May 2nd, 1:00 PM

Paper Session I-B - U.S. Expendable Liquid Rocket Propulsion Technology Trends: A Historical Perspective

Mark L. Coleman
The Johns Hopkins University/Chemical Propulsion Information Agency

The 37th Space Congress
Cape Canaveral, Florida
1-5 May 2000

U.S. Expendable Liquid Rocket Propulsion Technology Trends: A Historical Perspective

Mark L. Coleman
The Johns Hopkins University/Chemical Propulsion Information Agency
10630 Little Patuxent Parkway, Suite 202
Columbia, MD 21044-3204

This paper was presented at the 37th Space Congress, Cocoa Beach, FL, May 2000.

Introduction

U.S. liquid rocket propulsion technology has evolved over the past four decades to meet the changing needs of the user community and to enhance the national access to space capability. The lineage of today's Atlas, Delta, and Titan Expendable Launch Vehicles (ELVs) is traceable to strategic missile system programs initiated in the 1950s. The Atlas and Delta ELVs were used to deploy the first weather, scientific, and communications satellites, and the Atlas D and Titan II ELVs were used to support NASA's Mercury and Gemini manned space flight programs. Atlas, Delta, and Titan launch systems have continuously evolved over the years and have been used to deploy numerous lunar, planetary, and deep space exploration missions. The Titan III was the first ELV to incorporate solid strap-on booster motors to increase mission capability, and several variants of the Titan III vehicle were entered into service to adapt to East coast and West coast launch facilities and civil and military payloads. The Delta launch vehicle began to incorporate smaller solid strap-on boosters in the mid-1960s to increase performance and satisfy the demands of steadily increasing payload mass. The Atlas II launch system adopted the use of solid strap-on boosters in the early 1990s to accommodate a larger range of commercial payload mass (R-1).

U.S. ELV propulsion systems have been performance driven since their inception. Early ELVs employed open-cycle engines that were periodically uprated or replaced with higher-thrust engines to deliver additional performance while manufacturers implemented design enhancements through product improvement programs (R-1, R-2, R-3, R-4, R-5). As performance demands steadily increased, launch vehicle prime contractors uprated engine thrust levels, incorporated elongated and/or increased diameter booster stage propellant tanks, and introduced higher-energy upper stages. Payload fairing volumes were also steadily enlarged to accommodate payload size growth (R-1). Presently, commercial payloads continue to grow in weight and size to maximize revenue streams because launch costs remain high. Size and weight of U.S. military payloads has stabilized and begun to decrease due to adaptation of advanced technologies (R-6, R-7).

This paper presents a brief history of expendable liquid propulsion technology trends, and investigates the design characteristics of new ELVs in development. Performance, cost, and operability characteristics are also discussed.

Early ELV Performance History

ELVs currently in service evolved from the first operational Intercontinental and Intermediate Range (ICBM and IRBM) ballistic missile systems (R-1). The North American Aviation Corporation formed the Rocketdyne Division in 1955 to execute an Air Force contract to develop the propulsion system for the Atlas long-range ICBM. Production of the Atlas engine systems proceeded concurrently with vehicle flight testing and engine design improvement efforts due to the urgency of the ICBM program (R-2).

The Atlas missile systems incorporated a 1 _ stage design powered by MA-series booster and sustainer engine assemblies. The engine assemblies included dual thrust chamber booster engines, single thrust chamber sustainer engines, and two vernier engines for attitude and roll control. Booster engines were optimized for sea-level performance and sustainer engines were optimized for high-altitude performance. The booster turbopumps were operated in parallel and were powered by a single gas generator. All thrust chambers were fed from common Liquid Oxygen (Lox) and Rocket Propellant-1 (RP-1, kerosene) propellant tanks. The tube-wall, regeneratively cooled thrust chambers with bell nozzles were gimbaled for pitch and yaw control. Rocketdyne developed the MA-1 engine assembly to power developmental Atlas missile systems. The MA-1 engine developed a total of approximately 354 klbf thrust. The MA-2 engine was similar but slightly uprated and was used to power the first operational ICBM, the Atlas D. The MA-3 was a simplified version of the MA-2 where the booster engines operated independently of each other with separate turbopumps and gas generators. The MA-5 is an uprated, non-military version of the MA-2 and has been used to power most Atlas space launch vehicles through 1990, including John Glenn's Mercury orbital mission in 1962 (R-1, R-2).

This paper was presented at the 37th Space Congress, Cocoa Beach, FL, May 2000.

Atlas engine performance history is tabulated in Table 1.

TABLE 1 Atlas Propulsion System Performance (R-2)	
Engine Assembly	**Sea-Level Thrust / Isp**
Atlas MA-1 Booster Sustainer	~ 300 klbf / ~ 245 lbf-sec/lbm ~ 54 klbf / ~ 210 lbf-sec/lbm
Atlas MA-2 Booster Sustainer	~ 309 klbf / ~ 248 lbf-sec/lbm ~ 57 klbf / ~ 213 lbf-sec/lbm
Atlas MA-3 Booster Sustainer	~ 330 klbf / ~ 250 lbf-sec/lbm ~ 57 klbf / ~ 214 lbf-sec/lbm
Atlas MA-5 Booster Sustainer	~ 377.5 klbf / ~ 259 lbf-sec/lbm ~ 60.5 klbf / ~ 220 lbf-sec/lbm

The Delta launch vehicle family originated in 1959 when NASA contracted with the Douglas Aircraft Company to design, manufacture, and integrate 12 launch vehicles. The original Delta design included modified Thor IRBM booster stages and the Navy's Vanguard 2nd and 3rd stage propulsion systems. The first Delta launch vehicle was available 18 months after go-ahead. Rocketdyne's MB-3 engine assembly was used to power stage 1, and Aerojet's AJ10-118 engine was used to power stage 2. A Hercules X-248 solid rocket motor was used for stage 3 propulsion. The MB-3 (Thor engine) consisted of a single gas generator cycle engine and two vernier engines. The single-start, fixed-thrust, pump-fed engine operated with a liquid oxygen and Ramjet fuel (RJ-1) propellant combination and developed approximately 155 klbf sea-level thrust with a mixture ratio of 2.29:1 and a chamber pressure of 538 psia. The regeneratively cooled thrust chamber was gimbaled for pitch and yaw control (R-8). The AJ10-118 is a single chamber engine that uses storable hypergolic propellants. The stainless steel thrust chamber is regeneratively cooled and develops more than 7.5 klbf thrust with a 20:1 nozzle expansion ratio (R-1).

The MB-3 engine assembly, designated LR97-NA-5, was uprated to LR97-NA–7 (Block-1), -9 (Block-II), and –11(Block-III) models to power later Deltas. Each uprate allowed the engine to operate with slightly higher chamber pressures and develop additional thrust. Other improvements included reducing engine weight, transitioning from pyrotechnic to hypergolic ignition systems, and other mechanical improvements. Sequencing of the propellant valve was electronically controlled in conjunction with a pneumatic system (R-8).

The RS-27 Lox/RP-1 engine was introduced in the early 1970s to replace the MB-3 engine. The RS-27 is a fixed thrust, pump-fed, gas generator cycle engine that develops approximately 200 klbf thrust. The regeneratively cooled thrust chamber is gimbaled for pitch and yaw control. The TRW TR-201 engine replaced the AJ10-118 second stage engine during the same timeframe. The TR-201 is a modified (fixed-thrust) variant of the Lunar Module Descent Engine (LMDE) that operates with storable propellants and develops approximately 10 klbf thrust (R-1).

Most of the Delta launch vehicles flown since the early 1970s were powered by the RS-27 1st stage engine, and various vehicle configurations emerged between 1970 and 1989. Improved variants of stage zero Castor motors were introduced as they became available, and second and third stage propulsion systems were selected based on performance and mission requirements. Increases in total impulse were introduced on various occasions by elongating stage 1 propellant tanks and by elongating and increasing the diameter of stage 2 propellant tanks (R-1).

Delta stage 1 propulsion system performance is provided in Table 2.

TABLE 2 Delta Booster Engine Performance (R-8)	
Engine Assembly	**Sea-Level Thrust/ Specific Impulse**
MB-3	~ 148 klbf / ~ 247 lbf-sec/lbm
MB-3 Block-I	~ 150 klbf / ~ 247.4 lbf-sec/lbm
MB-3 Block-II	~ 150 klbf / ~ 247.4 lbf-sec/lbm
MB-3 Block-III	~ 170 klbf / 252.9 lbf-sec/lbm
RS-27	~ 200 klbf / ~ 262 lbf-sec/lbm

The Titan program was initiated in 1955 when the U.S. Air Force awarded the Martin Company a contract to develop the Titan I ICBM. The two-stage Titan I was powered by gas generator cycle, Lox/RP-1 first and second stage engines built by Aerojet. The Titan I provided the greatest range and throw-weight in the U.S. ballistic missile arsenal. Titan I operations required propellant loading and missile elevation prior to launch. Titan I was quickly replaced with the Titan II ICBM to improve launch readiness. Titan II incorporated variants of the Titan I first and second stage engines that operated with nitrogen tetroxide and Aerozine 50 (a 50-50 weight % mixture of hydrazine and unsymmetrical dimethyl hydrazine). The Titan II engines provided increased thrust and the missile carried additional propellant providing increased range and throw-weight. The Titan II system was fielded in underground silos and used storable propellants to enable nearly instantaneous readiness (R-1, R-3, R-4, R-5).

The conversion of the Titan I engines to storable propellants required a redesign of engine fluid systems to provide the right mixture ratio and flowrate. Injector orifice diameters and impingement angles were increased slightly. Also, hardware compatibility with the new propellant was evaluated. The big gain for the Titan II engine over Titan I was simplicity and, therefore, increased reliability. All Titan storable engines are hydraulically balanced and require no active controls, whereas Titan I used a thrust controller and propellant utilization valve. The storable hypergolic propellants eliminate the need for an igniter (R-9).

Titan II ICBM was operational from 1961 to 1988. During this time period, the Titan II booster also served as the booster for Gemini spacecraft, the liquid propellant core for Titan III and Titan IVA, and for Titan II space launch vehicles. Aerojet conducted a series of twelve full duration engine firings on two sets of first and second stage engines to demonstrate engine reliability and assess design and operating margin for initial flight qualification. Each of the engine tests were nominal and nothing was done to the engines between firings. The engines were disassembled and inspected after completion of twelve firings, and critical components from each of the engines were determined to be in excellent condition. The post-test condition of the hardware and uneventful test series demonstrated that the engines were ready for active service. Prior to delivery, Aerojet conducts engine balance and acceptance tests on each engine. Engines are disassembled, inspected, cleaned, and reassembled after acceptance testing and then packaged for delivery to the customer. For the Gemini program, each engine was assigned a Production/Quality Assurance Chaperone that had oversight of all aspects of production and launch site integration and test. The chaperone’s responsibility began with oversight of material receiving and inspection, and continued into manufacturing, assembly, test, shipping, and launch site operations. No specific testing program was implemented to further demonstrate safety and reliability for the manned spaceflight program (R-4, R-5, R-9).

The engine injectors/combustors were later subjected to a series of man-rating stability tests for the Manned Orbiting Laboratory (MOL) program. Stability test results led to adaptation of radial and tangential baffles to first and second stage injectors for added stability before the MOL program was terminated (R-9). In 1985 the Air Force received approval to convert decommissioned Titan II boosters to space launch vehicles (R-1).

The Titan II engines, designated LR87-AJ-5 (stage 1) and LR91-AJ-5 (stage 2), are storable, fixed thrust, gimbaled engines with 8:1 and 49.2:1 nozzle expansion ratios for stages 1 and 2, respectively. The stage 1 engine area ratio was increased to 12:1 for Titan 23B and Titan 34B applications using ablative nozzle extensions. Higher stage 1 area ratio nozzle extensions (15:1 and 16.2:1) with aft closures were introduced for Titan vehicles integrated with large, zero stage solid rocket motors. Titan III, IIID, IIIE, and 34D stage 1 engines were started at altitude after stage zero separation (R-3, R-4, R-5).

The Air Force contracted with Martin Marietta in 1985 to develop the Complementary Expendable Launch Vehicle (CELV). The program was initiated to complement Shuttle operations and better ensure access to space for national defense payloads. The original contract called for 10 launch vehicles with the capability to place 12.5 klbm into Geosynchronous Earth Orbit (GEO). The CELV was derived from the Titan 34D. The Titan 34D core stage propellant tanks were elongated and new, seven-segment, solid booster motors were developed by United Technologies Chemical Systems Division (84% solids, PBAN) (R-1). The CELV was eventually renamed Titan IV and two variants of the heavy-lift launch vehicle emerged. The Air Force contracted with Hercules Aerospace Corporation in the mid-1980s to develop a new, higher performing booster motor for Titan IV. The new three-segment motor, designated the Solid Rocket Motor Upgrade (SRMU), included new propellant (88% solids HTPB), a composite case, and flexseal Thrust Vector Control (TVC). The SRMU was qualified in 1993. Titan IVs that flew with the seven-segment booster motors were designated Titan IVA. Titans flying with the SRMU booster motors are designated Titan IVB. The inventory of seven-segment booster motors has been expended and Titan IVB is the only variant currently in service. A total of 41 Titan IVs have been procured to date. The Air Force currently envisions phasing Titan IV out of service in the 2006-2010 timeframe. Once demonstrated, heavy-lift versions of the new Evolved Expendable Launch Vehicle (EELV) systems will be used to deploy Titan-class payloads. Titan engine performance is provided in Table 3.

TABLE 3 Titan Engine Performance (R-3, R-4, R-5)	
Engine Assembly	**Thrust / Specific Impulse**
LR87-AJ-5 (Titan II Stage 1)	~ 430 klbf / 256 lbf-sec/lbm (SL)
LR91-AJ-5 (Titan II Stage 2)	~ 100 klbf / 308 lbf-sec/lbm (Altitude)
LR87-AJ-7 (Gemini Stage 1)	~ 430 klbf / 258.3 lbf-sec/lbm (SL)
LR91-AJ-7 (Gemini Stage 2)	~ 100 klbf / 315 lbf-sec/lbm
LR87-AJ-9 (Titan II, Gemini, Titan III A, B, C Stage 1)	~ 430 klbf / 256 lbf-sec/lbm
LR91-AJ-9 (Titan II, Gemini, Titan III A, B, C Stage 2)	~ 100 klbf / 315 lbf-sec/lbm
LR87-AJ-11 (Titan II, Titan IV Stage 1)	~ 548 klbf / 301 lbf-sec/lbm (Altitude)
LR91-AJ-11 (Titan 23B, 34B, III, III C, D, E, IV Stage 2)	~ 105 klbf / 314 lbf-sec/lbm (Altitude)

Medium Launch Vehicles

The U.S. Air Force initiated procurements for medium-lift capability launch services beginning in the late 1980s for deployment of Global Positioning System (GPS) and other military satellite systems. McDonnell Douglas developed the Delta II launch system in response to Air Force Medium Launch Vehicle-1 (MLV-1) performance requirements to launch GPS Block-1 satellites. Delta II was introduced (first flight) in 1989 and is a growth version of the Delta 3920/PAM-D vehicle. The original Delta II vehicle incorporated three, four, or nine Thiokol Castor IVA booster motors, the uprated RS-27A booster engine, and the Aerojet AJ10-118K 9.6 klbf thrust second stage engine. The stage 1 and stage 2 propellant tanks have been elongated and the structure has been strengthened to accommodate the additional flight loads. A new third stage design incorporated the STAR-48B solid rocket motor with a spin table, payload attach fitting, and control and telemetry systems. Use of the Castor IVA booster motors was phased out early and the majority of Delta II flights have been conducted using the higher-thrust, higher Isp Graphite Epoxy Motors (GEMs) developed by Hercules Aerospace Corporation (Alliant TechSystems, Inc.). The Delta II is capable of placing approximately 8.78 klbm into a 100 nautical mile Easterly orbit and 3.19 klbm to Geosynchronous Transfer Orbit (GTO) with Castor IVA booster motors, and 11.2 klbm to the same LEO orbit and 4.0 klbm to GTO with GEM boosters. By comparison, the Delta 3920/PAM-D was capable of placing 2.8 klbm into GTO (R-1, R-10).

General Dynamics developed the Atlas II in response to Air Force requirements for the MLV-2 program. The Atlas II was introduced in 1991 and is a growth version of the Atlas I vehicle. The Atlas II incorporated the uprated MA-5A booster/sustainer engine assembly, elongated booster and Centaur propellant tanks, and hydrazine roll-control engines in place of the Lox/kerosene vernier engines flown on earlier Atlas vehicles with the MA-5 engine assembly. The Atlas II vehicle included the elongated, dual-engine Centaur upper stage powered by RL10-3-3A engines. Each RL10-3-3A produces 16.5 klbf thrust and 444 seconds of Isp. The Atlas II, which is no longer in service, was capable of placing 6.2 klbm into GTO, compared to 4.97 klbm for Atlas I (R-1).

The U.S. Air Force awarded McDonnell Douglas the MLV-3 contract in 1993 to launch GPS Block-2R replenishment satellites. The MLV-3 contract included a new requirement for launch-on-demand within 40 days of notification and included options for up to 36 launch vehicles. Each of the MLV contracts included incentives for reliability improvements by including the option to withhold launch cost payments for failed missions.

Lockheed-Martin and Boeing have been able to capture a large portion of the commercial launch market since 1990 as a result of MLV performance upgrades and the high degree of modularity incorporated in current versions of the Atlas II and Delta II launch vehicle systems. Lockheed-Martin has introduced the higher performing Atlas IIA and Atlas IIAS vehicles, both of which incorporate higher thrust RL10 upper stage engines with Extendable Nozzle Exit Cones (ENECs) for additional performance. The Atlas IIAS incorporates four Thiokol Castor IVA zero stage booster motors that enable delivery of an additional 2.5 klbm to GTO, relative to the Atlas IIA (R-11). Two and three stage Delta II vehicles are available with three, four, or nine GEMs and a choice of two different size payload fairings. Two stage variants service LEO and sun-synchronous missions while three stage variants support GTO and Molniya missions (R-10).

Atlas II and Delta II engine performance parameters are provided in Table 4. Performance of early and currently operational ELVs for selected orbits is provided in Figures 1 and 2.

TABLE 4 Atlas II and Delta II Engine Performance (R-1, R-2, R-10, R-11, R-12)	
Engine Assembly	**Thrust / Specific Impulse**
Atlas MA-5A Booster (Sea-Level)	429.5 klbf / 265.8 lbf-sec/lbm
Atlas MA-5A Sustainer (Sea Level)	60.5 klbf / 220 lbf-sec/lbm
Atlas MA-5A Sustainer (Altitude)	85 klbf / 309.4 lbf-sec/lbm
Delta RS-27 Booster Engine (Sea-Level)	200 klbf / 254.2 lbf-sec/lbm
Delta RS-27 Booster Engine (Altitude)	244 klbf / 301.7 lbf-sec/lbm
Delta AJ10-118K 2nd Stage Engine (Altitude)	9.8 klbf / 319.2 lbf-sec/lbm

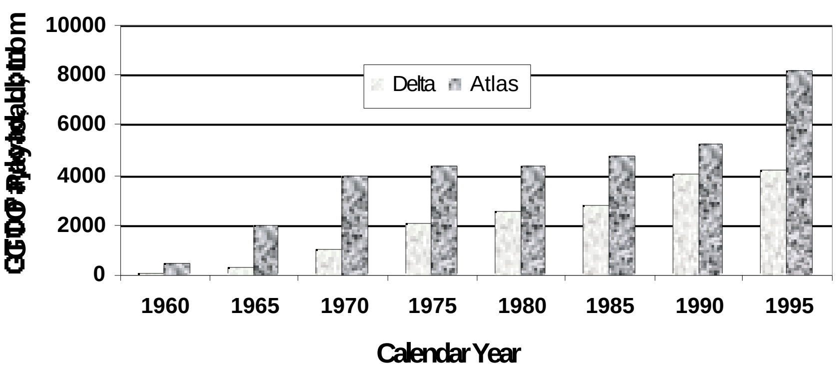


FIGURE 1 Atlas & Delta GTO Performance Growth, 1960-1995, 90 x 19,324 nm, 28.5 Degree Inclination, (R-1, R-10, R-11)

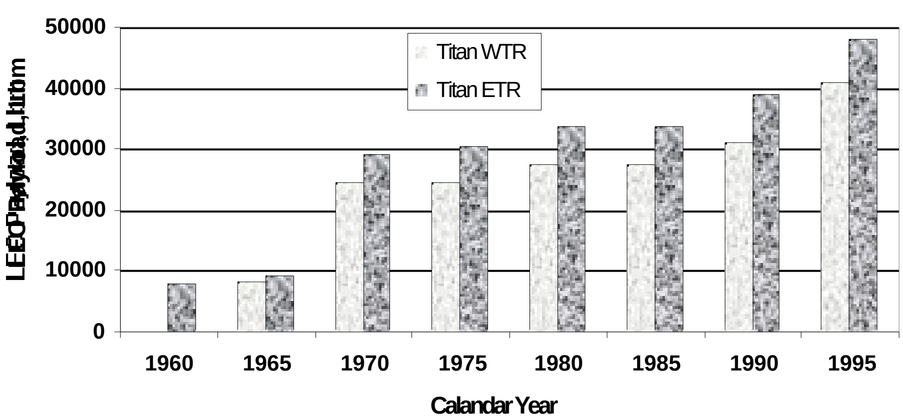


FIGURE 2 Titan Vehicle Family LEO Performance Growth, 1960-1995, 100nm, 28.5 Degree and 90 Degree Inclination, (R-1, R-5)

New Expendable Launch System Developments

The Commercial Space Transportation Advisory Committee's (COMSTAC) 1999 Commercial Space Transportation Forecast projects continued growth in the number of commercial payloads in the 9klbm to 12klbm range over the next decade (R-7). Consequently, Lockheed-Martin and Boeing are developing new expendable launch systems to meet this performance requirement. The new launch systems, designated Atlas III (Lockheed-

Martin) and Delta III (The Boeing Company), incorporate more powerful boosters than earlier Atlas and Delta launch vehicles and are expected to be more cost-competitive. The new vehicles are designed to capture medium and medium-heavy payloads, reflecting the growth trend for commercial payloads (R-7).

Lockheed Martin has teamed with Pratt & Whitney and NPO Energomash to develop the RD-180 high-thrust, Lox/kerosene, staged combustion cycle engine to power the Atlas III. The RD-180 is a very high thrust-to-weight engine with heritage traceable to the Russian Energia RD-170 booster engine. The RD-180 develops approximately 860 klbf sea-level thrust and 311 seconds of Isp at a chamber pressure of 3,722 psia. The engine develops more than 900 klbf vacuum thrust and 337 seconds vacuum Isp (R-14). The new Atlas III will be available with two Centaur (cryogenic) upper stage options. The Atlas IIIA Centaur will be powered by a single RL10A-4-1, and the Atlas IIIB will be powered by two RL10A-4-2 engines. The new Atlas III propulsion systems provide significant performance growth and eliminate numerous staging events (R-11).

Boeing's Delta III incorporates the flight proven RS-27A booster engine, the uprated RL10B-2 upper stage engine, and a solid third stage motor. The Delta III zero stage motors are elongated and larger diameter versions of the Delta II GEMs, designated GEM LD-XL (R-15). The Delta III will be available in two and three stage configurations. Atlas III and Delta III launch vehicle performance values are provided in Figure 3.

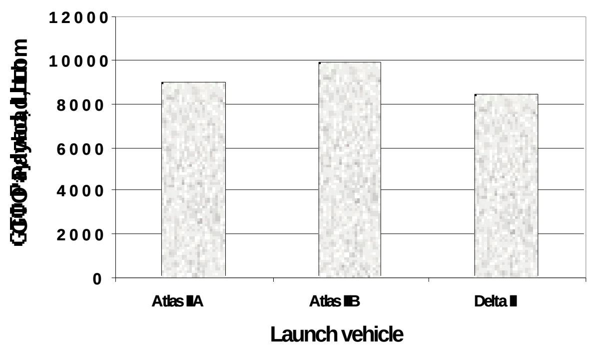


FIGURE 3 Atlas III & Delta III Launch System GTO Performance, 100 nm x 19,324 nm, 28.5 Degree Inclination, (R-11, R-15)

Evolved Expendable Launch Vehicle (EELV) Program

The U.S. has conducted numerous studies since 1985 to evaluate alternatives for upgrading the U.S. access to space capability. After consideration of various fleet-upgrade alternatives and several new heavy-lift options (HLLV, ALS, NLS, etc.), the Air Force elected to develop a new, modular launch system to provide the desired range of performance and reduce the cost of access to space. Rather than initiate a conventional launch vehicle procurement contract, the Air Force elected to enter into a partnership with industry to jointly develop a national launch capability that satisfies both government and commercial payload requirements. This decision was prompted by continued growth in the commercial launch market, declining DoD budgets, the desire to increase the U.S. space launch industries competitiveness in the international commercial launch market, and the knowledge that a newly designed system could significantly reduce launch costs. The Air Force-industry partnership allows both parties to share development costs (R-16).

The Air Force awarded competitive contracts in late 1995 for concept definition of new expendable launch systems with potential to drastically reduce launch costs. In addition, the Air Force instituted various acquisition reform initiatives to reduce the amount of government resources necessary to manage system development. Lockheed-Martin and Boeing were selected for the Pre-Engineering Manufacturing and Development phase, and both contractors were eventually awarded development contracts. The decision to develop two launch systems rather than one allows the Air Force to compete both contractors over the life of the program to achieve lowest cost (R-16).

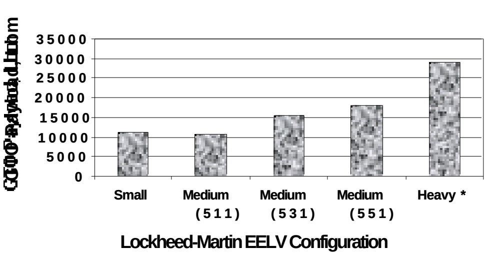
Lockheed-Martin and Boeing are each developing a family of modular expendable launch vehicles with standard interfaces with their respective launch processing facilities and common interfaces to U.S. Government and commercial payloads. Both vehicle systems will make use of liquid booster stages that can be flown singularly (with a choice of upper stages for small and medium payloads) or can be mated three-abreast (and flown with a choice of upper stages) for heavy-lift vehicles. The new EELV families are designated Atlas V (Lockheed-Martin), and Delta IV (Boeing) (R-17, R-18).

The Atlas V Common Booster Core™ will be powered by the RD-180 developed for the Atlas III program. The RD-180 is a dual-thrust chamber, oxygen-rich staged combustion cycle engine with hydraulics for control valve actuation and thrust vector gimbaling, and pneumatics for valve actuation and system purging, all mounted in a common thrust frame. The Atlas V vehicle family will include storable (Agena 2000) and cryogenic (two-engine Centaur) upper stages. The Common Booster Core™ stages can be mated with solid strap-on booster motors to provide a range of intermediate configurations (R-17, R-19). Advantages of the Lockheed-Martin concept include a high degree of modularity, high thrust-to-weight booster stages, significant engine performance margin, and minimum Common Booster Core™ dimensions due to the high-density fuel.

The Boeing Company is developing a new oxygen-hydrogen, gas generator cycle engine to power the Delta IV common booster stages. The new engine is designed for simplicity and low cost, and includes some design features that trade performance and/or weight in favor of lower manufacturing costs. The open cycle engine develops 650 klbf sea-level thrust with a chamber pressure of 1410 psia at 100% power level. The engine is designed to operate at either 60% or 100% power level (R-20). Delta IV upper stage options include the Delta II storable upper stage powered by Aerojet's AJ10-118K engine, the Delta III single engine Centaur stage powered by Pratt & Whitney's RL10B-2 engine, and a modified, higher-performing Delta III Centaur upper stage. The Delta IV vehicle family will include a total of six configurations. Three variants of the medium class vehicle will incorporate solid strap-on booster motors to tailor performance requirements for commercial customers (R-18). Advantages of the Boeing EELV concept include high-energy propellants, clean exhaust products, a high degree of modularity, and engine design and performance margin. EELV engine performance parameters are provided in Table 5. Selected performance capabilities for Lockheed-Martin and Boeing EELV launch vehicle families are provided in Figure 4.

TABLE 5 EELV Engine Performance (R-14, R-20)

Engine Parameter	Lockheed-Martin RD-180	Boeing RS-68
Engine Cycle	Staged Combustion (Closed)	Gas Generator (Open)
Sea-Level Thrust / Isp	860.2 klbf / 311.3 lbf-sec/lbm	650 klbf / 365 lbf-sec/lbm
Vacuum Thrust / Isp	933.4 klbf / 337.8 lbf-sec/lbm	745 klbf / 410 lbf-sec/lbm
Engine Weight	11,889 lbm	14.56 klbm
Mixture Ratio	2.72:1	6.0:1
Chamber Pressure	3,722 psia	1410 psia
Nozzle Expansion Ratio	36.87:1	21.5:1



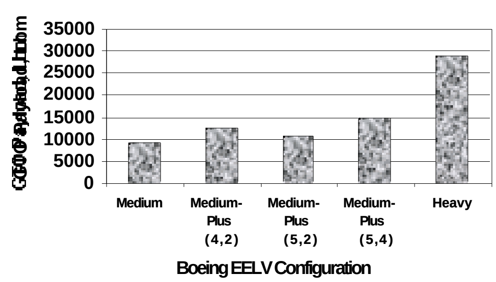


FIGURE 4 Selected EELV GTO Performance Capability, 19 x 19,324 nm, 28.5 degree Inclination, (R-16, R-17, R-18, R-19)

* L/M EELV Heavy 29 klbm GTO Performance Normalized From 14.5 klbm GEO Direct Insertion, Three-Burn Centaur Mission

Summary

U.S. expendable launch vehicle performance has evolved over the past four decades to meet the needs of the user community. DoD and NASA missions dominated early use of Atlas, Delta, and Titan ELVs to launch military and civil payloads. Modified Atlas D and Titan II launch vehicles were used to support NASAs manned spaceflight program. ELV engines have been uprated and vehicle designs have been modified to carry additional total impulse on numerous occasions since 1960 in order to deliver more and more performance.

Presently, the commercial launch market has grown to the extent that commercial missions and commercial design practices are having a large influence on launch system designs and development programs. However, performance remains a key system parameter because commercial payloads continue to grow. Launch service providers must deliver the performance demanded by the market in order to remain competitive. Commercial payload mass will continue to increase until launch service costs begin to decrease. Satellite manufacturers will tend to add more power and more transponders to commercial satellites in an effort to orbit the most capability per launch. Launch costs will need to decrease significantly before it will become economical for satellite builders to build and launch two satellites rather than one.

Although performance continues to be a key ELV design criteria, other parameters are receiving a great deal more attention than in the past. New launch systems currently emerging in the U.S. are designed to be more operable, with standard launch processing and payload interfaces. New vehicle design practices are being adopted to reduce manufacturing, procurement, and operational costs, and new launch processing facilities are being developed to maximize launch rates. Engine manufacturers are adopting new manufacturing technologies that reduce component variability, reduce quality assurance inspection requirements, and reduce costs. Missions and objectives have evolved to the point where users demand more performance, lower cost, and very high mission success rates and hardware reliability. The current ELV operational and design philosophies discussed are expected to continue for the foreseeable future to drive costs downward. New launch systems coming on-line are designed to meet the needs of commercial and DoD users with proven technologies and smarter design and operational practices.

References

R-1 "International Reference Guide To Space Launch Systems," Steven J. Isakowitz, Second Edition, Published by the American Institute of Aeronautics and Astronautics, 370 L'Enfant Promenade, SW, Washington D.C. 20024-2518.

R-2 "Atlas Engines – A History," H. Minami, In AIAA 91-1943, Presented at the AIAA/SAE/ASME 27th Joint Propulsion Conference, June 24-26, 1991, Sacramento, CA.

R-3 "Titan Program Overview," Titan Training Short Course Handbook, Aerojet TechSystems, November 1996.

R-4 "Titan III Propulsion Handbook," Aerojet TechSystems, October 1988.

R-5 "Titan IV Propulsion Handbook," Aerojet TechSystems, July 1994

R-6 "Commercial Spacecraft Mission Model Update," FAA/AST Commercial Space Transportation Advisory Committee, COMSTAC Technology & Innovation Working Group, May 1997.

R-7 "1999 Commercial Space Transportation Forecasts," FAA/AST Commercial Space Transportation Advisory Committee, May 1999.

R-8 "NASA Historical Data Book, Volume II, Programs and Projects, 1958-1968," Linda Neuman Ezell, NASA Scientific and Technical Information Division, 1988, National Aeronautics and Space Administration, Washington D.C.

R-9 Personal Communication, Mr. Roy B. Squires, GenCorp Aerojet Titan Engine Program Engineer, Retired, December 1, 1999.

R-10 "Delta II Payload Planners Guide," April 1996, McDonnell Douglas Aerospace, 5301 Bolsa Avenue, Huntington Beach, CA 92647-2099.

R-11 "Atlas Launch Systems Mission Planners Guide," Revision 7, December 1998, International Launch Services, 101 W. Broadway, Suite 2000, San Diego, CA 92101.

R-12 "Aerojet AJ10-118K Engine Data Sheet," P.O. Box 13222, Sacramento, CA 95813, www.aerojet.com

R-13 "Rockwell International, Rocketdyne Division, RS-27 Engine Data Sheet," Pub. 571-M-80a, Revision 7/89.

R-14 "Pratt & Whitney/NPO Energomash RD-180 Engine Data Sheet," MS-1/95-5000.

R-15 "Delta III Payload Planners Guide," March 1997, McDonnell Douglas Aerospace, 5301 Bolsa Avenue, Huntington Beach, CA 92647-2099.

R-16 Evolved Expendable Launch Vehicle Web Site: http://www.laafb.af.mil/SMC/MV/eelvhome.htm

R-17 Evolved Expendable Launch Vehicle Web Site Links: http://www.ast.lmco.com/astroweb/frameset.shtml?top=The_Programs,content=programs/eelv

R-18 http://www.boeing.com/defense-space/space/delta/delta4/delta4.htm

R-19 "Atlas Launch Systems Mission Planners Guide, Atlas V Addendum," January 1999, International Launch Services, 101 W. Broadway, Suite 2000, San Diego, CA 92101.

R-20 Boeing Space Website: http://www.boeing.com/defense-space/space/propul/RS68.html