<u>ELV Human Rating: Atlas Heritage and Future Potential</u>

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Exploration Launch Vehicle Concepts

ABSTRACT

The Atlas and Centaur Programs have enjoyed a rich history as the trusted vehicle of choice for a large number of NASA's Space Exploration voyages, including manned spaceflight programs. In addition, the US Air Force and National Reconnaissance Office have trusted the reliability of the expendable launch vehicle program to accurately deliver the most critical national security payloads, on which the lives of the warfighter often depend. During that course of space launch development, the Atlas Expendable Launch vehicles have matured well beyond the early days of spaceflight. Over the last decade and a half, the flight proven Atlas has fulfilled its responsibility 77 consecutive times to successfully launch payloads to their earth-synchronous or solar system bound trajectories, without fail. In that same time span, 8 Evolutionary Atlas first flight vehicle configurations on 3 new or significantly modified launch pads were also successfully introduced.

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 8 of 8 first flight vehicle configurations, with a current flight record of 77 consecutive successes.

The reason for this success has its roots in the hard won maturity in the areas of systems design robustness and processes discipline. These successful attributes resulted not solely by chance or ingenuity, but rather from many years of hard lessons, when around the turn of the decade in 1990, Atlas experienced 3 failures, almost consecutively. After a complete halt to launches and much soul searching, head scratching and investigation, Lockheed Martin invoked an overwhelming transformation in how we controlled and evolved not only the system design, but also the processes and operations associated with the entire launch system. As John Keats once said ' Failure is, in a sense, the highway to success'. That has never been truer than at the start of the Atlas launch vehicle program. The challenge now is to transfer that same successful mature and disciplined evolutionary approach into a launch system that is safe enough to fly a human into space, achievable not only technically, but also within the visionary boundaries of the NASA Space Exploration program.

This paper will address the attributes of the Atlas Expendable launch vehicle that makes it distinctively qualified to be a workhorse for Crew Exploration Vehicle launches. In addition, this paper will address an associated approach to human rating grounded in the tenets of the NASA Human Rating guide, NPG 8705.2, and taking into consideration the Office of Space Exploration ASARA principle – "As Safe As Reasonably Achievable".

INTRODUCTION: The Atlas launch vehicle development program began in the 1940's with studies exploring the feasibility of long range ballistic missiles. Its qualifications for use a launch vehicle beyond the role of an ICBM became clear as its power was demonstrated successfully during that program. Both NASA and the United States Air Force issued contracts to take 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 that was capable of safely launching human passengers into space.

HISTORICAL PERSPECTIVE: Atlas was chosen as the launch vehicle for America's fledgling human spaceflight program, the workhorse for Project Mercury. Within 3 years after the prime contract was awarded, the goal to orbit a man in space and returning him safely to earth was completed successfully. The final mission was accomplished when John Glenn was launched and orbited 22 times over a 34 hours period successfully.[1]

As a follow on to Project Mercury, Project Gemini began early in 1961. The early Gemini program flew two unmanned Gemini missions in addition to the manned flights. 10 manned missions were conducted for Project Gemini between 1965 and 1966, which used the early Titan vehicle, also formerly and ICBM. [2] 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 Program proved that human spaceflight can be safely accomplished starting with expendable launch vehicles designs that were originally developed for other purposes.

Centaur, the worlds 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 (LH2) and liquid oxygen (LO2) for propellants. The RL-10 was chosen as a highly reliable upperstage engine, and has proven its worth

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

- ***Mariner - First spacecraft to fly to another planet, Venus***
- ***Pioneer- First to use gravity assist by Jupiter and Saturn before solar system escape trajectory***
- ***Voyager- First to flyby Neptune and Uranus before solar system escape trajectory***

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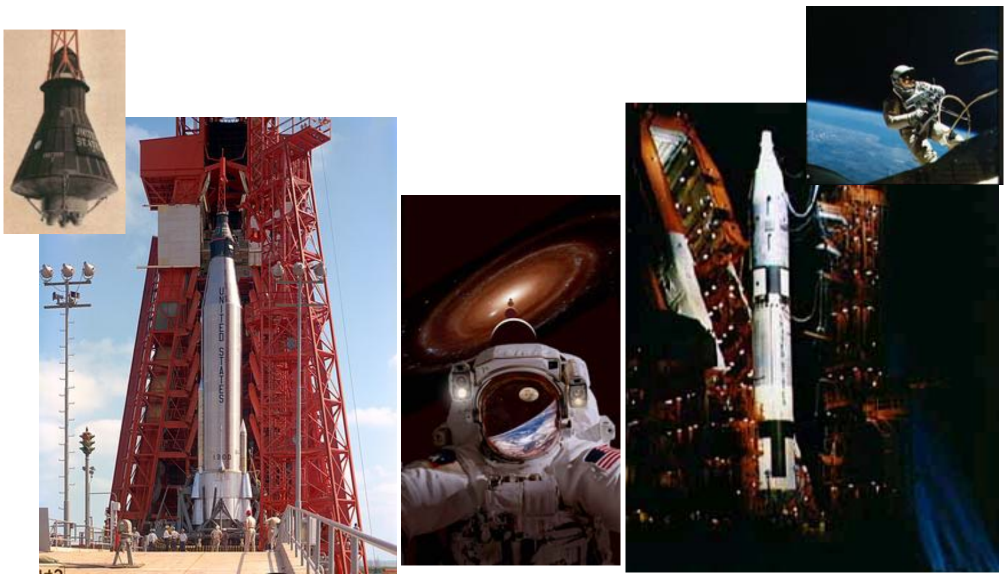
[1] Project Mercury, A Chronology. NASA SP-4001. Prepared by James M. Grimwood, Historical Branch, Manned Spacecraft Center, Houston, Texas, as MSC Publication HR-1 Office of Scientific and Technical Information, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. Washington, D.C. 1963

2 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

- ***Viking- First spacecraft to land on Mars***
- ***Surveyor- First US spacecraft to soft land on the moon.***
- ***Helios- 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 SOHO, SAX, Cassini, EOS, Pluto, MRO and SDO . Clearly, Atlas has already been significantly involved in the success of the nations Space exploration Program, both from a human spaceflight and critical planetary probe launch perspective.



Atlas Mercury :
4 successful human flights

Titan Gemini:
10 successful human flights

Figure 1: Today's Atlas V vehicle has its heritage in early launch vehicle developments including the successful human spaceflight versions used in Project Mercury and Gemini.

ATLAS EVOLUTION: The Evolution of the Atlas Centaur Program from the early flights was begun in 1990 and continues even today. Figure 2 outlines the development of the Atlas I thru the current Atlas V vehicle designs. The development philosophy for Atlas has followed a very low risk approach: introduce enhancements in small steps each time, fly these improvements to prove them successful before moving on to the next enhancement, thus avoiding wholesale changes to the entire LV and avoiding the introduction of significant uncertainty. Each of the 8 first flight configurations has been highly successful, while introducing components that make the vehicle more powerful, as well as significantly more reliable. The intense competition in the launch vehicle marketplace precludes the use of risky unproven technologies; a single LV failure can decimate the LV's business case. Rather, the Atlas launch vehicle development has followed a path of incorporating increasingly reliable components and architectures, resulting in a vehicle that is essentially single fault tolerant in the avionics systems, with a reliability that exceeds 0.995 (specific reliability numbers are proprietary). A brief overview of the evolutionary enhancements for these vehicle variants follows.

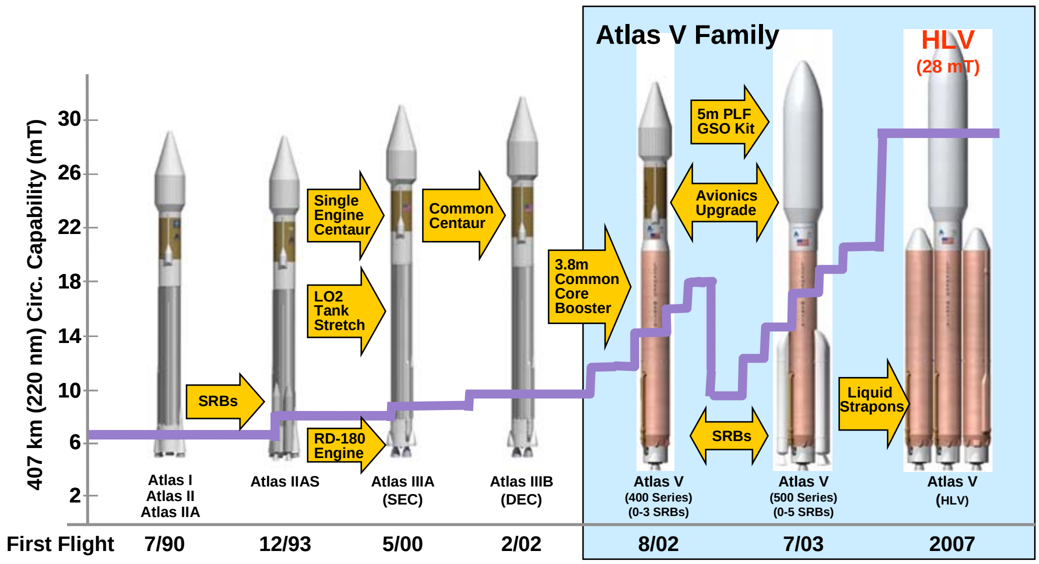


Figure 2: Atlas low risk evolution approach has resulted in 8 first flight vehicle configurations, each of them flown successfully the first time.

Atlas I - The first flight of an Atlas I was on July 25, 1990. Originally, 18 Atlas I vehicles were planned for manufacture. With the award by the USAF to General Dynamics of the MLV-II vehicle development contract for the Atlas II launch vehicle, the Atlas program rescoped Atlas I production commitments to 11 vehicles and converted the remaining commitments to the Atlas II/IIA/IIAS production effort

The Atlas II family includes 3 variants all based around an enhanced core vehicle. The Atlas II booster is 9 feet longer than an Atlas I and includes uprated Rocketdyne MA-5A engines. The Atlas I vernier engines are replaced with a hydrazine roll control system. The Centaur stage is stretched 3 feet over the Centaur I stage. Fixed foam insulation replaces the jettisonable insulation panels.

Atlas II - Originally developed to support the United States Air Force Medium Launch Vehicle II program. Centaur uses RL10A-3-3A engines. The first Atlas II flew on December 7, 1991.

Atlas IIA - Higher performance RL10A-4 engines replace the RL10A-3-3A engines. These engines are offered with or without extendable nozzles, which further increase performance. The first Atlas IIA lifted off on June 9, 1992.

Atlas IIAS - Four Thiokol Castor IVA solid rocket motors are attached to the Atlas stage to provide additional thrust. Two are ignited at liftoff, with the second pair ignited in flight. After each pair burn out, they are jettisoned and fall into the ocean. The first Atlas IIAS was launched on December 15, 1993, the last was launched August 31, 2004.

Atlas IIIA and IIIB

The Atlas IIIA configuration is a major redesign of the Atlas launch vehicle. The booster stage is stretched 11.5 feet over the Atlas II, most of which accommodates a larger liquid oxygen tank. The Rocketdyne MA5A engines have been replaced with a single Russian RD-180 engine with two nozzles. This configuration completely eliminates the separation of booster components during boost stage of flight. The first major separation event for this configuration is after booster engine cutoff, when the new single engine Centaur separates from the booster. The single RL10A-4-1B engine of the Atlas IIIA Centaur significantly reduces the complexity of the vehicle and eliminates the cost of the second engine. Significant avionics changes have also been incorporated into both the Atlas booster and Centaur upper stage. The first Atlas IIIA was launched on May 24, 2000, the second (and last) on March 13, 2004. The Atlas IIIB vehicle uses the same booster stage as the Atlas IIIA, but the Centaur upper stage is stretched and can be configured with either one or two RL10A-4-1B engines. The first Atlas IIIB lifted off successfully on February 21, 2002, the last on February 3, 2005

Atlas V

The Atlas V vehicle uses the same Centaur upper stage as the Atlas IIIB, and the same RD-180 booster engine as all Atlas III vehicles, but (among other changes) the booster tanks are a structurally stable design rather than pressure stabilized. The Atlas V family allows for a broad configuration of components, including 4 or 5 meter fairings and up to five solid rocket booster motors. The first Atlas V, a 401 configuration (4-meter fairing, no solid rocket boosters, single-engine Centaur) launched on August 21, 2002

Future Atlas Evolution

The Atlas V vehicle provides the best starting point for evolving a vehicle to satisfy the needs for both the crew and cargo versions of launch vehicles for Space Exploration. Because of its already demonstrated reliability and incorporation of fault tolerance and affordability, it has a significant potential to make the jump to a human rated launch vehicle more straightforward and doable than nay other LV configuration. The Apollo clean sheet design incorporated many design features now inherent on the current Atlas V configuration, redundant flight control systems, robustness and improved process control. The evolutionary concepts developed under study for NASA over the last couple of years provides even further upgrades that can provide increasing reliability and engine out capability, while maintaining a flight base of existing customers. As seen in figure 3, the

Atlas Evolution from our current Atlas V fleet provides additional capability to meet the Space Exploration program requirements without requiring a huge investment in infrastructure.

The Phase I vehicle incorporates a friction stir welded structurally stable aluminum – lithium lightweight 5.4M diameter Centaur tank. With a mass faction that is improved over today's Centaur at 0.90, is the best mass fraction of any LV flying today. Varying tank sizes can be achieved by adding additional 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 it provides the opportunity to improve crew safety with engine out capability. In addition, the development cost is minimized since there are only minimal modifications to the launch site to handle the increased propellant capacity and wider Centaur tank. 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 LEO with a 13.3 mT capability for a Phase I single stick (no solids) 6 RL-10 configuration. In addition, this Centaur can be configured for long duration for Space Exploration up to a year with the incorporation of passive insulation technologies as a result of the common bulkhead.

The Phase II atlas increases the diameter of the booster to 5.4M diameter to match the Centaur tank. The dual RD-180 configuration now provides the opportunity to improve crew safety further with booster engine out capability. Similar to the Phase I vehicle, the development cost for s single stick CLV is minimized since there are again 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) 6 RL-10 configuration.

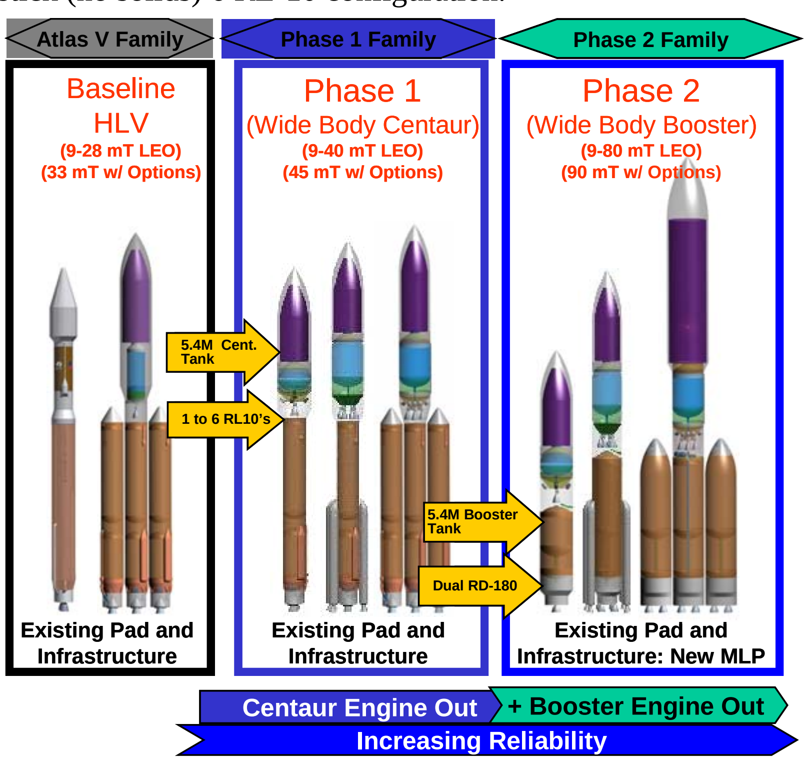


Figure 3: Atlas Evolution for Space Exploration meets the requirements for both crew and cargo launch vehicles.

THE HUMAN RATED ATLAS

In some circles it has been said (incorrectly) that an expendable launch vehicle program could not be human rated. The discussion there centers on the premise that expendable launch vehicles were designed for the commercial customer, and that the design focuses on cost considerations as the primary objective. While cost is an objective, reliability improvement ranks as the number 1 imperative in evolving launch vehicle design. The EELV program could scarcely afford to become the cheapest ride around, sacrificing the nations critical scientific, defense and reconnaissance satellites costing several hundred million or billions of dollars, for a launch cost in the neighborhood of $100M dollars that often pales in significance to the overriding cost and potential loss of a critical national asset. It just doesn't make logical sense to be penny wise and pound foolish. Rather, the commercial customer benefits from the investments made by Lockheed Martin and the USG to improve reliability and affordability, Mission Success ® is critical each and every time; cost and schedule are subservient to that overriding goal. The reduction of cost stems from the incorporation of improved manufacturing techniques and 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 reliability and affordability due to an ongoing product improvement program initiated at the outset of the Atlas I program. The connotation of expendability as "cheap" is incorrect, expendables are not deferential to insurance and cheap rides; rather the failure of one vehicle affects the industry as a whole, both in insurance, downtime and loss of business. As one insurance company notes, good drivers are rewarded with lower rates.

As has been 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 embedded in the fact that the "System" is human rated. For the launch system, this has been clearly identified that the combination of the launch vehicle and CEV as a system would be symbiotically designed to meet the standards of the latest human rating document, NPG 8705.2. In addition, the As Safe As Reasonably Achievable (ASARA) principle points toward a solution that

Some key measures for a human rated launch system in the NPG 8705.2 including the Atlas launch vehicle capability to meet them are discussed below:

1. <u>Fault Tolerance:</u> *The CLV shall provide single failure tolerance to loss of mission and critical hazards except where the CLV meets NASA approved `Design for Minimum Risk' Criteria.* <u>*And*</u> *The CLV design shall prevent or mitigate the effects of common cause failures in time-critical software.*

Sometimes described as "The cornerstone of safety in human spaceflight", dual fault tolerance is intended to be met 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. Active Single Point Failures (SPF's) have also been identified and mitigated through a rigorous risk mitigation process to help ensure Mission Success. In addition, the NASA "Design for Minimum Risk" (DFMR) approach provides additional paths for evaluation and incorporation of additional redundancy or other measures for improving crew safety. The next generation Atlas design concepts, namely the Phase 1 and 2 Evolution vehicles, provide the potential for additional Fault Tolerance in the booster and upper stage propulsion systems by providing engine out capabilities and enhanced ascent abort options (abort to orbit under most engine failures.

The "common cause" requirement for time critical software provides protection against 'generic' SW failures. As the NPG explains, several concepts are available to satisfy this requirement including;

i. Redundant independent software running on a redundant identical flight computer.

ii. Use of an alternate guidance platform, computer and software (e.g., using the space craft guidance to control a booster).

iii. Use of nearly identical source code uniquely compiled for different dissimilar processors.

While all of these options are feasible for the EELV program, a recommendation on a final approach should be the subject of a trade study to evaluate the probability of increased mission success, against complexity and probability that the solution would not have the same or similar common cause failure mechanisms.

In addition, the Atlas program maintains a comprehensive Verification and Validation process that

2. <u>Reliability:</u> *The CLV shall provide 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 is the best measure of a vehicles potential for

success. The current demonstrated 100% success rate of the current Atlas fleet (including 8 of 8 first flight successes) provides a basis for ensuring crew safety. In addition, the Atlas Evolution Concepts reduce Probability of Failure (POF) by a factor of 6 relative to Atlas II family via 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 SPRD. In order to successfully meet that requirement several improvements to the previous design heritage had to be implemented, and were incorporated on a across the fleet fro all customers. The proof of the success of the modern Atlas ELV program is the successful first flights where infant mortality tends to show immediately. 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. While much of the un-reliability has been designed out of these modern ELV fleets, there is always room for improvement as new technologies and techniques are identified and matured. This is the essence of the Atlas product improvement program and as such we have identified further reliability upgrades that can be incorporated into the design as the Atlas evolves.

Another unique advantage of the expendable launch vehicle program is the ability to provide a greater number of flights and hence demonstrated reliability using launch vehicle elements of common to both the human rated and core launch vehicle programs. 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. In addition, the wealth of flight data provides the opportunity for rigorous post-flight characterization of flight data, enhancement of already rigorous closed loop processes, and a highly experienced and oft exercised design and development Team. Other benefits to a common fleet approach- include data reduction, anomaly trending, demonstrated reliability, ability to incorporate human rating mission kit passively on non-human flights, production and launch operations rate vs. familiarity and family, affordability.

3. <u>Process Discipline and Design Maturity:</u> Atlas has an unmatched first flight success record that can be traced to the incorporation of disciplined processes and mature system designs. Process discipline was learned the hard way, and as is sometimes the case, you have to experience failure before you can experience success. Failures early in the Atlas I program caused a great deal of pain in the program. Especially when the failure is repeated without finding root cause. This was the case on the AC-70 and 71 flights where a flaw in the overall systems engineering effort left the upper stage propulsion system vulnerable to environmental effects that caused the failure of the upper stage to ignite and left the payload in a useless orbit. After the first failure, the root cause was investigated, most probable cause identified, solutions incorporated and a successful flight between the 70 and 71 vehicles was accomplished. Unfortunately, the root cause had not been found and the systems flaw struck again on AC-71 several months later. Serious evaluation of not only the hardware but also the processes that led to the failure underwent intense scrutiny. Out of the ashes of that failure were borne some of the most disciplined processes imposed on the design, manufacturing and operational components of the program. Traced back to their roots, failures are often the result of poor process discipline, and the hardware merely a player in the saga. The root cause was indeed a systemic lack of process discipline, and the restructured process and procedures discipline now emulated that of the human rated launch vehicle design processes internally.

Subsystems and component design that avoid the use of risky unproven technologies and unnecessary design features that increase complexity are also key elements of improving reliability and safety. are result of failure. The last failure on the Atlas I program, AC-74 was the result of use of unnecessary design features that caused the engine thrust on the booster stage to decays due to a design feature that was totally unnecessary and unused. In the proceeding evolution to the current Atlas v, these principles would provide the basis for a highly successful first flight and recurring program virtually unmatched in the space industry today. Atlas uses the "One at a time launch" philosophy, that each rocket is a unique individual with no hardware corporate memory that its sibling LV was just recently launched successfully. That expertise resides within the experienced Atlas team.

4. Vehicle Health Monitoring for Safe Abort: *The CLV shall automatically detect and annunciate conditions that could result in loss of human life, loss of vehicle, loss of mission, or significantly impact mission capability.* The LVHM concepts developed over the last several years for Atlas human spaceflight include a robust, independent VHM system to monitor critical systems using independent fault tolerant health management system, providing the crew with situational awareness, and automatic or manual abort initiation should that become necessary. The LVHM concept developed is consistent with the philosophy of previously human rated expendable LV's LVHM systems that were safe, reliable and non-complex. Because the expendable LV portion of the VHM system is designed for a short flight duration, it can be designed- with simplicity and reliability in mind, as were the previous human rated programs VHM system designs. Figure 3 provides a summary comparing the various LVHM systems for the early expendable Human spaceflight LV's.

	Title	Description	Abort initiation	# of Systems Monitored:	Type of Systems Monitored
Atlas Mercury	Abort Sensing and Implementation System (ASIS)	Analog electronic system with wire harnesses, sensors, and sequencer relays	Abort initiated by Automated system with Crew and Ground (LD/FD/RSO) capability	6 separate measurement types with Dual Redundant Sensors	Attitude, Electrical Power & Interface, Engine & Hydraulics, and tank pressures
Titan Gemini	Gemini Malfunction Detection System (MDS)	Analog electronic system with wire harnesses, sensors, and sequencer relays	Abort initiated only by Crew and Ground (LD/FD/RSO) (non-automated, except backup guidance system)	10 separate measurement types with Dual Redundant Sensors	Attitude, Electrical disconnects, Engine & Injector pressures, and propellant tank pressures

Saturn V Apollo	Apollo Emergency Detection System (EDS)	Triple redundant digital modules and sensors that allowed two of three voting logic. It also provided situational awareness of launch vehicle health to the crew via caution and warning indications and other displays	Automatically triggered abort during some portions of the ascent Crew initiated abort was preferred for most of the flight regime Ground (LD/FD) could issue abort request to crew, and RSO initiated (engine shutdown, EDS detect and abort)	Multiple separate measurement types with Triple Redundant Sensors	Sensors monitored tank pressures, attitude rates, engine pressures, staging breakwires

Figure 4: Launch Vehicle Health Monitoring schemes in previous Expendable LV Human Space Flight programs have focused on simplicity and reliability.

The approach that provides an affordable LVHM system is to determine the minimum number of indicators that provide the highest level and most reliable identifiers of impending failure. Incorporation of dual fault tolerance can be accomplished through redundancy and/or independent sources of information, and that information is provide to the crew and LVHM abort logic. As is seen on the previous programs, the systems were as safe and non-complex as possible in order to provide safe and reliable conditions for the crew. Complexity can sometimes be seen as the enemy of reliability and safety. This LVHM system can fly passively on all Atlas missions (commercial and government) to collect VHM and systems performance characterization data to enhance understanding of LV and the LVHM system itself prior to incorporation on a human flight. It is important that NASA commit near-term funding to VHM design, development, and demonstration flights

SUMMARY

The success of any program is rooted in its ability to control its processes, evolve and grow to meet the ever increasing need for reliability and safety. Atlas is up to the challenge. As has been shown in past programs, Atlas has continually evolved from an improving reliability and performance standpoint, in addition to the affordability part of the equation. In order to make Space Exploration a viable reality, Atlas ELV can be upgraded to meet the needs of the human rated spaceflight program readily and affordably. Its current design already incorporates many of the features and requirements that are necessary to make it successful. The envisioned Atlas evolution will continue to improve its reliability, while improving crew safety with the addition of increased performance to accommodate trajectory shaping and engine out profiles that meet crew safety requirements at the system level.