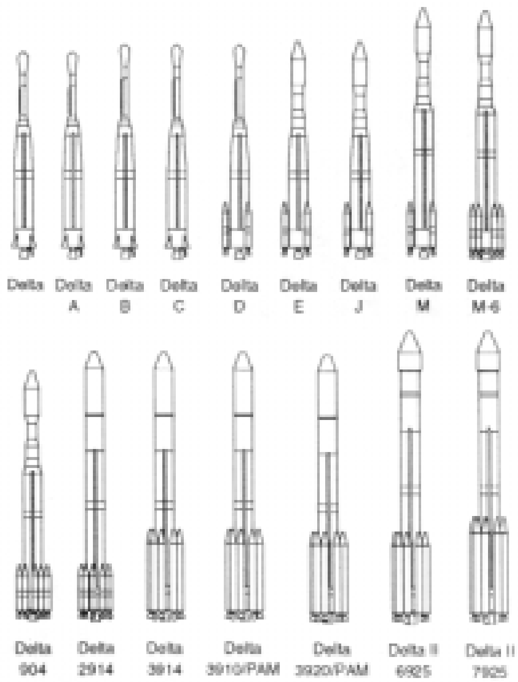

Figure 3. Delta Launch Vehicle Evolution

Following the slow evolution of the Thor to the Delta and then to the Delta 2, there has been a more radical improvement with the development of the Delta 3 and then the Delta 4 EELV. The Delta 3 has a larger diameter first-stage fuel tank than Delta 2 and uses nine solid fuel graphite-epoxy motors derived from those on Delta 2 but with 25 percent more thrust. The Delta 3's second stage carries more propellant than Delta 2 and burns cryogenic fuels, which produce more energy than those used by the Delta 2, allowing it to launch heavier payloads.

The Delta 4 involves even more improvements. It consists of a new "common booster core" first stage using the new Rocketdyne RS-68 engine. This engine has 95 percent fewer parts than the Space Shuttle Main Engine (which is a comparable engine in terms of thrust) and requires only 8,000 hours of touch labor, compared with 171,000 hours for the Shuttle engine. It is supplemented by solid fuel graphite-epoxy motors, two types of upper stages, and three payload fairings depending on customer needs. A heavy lift version will also be available and will involve a combination of three core boosters with an upper stage and larger fairing. Boeing offers five different versions of the Delta 4 addressing a broad range of payload mass classes. Like the Atlas 3 and Atlas 5, the Delta 4 will replace the Delta 3 once it is introduced into service over the next few years.

LAUNCH VEHICLE GROWTH TRENDS

As can be seen from the development of the Atlas and Delta launch vehicles, the tendency in launch vehicle development has been for vehicles to grow in capacity and, hence, in size. Although micro-satellites have been developed, the tendency has been to produce larger, more capable commercial satellites rather than to stabilize or reduce satellite size. Thus, there is a continuous interplay between satellite and launch vehicle size. Neither set of designers wishes to exceed the other's needs or capabilities, but both seek to use greater capacity as a selling point. No signs at this point indicate that either satellite or launch vehicle growth has reached its end (although it is possible to get too far ahead of the market and suffer accordingly, as the failure of the commercial Titan 3 demonstrated).

A case that proves this is that of the Delta Lite launch vehicle sought by NASA under its Med Lite launch vehicle contract in the mid-1990s. This program was intended to produce a lower-priced version of the Delta launch vehicle by reducing its payload size and payload capacity. Ultimately, McDonnell Douglas determined that there was insufficient market demand for such a vehicle and chose to provide NASA with launches on larger Delta variants rather than pay to develop the Delta Lite for the limited number of launches planned under the Med Lite launch procurement contract.

Vehicle	Intro Year	Vehicle Weight (kg)	GTO Performance (kg)
Thor	1957	49340	N/A
Thor Able	1958	51608	N/A
Thor Agena A	1959	53130	N/A
Thor Able-Star	1960	53000	N/A
Thor Agena B	1960	56507	N/A
Delta	1960	52442	45
Delta A	1962	51555	68
Delta B	1962	51984	68
Delta C	1963	52004	82
Delta D	1964	64679	104
Delta E	1965	69023	150
Delta J	1968	69497	263
Delta M	1968	89881	356
Delta M-6	1969	N/A	454
Delta 904	1971	N/A	635
Delta 2914	1972	130392	724
Delta 3914	1975	190799	954
Delta 3910/PAM	1980	191633	1156
Delta 3920/PAM	1982	190721	1270
Delta 4920	1989	200740	1270
Delta 5920	1989	201580	1360
Delta 2 6925	1990	217920	1447
Delta 2 7925	1990	229724	1820
Delta 3	1998	301450	3810
Delta 4 Medium	2002	249500	5845
Delta 4 Medium-Plus (4,2)	2002	N/A	4640
Delta 4 Medium-Plus (5,2)	2002	N/A	4640
Delta 4 Medium-Plus (5,4)	2002	N/A	6565
Delta 4 Heavy	2002	733400	13130

Table 2: Evolution of Delta Mass and GTO Payload Capacity

Also interesting to note is that this phenomenon of vehicle growth does not seem to be dependent on the country or company developing the vehicle. Table 3 shows the growth in payload capacity of selected Russian and European launch vehicle families over the course of their development.

VEHICLE RELIABILITY

Over time, reliability has improved for both the Delta and Atlas vehicles. The Atlas vehicle's cumulative reliability has ranged from a low of 29 percent after seven launches in 1960 to the current level of 87 percent first achieved in 1997 (see Figure 4). Delta's cumulative reliability has improved from a low of 91 percent after 23 launches in 1965 to 97 percent since 1998 (see Figure 5).

CONCLUSION

Launch vehicles are have tended to become increasingly capable over time. It is clear that both capacity and reliability can be increased considerably if the demand for greater capability remains and resources are directed towards those ends. The Delta 4

Initial Vehicle	**GTO Capacity (kg)**	**Intro Year**	**Current Vehicle**	**GTO Capacity (kg)**	**Intro Year**	**Increase in GTO Capacity**
Ariane 1	1,850	1979	Ariane 44L	4,520	1989	144%
Sputnik (LEO)	1,300	1957	Soyuz (LEO)	7,000	1963	438%
Proton (SL-8, LEO)	12,200	1965	Proton SL-12 (LEO is SL-13)	20,900	1967	71%

Table 3. Launch Capacity Growth in Vehicles Worldwide

and Atlas 5 are particular examples of how much vehicles can grow if their development is sustained. While the availability of resources and demand for launch services cannot be guaranteed at any given time in the future, one thing is clear: later versions of a launch vehicle, possessing the operational understanding and technological refinement that are developed over time, are likely to be far more capable and less risky than their familial predecessors.

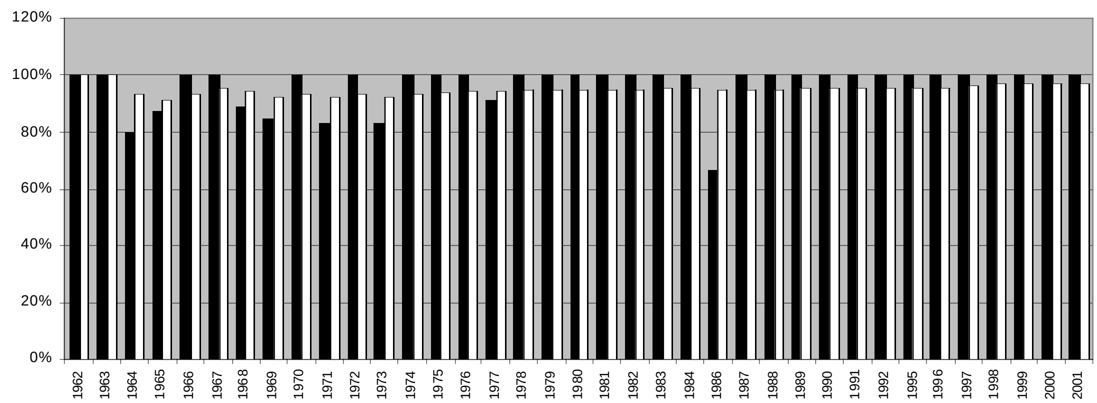

Figure 4. Atlas Launch Vehicle Reliability

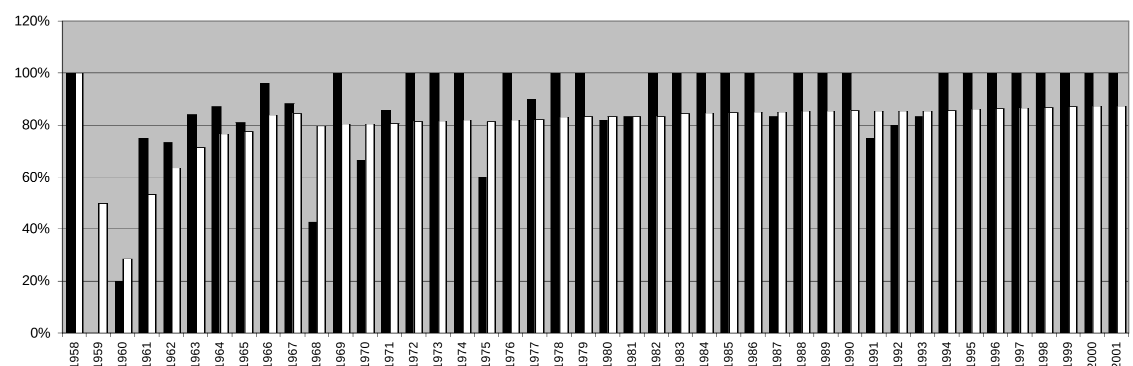

Figure 5. Delta Launch Vehicle Reliability