Atlas® V: Safe and Affordable Human Spaceflight[1]

Mike Holguin[*]
Lockheed Martin Space Systems Company, Denver, CO, 80127

The Atlas and Centaur programs have enjoyed a rich history as a trusted vehicle for numerous NASA Space Exploration missions, including manned spaceflight programs. Throughout space launch development, the Atlas expendable launch vehicles (ELV) have matured well beyond the early days of spaceflight. This paper addresses the attributes of the Atlas ELV that qualify it to be a workhorse for the Crew Exploration Vehicle (CEV) and Cargo for Space Exploration launches. By maintaining the exploration systems mission directorate goals of safe and affordable human spaceflight, Atlas keeps the affordability part of the equation intact. Atlas® V has met the goals of the evolved ELV (EELV) program to reduce the cost per pound to orbit by 25–50% over the heritage launch systems. Also, the incorporation of fault tolerance, design simplification, and robustness significantly improved vehicle reliability. Moreover, this paper explores the advantages of vehicle commonality with existing programs with emphasis on vehicle characterization (flight test) and demonstrated reliability inherently available due to synergy gained from higher production and flight rates.

Atlas I	Atlas II	Atlas IIA	Atlas IIAS	Atlas IIIA	Atlas IIIB	Atlas V-400	Atlas V-500
AC-69	AC-102	AC-105	AC-108	AC-201	AC-204	AV-001	AV-003

The Atlas evolutionary approach has successfully proven all eight first-flight vehicle configurations with a current flight record of 76 consecutive successes.

Unparalleled in success over the last decade and a half, the Atlas has launched payloads to its Earth orbit or solar system bound trajectories an astounding 76 consecutive times without failure. In that time, eight evolutionary Atlas first-flight vehicle configurations on three new or significantly modified launch pads were also successfully introduced. The Atlas human rating approach combines a highly reliable, fault-tolerant launch vehicle (LV) with disciplined processes to enable mission success. This approach, combined with launch vehicle health monitoring (LVHM) and crew situational awareness, provides the means to safely abort. Expanded maturity in areas of systems design robustness and processes discipline provides the basis for consistent Atlas success. These attributes of difficult lessons learned date back to the early 1990s when Atlas experienced three failures almost consecutively. A complete halt to launches invoked the conduction of detailed failure investigations, which resulted in the installation of a revamped process discipline imperative. Lockheed Martin underwent an overwhelming transformation in how to control and evolve not only system design, but also the processes and operations associated with the entire launch system. The Atlas evolution provides a straightforward path using the maturity of the vehicle's design plus the enhancements identified to meet the human rating plan. The goal now is to evolve

[*] Program Manager, Advanced Programs and Strategic Development, P.O. Box 179/Mail Stop T9115

that same successful mature and disciplined evolutionary approach into a launch system that is safe for human spaceflight, achievable technically, and meets the criteria identified in the visionary objectives of the NASA Space Exploration program.

I. Introduction

The Atlas launch vehicle development program began in the 1940s with studies exploring the feasibility of long-range ballistic missiles. Qualification for use as a launch vehicle beyond the role of an inter-continental ballistic missile (ICBM) became clear as its power was successfully demonstrated during that program. Both NASA and the U.S. Air Force issued contracts to modify the Atlas vehicle from an ICBM to a space launch vehicle. The first launch occurred in 1957 and was eventually transformed into a reliable vehicle capable of safely launching humans into space.

II. Historical Perspective

NASA chose Atlas as the launch vehicle for America's fledgling human-spaceflight program, the workhorse for Project Mercury. Three years after the prime contract was awarded, the goal to orbit humans in space and return them safely to Earth was successfully completed. The most historic mission was accomplished when John Glenn launched into space and successfully orbited three times over nearly a 5-hour period.[†] In total, the Project Mercury program conducted six manned flights, four Atlas and two Redstone launches.

Following Project Mercury, Project Gemini began early in 1961. The early Gemini program flew two unmanned Gemini missions in addition to the manned flights. Ten manned missions were conducted for Project Gemini between 1965 and 1966 using the early Titan vehicle, also formerly an ICBM.[‡] The Current Atlas V launch vehicle incorporates the structurally stable booster-core design feature from the Titan program to enhance ground-processing operations.

Both the Atlas Mercury and the Titan Gemini programs (Fig. 1) proved that human spaceflight can be safely accomplished based on ELV designs originally developed for other purposes.

Centaur, the world's first in-flight ignited, hydrogen-powered vehicle, began development in 1958 to launch NASA spacecraft on lunar and planetary missions. Centaur's design was based on the thin-walled, pressure-stabilized Atlas booster but used liquid hydrogen (LH_2) and liquid oxygen (LO_2) for propellants. The RL-10 was chosen as a highly reliable upperstage engine.

Beyond John Glenn's historic Atlas flight, the Atlas Centaur continues as the choice to launch America's Space Exploration probes over the last several decades. These include the following historic firsts from NASA:

1. *Mariner—First spacecraft to fly to another planet, Venus*
2. *Pioneer—First to use gravity assist by Jupiter and Saturn before solar system escape trajectory*
3. *Voyager—First to fly to Neptune and Uranus before solar system escape trajectory*
4. *Viking—First spacecraft to land on Mars*
5. *Surveyor—First U.S. spacecraft to soft land on the moon*
6. *Helios—First solar probes*

Other critical national missions have been entrusted to the safety and reliability of the Atlas launch vehicle, including recent and upcoming missions such solar and heliospheric observatory (SOHO), SAX, Cassini, Earth observing system (EOS), Pluto, Mars Reconnaissance Orbiter (MRO), and solar dynamic observatory (SDO). Clearly, Atlas has had significant involvement in the success of the nation's Space Exploration program, from both a human spaceflight and a critical planetary-probe launch perspective.

† Project Mercury, A Chronology. NASA SP-4001. Prepared by James M. Grimwood, Historical Branch, Manned Spacecraft Center, Houston, Texas, as MSC Publication HR-1, Office of Scientific and Technical Information, NASA. Washington, D.C. 1963. http://history.nasa.gov/SP-4001/contents.htm

‡ Project Gemini. Technology and Operations, A Chronology. Published as NASA Special Publication-4002. Prepared by James M. Grimwood and Barton C. Hacker with Peter J. Vorzimmer. http://history.nasa.gov/SP-4002/contents.htm

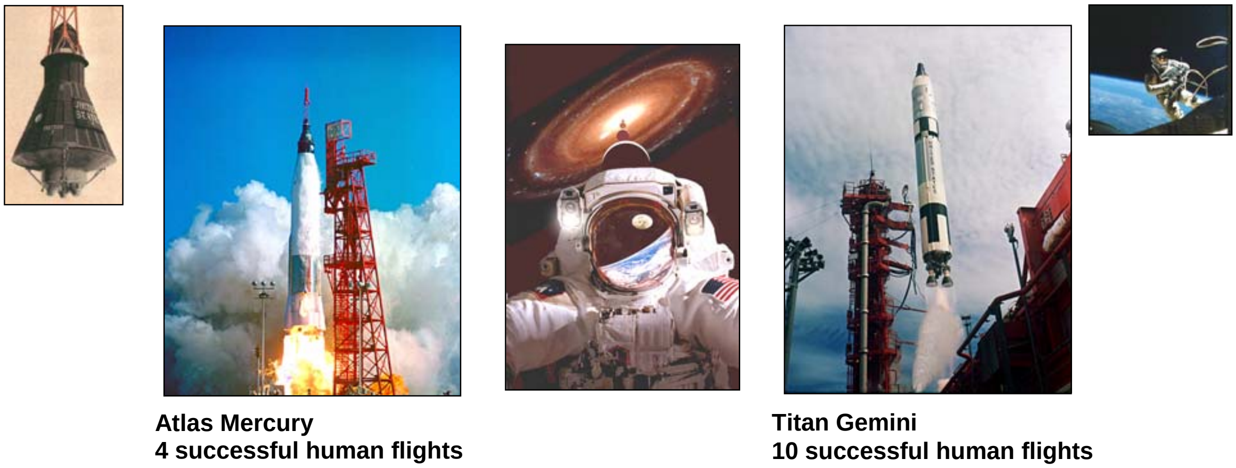

Figure 1. The heritage of early launch vehicle development in today's Atlas V includes the successful human spaceflight versions used in Project Mercury and Gemini. (Images courtesy of NASA)

III. Atlas Evolution

The evolution of the Atlas Centaur program started in 1958 with the X-11 and X-12 (Atlas A&B) and evolved to the Atlas D used for Project Mercury. In 1990, the establishment of Atlas I marked the beginning of the latest series of modern evolutionary enhancements, continuing today. Figure 2 outlines the development of the Atlas I through the current Atlas V vehicle designs. The development philosophy for Atlas follows a low-risk approach. First, consistently introduce enhancements in small steps; then fly these improvements to confirm their success before moving on to the next enhancement, thus avoiding wholesale changes to the entire launch vehicle and the introduction of significant uncertainty. Each of the eight first-flight configurations has been highly successful, meanwhile introducing components that make the vehicle more powerful and significantly more reliable. A single LV failure can cause significant upset in the launch program. These high stakes preclude the use of risky unproven technologies in the LV marketplace. As such, Atlas LV development has followed a path of incorporating increasingly reliable components and architectures that resulted in a vehicle essentially single-fault tolerant in the avionics systems with a reliability that exceeds 99.5%.

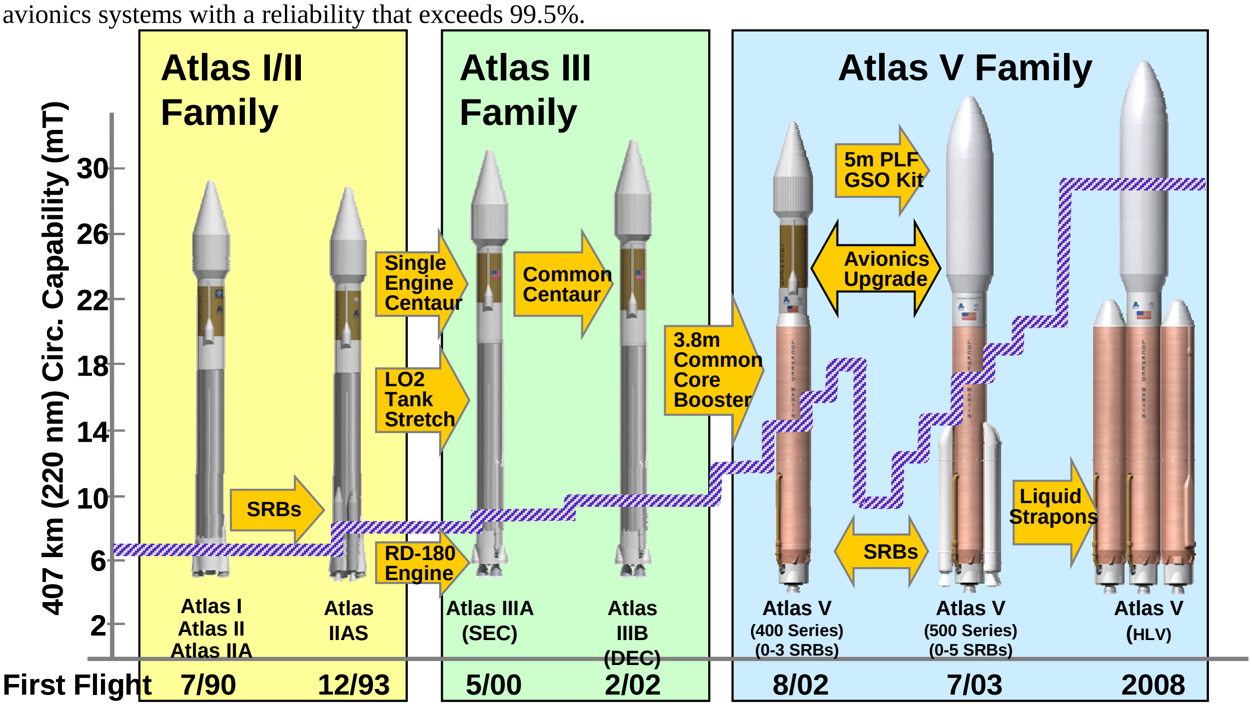

Figure 2. Atlas low-risk evolution approach has resulted in eight first-flight vehicle configurations; each of them flown successfully the first time.

A. Future Atlas Evolution

The Atlas V vehicle provides the best starting point for evolving a vehicle to satisfy the needs of both the crew and cargo versions of Space Exploration LVs. Demonstrated reliability and incorporation of fault tolerance and affordability imparts significant potential to safely evolve to a human-rated launch vehicle more easily than any other LV configuration. The Apollo clean-sheet design incorporated numerous design features now inherent on the current Atlas V configuration, including redundant flight-control systems, robustness, and improved process control. Recent studies for NASA resulted in new evolutionary concepts that provide even further upgrades to reliability and engine-out capability while maintaining a flight base of existing customers. As seen in Fig. 3, the evolvement from our current Atlas V fleet provides additional capability to meet Space Exploration program requirements without requiring a substantial investment in infrastructure. This approach builds on the successful Atlas heritage of incorporating manageable evolutionary steps to improve LV reliability and performance.

The Phase I vehicle incorporates a friction stir-welding (FSW) structurally stable aluminum-lithium lightweight 5.4-m diameter Centaur tank. With a mass fraction exceeding today's Centaur at 0.90, it is the best mass fraction of any LV today. The variance of tank sizes can be achieved by adding common barrel sections to the structurally stable tank. The multiple RL-10 configurations using a common mounting scheme similar to today's Atlas V single- and dual-engine configurations provide the opportunity to improve crew safety with engine-out capability. Also, limited modifications to the launch site in handling increased propellant capacity and the wider Centaur tank minimize overall development cost. By using the current modern set of avionics with some reliability enhancements, the Phase I vehicle provides the initial stepping stone to providing crew capability to low Earth orbit (LEO) with a 13.3-mT capability for a Phase I single stick (no solids) six-RL-10 configuration. This Centaur can also be configured for long-duration Space Exploration, up to 1 year, with the incorporation of passive insulation technologies resulting from the common bulkhead.

The Phase II Atlas increases the diameter of the booster to 5.4-m to match the Centaur tank. The dual RD-180 configuration provides the opportunity to further improve crew safety with booster engine-out capability. Similar to the Phase I vehicle, the development cost for a single stick Crew LV (CLV) is minimized because there are only slight modifications to the launch site to handle the increased propellant capacity and wider Centaur tank. Again, the current modern set of avionics with additional reliability enhancements provides a crew capability to LEO with up to 25.1-mT capability for a Phase II single stick (no solids) six-RL-10 configuration.

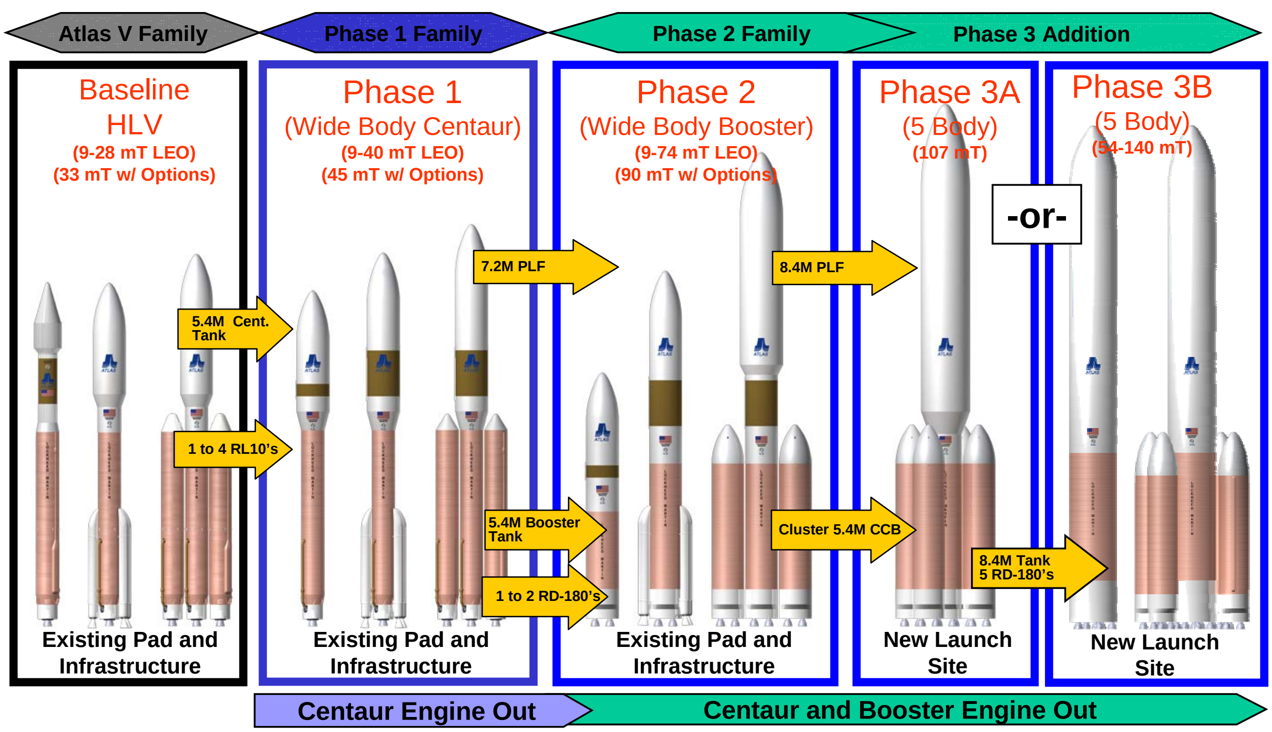

Figure 3. Atlas evolution for space exploration meets the both crew and cargo launch vehicle requirements.

B. Common Integrated Evolved Cryogenic Stage

Space Exploration missions benefit from the high inertial specific pressure (ISP) of LO_2/LH_2, which reduces the initial mass to LEO (IMLEO) requirements to less than half of those using storable propulsion stages. For upper stage and in-space stage commonality, the Lockheed Martin integrated evolved cryogenic stage (ICES) provides the most affordable, reliable design for launch vehicle upper stages and other Space Exploration in-space transportation stages, required by NASA. The ICES architecture with common tanks, propulsion, and cryo-management technologies for long-duration LO_2/LH_2 transportation stages provides significant benefits for Space Exploration's LEO, lunar, and Mars missions as shown in Fig. 4. The flight-proven Centaur evolved into ICES, which provides an extensible design to meet the performance, safety, and reliability requirements of an efficient Earth-to-orbit upper stage and the in-space transportation stages for the entire Space Exploration architecture. The existing Centaur upper stage provides the highest mass fraction available with the high ISP of LO_2/LH_2 propulsion. ICES increases the propellant capacity 1.5 to 6 times the current volume and increased load carrying capability while improving mass fraction through the development of a 5.4-m FSW tank. These improvements are accomplished using an optimized system-level design that synergizes and integrates structural, thermal, and propulsion subsystems.

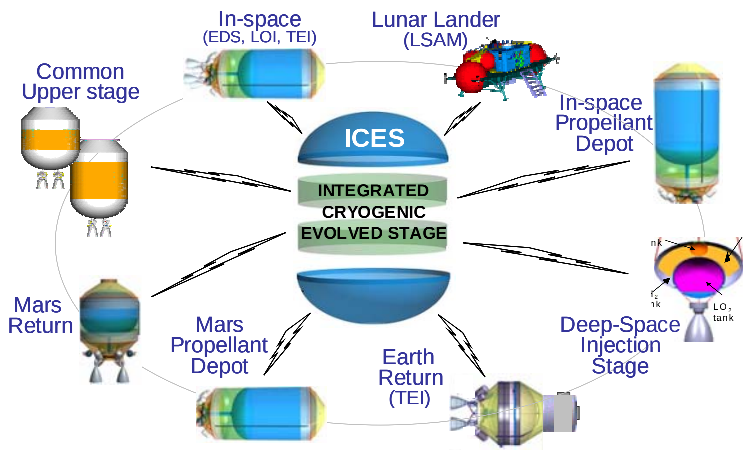

Figure 4. The Lockheed Martin ICES provides the most affordable, reliable design for launch vehicle upper stages and other Space Exploration in-space transportation stages.

The commonality of this design allows the Space Exploration architecture to benefit as follows:

1. *Structurally stable configuration provides an increased load-carrying capability for both Earth to orbit (ETO) and in space, increasing safety by using FSW of thin gauge, monocoque aluminum.*
   - Common bulkhead provides volumetric efficiency.
   - Cylindrical barrel sections provide multiple propellant loads by using one, two, or three stacked barrels depending on mission requirements.
   - FSW thin-gauge aluminum structures demonstrate capability under the Human and Robotics Technology (H&RT) contract (reference NASA Project Control No. 1424672).
2. *Thermal considerations are integrated into the system design for long-duration spaceflight.*
   - Common bulkhead optimizes thermal management through heat transfer from LO_2 to LH_2 and minimizes tank penetrations.
   - Structure design minimizes conductive paths for heat leaks.
3. *Multiple engine propulsion system is enabled by common design configurations.*
   - Common feed system and thrust structure support one to six RL-10 engines engine-out capability.
   - Leak-free propellant fill/drain lines are thermally isolated from the tank, under the H&RT contract (reference NASA Project Control No. 1424672).

C. Key Space Exploration Initiative Performance Measures

1. *Affordability—Common design for multiple mission minimizes development and recurring production costs.*
2. *Reliability—Evolved approach builds on demonstrated reliability of flight-proven Centaur upper stage.*
3. *Safety—Human-rating enhancements increase safety.*
4. *Extensibility—ICES enables commonality for multiple Space Exploration elements by using common features:*

- Common avionics
- Common production and operations infrastructure
- Common hardware (adapters, fairings, and separation systems)
- Various barrel lengths to enable multiple performance levels
- Long-duration cryo fluid management to maximize on-orbit duration
- Common propulsion (RL-10s, RCS, feed system) with multiple engine capability to meet high or low thrust requirements and potential engine out (one to six RL-10s satisfy most thrust requirements)
- Integrated propulsion (RCS, pneumatics) to maximize synergy with main propulsion system

IV. The Human-Rated Atlas

Human-rating of the early Atlas and Titan LVs consisted of making targeted reliability upgrades to an existing LV by adding health monitoring and a launch escape system combined with a logical test program. This was considered the simplest and most reliable approach.§ The modern EELV is significantly more capable of meeting the human-rated system requirements than its human-rated expendable predecessors as the reliability has increased from about 65 to a demonstrated 100% over 76 consecutive flights . The term expendable can carry the incorrect connotation of being unreliable or built with less stringency. The ELVs are not controlled by the commercial customer's market price but rather the benefit from the reliability requirements imposed by the U.S. government. The failure of one vehicle affects the industry as a whole, in both loss of mission and loss of business.

As such, the ELVs were primarily designed to meet the reliability demands of the U.S. government. While cost remains one of many objectives, reliability improvement ranks as the number one priority in evolving launch vehicle design.

Likewise, the EELV program could not afford to sacrifice reliability for cost, especially considering that the cost of launching the payload is typically only one tenth of the total program cost. Evading the potential loss of the nation's scientific, defense, and reconnaissance satellites greatly exceeds any benefit in achieving a lower cost at the expense of ever critical mission success. The commercial customer benefits from the investments of Lockheed Martin and the U.S. government in improving reliability and affordability.

Despite the attention to reliability versus cost, the program was still able to meet the government's requirement to reduce cost by 25–50% over previous systems by incorporating improved processes, manufacturing techniques, materials, and reduction of complexity. The Atlas V has nearly an order of magnitude less parts and staging events than the earlier 100% successful Atlas IIAS. This approach improves both reliability and affordability due to an ongoing product-improvement program initiated at the outset of the Atlas I program.

As previously discussed in the human-rating workshops for the Space Exploration program, the potential for human-rating any launch vehicle in a reliable and affordable manner is facilitated by the fact that the *system* is human-rated. For the launch system, the combination of the launch vehicle and CEV as a system would be designed so that as a system, it meets the standards of the latest human-rating document, NPG 8705.2. For the Earth-to-orbit portion of flight that is short duration compared to the rest of the mission, the option of using health monitoring with a CEV abort capability provides the most effective method for ensuring crew safety. Figure 5 describes the elements of this approach.

The approach previously used on the Mercury and Gemini ELV programs is a proven method for providing crew safety. Combining the Atlas V increased reliability with LVHM of critical systems and a reliable CEV abort system to ensure the crew can safely abort to orbit or return to Earth meets the necessary standards. Atlas evolution has excess performance to provide the crew with trajectories tailored to meet the requirements of NASA Std. 3000 and of the Space Exploration program. Figure 5 below describes the capability of the Atlas launch to meet key measures for a human-rated launch system in the NPG 8705.2.

[§]Mercury Program overview, NASA KSC external relations
http://www-pao.ksc.nasa.gov/kscpao/history/mercury/mercury.htmRevised 4/24/2003.

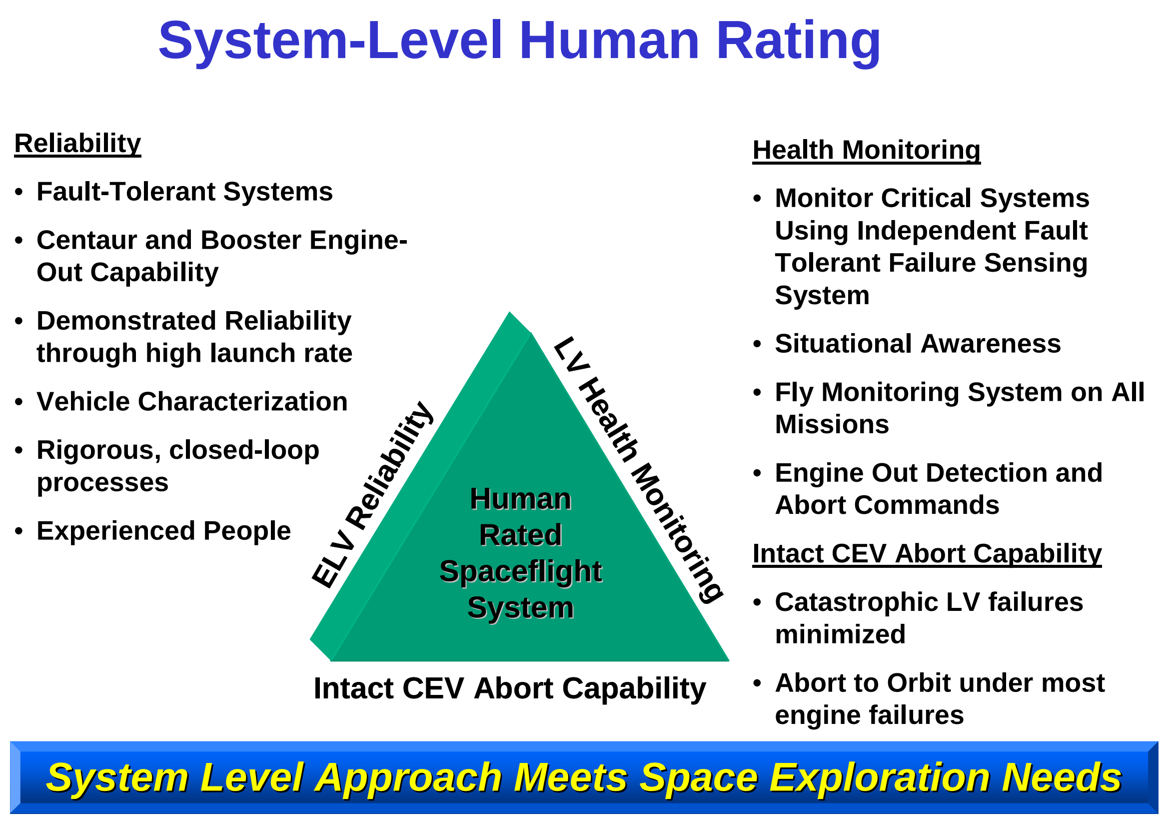

Figure 5. A robust system consisting of a reliable launch vehicle with health monitoring and CEV abort capability provides the crew the safest and most effective means of the Earth-to-orbit portion of the mission.

A. Fault Tolerance

The CLV provides single-failure tolerance to loss of mission and critical hazards except where the it meets NASA-approved "design for minimum risk" criteria. The CLV design also prevents or mitigates the effects of common cause failures in time-critical software.

As the cornerstone of safety in human spaceflight, dual-fault tolerance starts at the system level. In conjunction with the capability of the CEV to abort as a leg of fault tolerance, the current Atlas provides the single-fault tolerant design in mission-critical flight control systems. Through a rigorous design process aimed at minimum risk, the identification and mitigation of active single point failures (SPF) help ensure mission success. The next generation of Atlas design concepts, namely Phase 1 and 2 evolution vehicles, provides potential for additional fault tolerance in the booster and upper-stage propulsion systems by providing engine-out capabilities and enhanced ascent abort-return or abort-to-orbit.

Time-critical software human-rating requires protection against common cause or generic software failures. As the NPG explains, several concepts are available to satisfy this requirement, including:

1. *Redundant independent software running on a redundant identical flight computer*
2. *Use of an alternate guidance platform, computer, and software (e.g., using the spacecraft guidance to control a booster)*
3. *Use of nearly identical source code uniquely compiled for dissimilar processors*

Although these options are all feasible for the EELV program, a trade study should determine the final approach. This study would evaluate the probability of increased mission success against complexity and the probability that the solution would not have identical or similar common cause failure mechanisms.

B. Reliability

The CLV provides a predicted ascent success probability to the Earth ascent target orbit of 0.99325 at 80% confidence with an objective of 0.99325 at 95% confidence. Demonstrated, rather than theoretical, reliability functions as the best measure of a vehicle's potential for success. The demonstrated 100% success rate of the current Atlas fleet, including eight of eight first flight successes, provides a basis for ensuring crew safety. Also, the Atlas evolution concepts reduce probability of failure (POF) by a factor of six relative to Atlas II family through the use of large factors of safety and enhanced design margins.

Atlas responded to the requirement from the EELV development program to increase reliability to that specified in the systems program requirements document (SPRD). To successfully meet that requirement, the program implemented and incorporated several improvements to the previous design heritage across the entire fleet for all customers. The development of a vehicle with a specified design reliability requirement proves that an existing vehicle design can meet higher standards for a human-rated vehicle design. Given even a greater requirement, the Atlas has shown that it can incorporate these improvements cost effectively and efficiently, as shown in Fig. 6. Although much of the unreliability has been omitted from modern ELV fleets, newly identified and matured technologies and techniques provide a means for continual improvement. This represents the essence of the Atlas product-improvement program; we consistently seek and identify further reliability upgrades that can improve the design as the Atlas evolves. With 100% demonstrated success on the modern Atlas family of vehicles, the Phase 2 Atlas can exceed the mission reliability requirement as seen in Fig. 5 by eliminating complexity and adding redundancy and engine out.

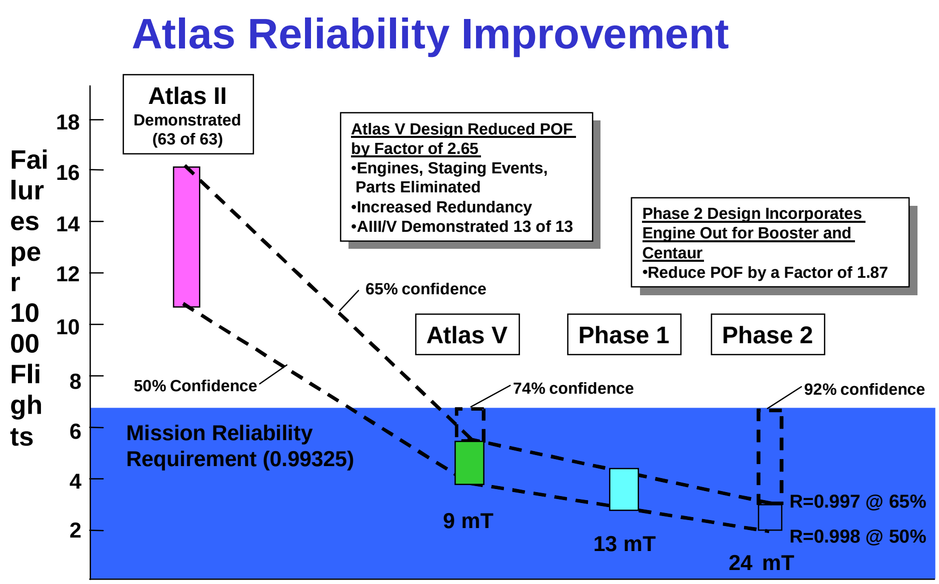

Figure 6. By reducing the parts count and staging events and by incorporating booster and Centaur engine-out capability, the Atlas evolution exceeds the mission requirement for the CEV launch vehicle program.

C. High Flight Rate Using Common Launch Vehicle Elements

The ability to provide a greater number of flights and build demonstrated reliability using launch vehicle elements common to both the human-rated and core launch vehicle programs serves as yet another unique advantage of the ELV program. A high launch rate provides the basic understanding and characterization of components that would otherwise be relegated to an expensive test program unique to a non-EELV design. The proof of success in the modern Atlas ELV program lies in the successful first flights where infant mortality tends to propagate. Figure 7 describes the role of infant mortality and its relationship to flight rate. Design flaws tend to manifest themselves in early flights but are minimized by the evolutionary development approach that incrementally proves each new enhancement. With a common fleet, unmanned flights can prove design sufficiency before ever placing a human in a launch vehicle. This evidence also relieves some burden of an expensive dedicated test program. Beyond the initial flight phase that proves out the design for the vehicle, process flaws (quality, human error) must be mitigated by continuous improvement driven by flight and test results. Flight data provide the opportunity for rigorous post-flight characterization and the enhancement of already rigorous closed-loop processes. In addition, the highly experienced

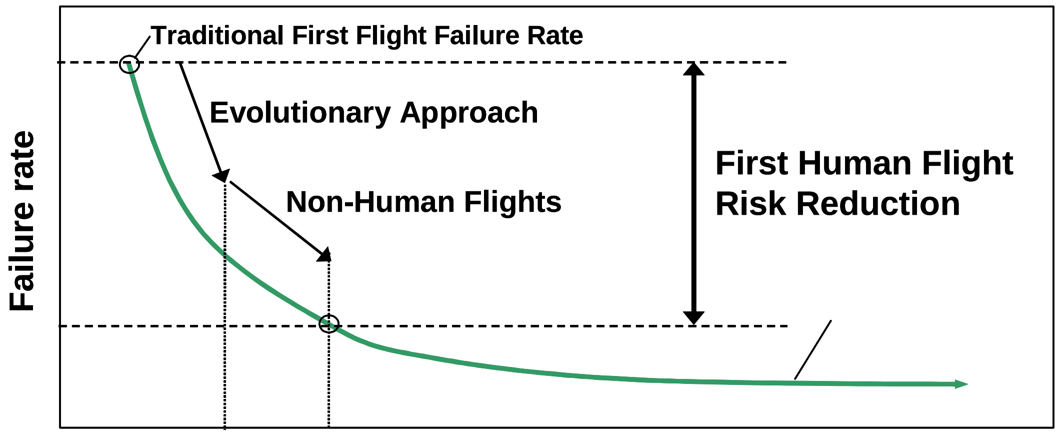

Figure 7. Infant mortality exposes design flaws early in the flight manifest; an evolutionary program with elements common to a recurring manifest provides the opportunity to retire risk without impacting the Space Exploration program with expensive, dedicated test flights.

team maintains proficiency through constant flight exercises and real-time operations. The benefits of a common-fleet approach include data reduction; anomaly trending; demonstrated reliability; and ability to incorporate a human-rating mission kit passively on nonhuman flights, production, and launch operations rate versus familiarity and family affordability.

Given that a common family of vehicles flys all missions, including, Air Force, National Reconnaissance Office (NRO), commercial cargo, exploration, and human flights, flight rates increase from about six to ten per year, therefore demonstrating reliability much sooner than a unique vehicle. The lessons learned from each flight about people, process, and product are factored in to the next flight. Hence, reliability is not only statistical, but also demonstrated (Fig 8).

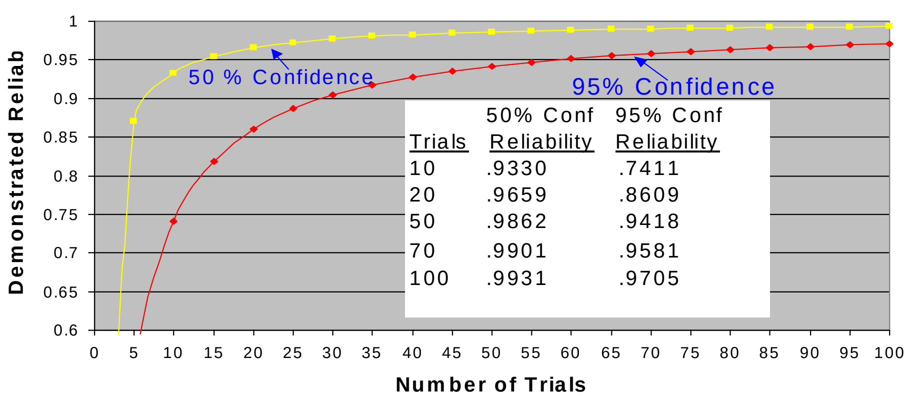

Figure 8. By using a common family of vehicles, the EELV can demonstrate reliability much sooner and more affordably than a dedicated test program for a unique vehicle.

D. Process Discipline and Design Maturity

Atlas retains an unmatched first-flight success record that can be traced to the incorporation of disciplined processes and mature system designs, as discussed in Fig. 9. The difficult progression of process discipline sometimes requires failure before success. Early failures in the Atlas I program caused a great deal of trial and tribulation.. These problems intensify when the root cause is overlooked and the failure repeats. For example, on the AC-70 and 71 flights, a flaw in the overall systems engineering effort left the upper-stage propulsion system vulnerable to environmental effects. This fatal error caused the upper stage to ignite and left the payload in a useless orbit. Following the AC-70 failure, thorough investigations identified the most probable root cause, provided solutions and subsequent incorporation, and resulted in successful flight execution of AC-72. Unfortunately, the same failure struck again on AC-71 a few days after the flight of AC-72, uncovering the fact that the real root cause had not been accurately identified the first time. Exhaustive evaluation of the hardware , as well as the processes that led to the failure, ensued.. From that failure, some of the most disciplined program processes imposed on the design, manufacturing, and operational components were created and implemented. Objective post-evaluation generally pinpoints poor process discipline as the root of the problem, and in this instance, hardware merely played a minor role. Now, the restructured process and procedures discipline emulates that of the human-rated launch vehicle design processes *internally*.

Figure 9. Atlas mission success centers on an experienced core program that combines experienced people, disciplined processes, and a well-designed product.

E. Vehicle Health Monitoring for Safe Abort

The CLV automatically detects and enunciates conditions that could result in loss of human life, the vehicle, and/or the mission, or significantly impact mission capability. The recent LVHM concepts developed for Atlas human spaceflight include a robust, independent VHM system to monitor critical systems that use an independent fault-tolerant health management system. This provides the crew with situational awareness and automatic or manual abort initiation, if necessary. The LVHM concept preserves consistency with the philosophy of previously human-rated ELV health monitoring systems that were safe, reliable, and noncomplex. Because the ELV portion of the health monitoring system is designed for short flight duration, it can be designed with simplicity and reliability just as the previous human-rated program health monitoring system designs.

V. Summary

The success of any program relies on its ability to control its processes and the ability to evolve and grow to meet the ever-increasing need for reliability and safety. Atlas welcomes this challenge. As shown in past programs, it has continually evolved and improved in reliability and performance, -in addition to affordability. To make human space exploration a viable reality, Atlas ELV can be upgraded to meet the needs of the human-rated spaceflight program readily and affordably. The current design already incorporates many of the features and requirements necessary to achieve success. The projected Atlas evolution encompasses superior reliability while improving crew safety. Heightened capability to accommodate trajectory shaping and engine-out profiles that meet crew safety requirements at the system level provides the means to meet this goal. Also, Space Exploration missions benefit from the high ISP of LO_2/LH_2, which reduces the IMLEO requirements to less than half of those using storable propulsion stages. The ICES architecture with common tanks, propulsion, and cryo management technologies for long-duration LO_2/LH_2 transportation stages provides significant benefits for Space Exploration's LEO, lunar, and Mars missions. Conclusively, Atlas evolution can and will meet the needs for space exploration in an affordable and reliable manner, leading NASA to focus on the real technology of space exploration.

References

[1] Areas of Manuscript Referenced from: Holguin, M., "ELV Human Rating— Atlas Heritage and Future Potential," AIAA Joint Propulsion Conference 2005, Tucson, Arizona, USA.