Atlas V for Commercial Passenger Transportation

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The Atlas and Centaur Programs have enjoyed a rich history as a trusted vehicle for a large number of critical space exploration missions as well as the Mercury manned spaceflight program. The Atlas expendable launch vehicle has matured well beyond the early days of manned spaceflight and is uniquely poised to provide a near-term transportation solution for the emerging space tourism market. This paper addresses the attributes of the Atlas expendable launch vehicle that make it distinctively qualified to be a highly reliable, robust earth-to-orbit transportation solution for commercial passengers. The paper will detail the Atlas expendable launch vehicle system compliance to Human Rating requirements defined by the Federal Aviation Administration (FAA) and NASA Standard 8705.2A "Human-Rating Requirements for Space Systems" as well as the anticipated safety expectations of passengers and insurers. In addition, the paper will compare and contrast various approaches to achieving safety, some of which may drive highly complex, unreliable, and costly design solutions. Atlas has the unique capability to demonstrate the implementation of Human Rating requirements by validating designs on numerous unmanned launches. The Atlas high flight rate of unmanned missions quickly builds sufficient history to rely on flight demonstrated reliability, rather than analytically predicted reliability. Demonstrating these systems has the benefit of increasing reliability through commonality with commercial and government launches, in addition to continuing vehicle characterization due to the experience gained from higher flight and production rates. The Atlas expendable launch vehicle family is a mature system with demonstrated design robustness and processes discipline that provides a highly reliable, robust solution for commercial passenger transportation needs.

I. Introduction

THE key to the success of commercial space travel is a safe, reliable and affordable transportation system. This is especially true for orbital missions, where a failure would devastate this fragile emerging industry for years to come. The Atlas V launch vehicle has demonstrated that it would be the Earth-To-Orbit launch vehicle of choice due to its unsurpassed record of mission success. The Atlas V Program was successful on its maiden launch attempt, and has realized a 100% success record on all 8 Atlas V launches. The overall Atlas Program has demonstrated 79 consecutive successes since 1993, including 100% mission success record for all Atlas II, III, and V flights.

The Atlas Program approach to human rating is simple. Human rating should utilize a common-sense approach to ensuring 100% mission success and passenger abort survival. This includes maximizing the synergy between the passenger capsule and the launch vehicle, such that neither system levies unattainable requirements on the other. Finally, human rating requires maximizing reliability, applying redundancy where practical, providing system health monitoring and an emergency detection system, and ensuring all mission phases provide survivable abort modes.

Many believe that existing expendable launch vehicles can not be human rated due to inherent limitations to their design and operations because they were not initially designed to be human rated. The results of on-going analysis dispel this belief. Atlas is the only existing launch vehicle that can meet or exceed the identified requirements for providing commercial passenger transportation. Atlas has the added benefit of incorporating and demonstrating system upgrades prior to flying the first passengers. This is crucial, as leveraging the synergy with on-going

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commercial and government satellite launch missions significantly increases our understanding and characterization of system performance, and ultimately enhances our demonstrated reliability. We believe that analytically predicted reliability estimates will not be sufficient to convince prospective passengers of their personal safety, and that a demonstrated track record over a substantial number of flights will be required for a commercially viable service.

II. Baseline Passenger Vehicle Definition

The Atlas V Program has been involved in human transportation studies beginning with the Orbital Space Plane (OSP) Program, and continuing during early Crew Exploration Vehicle (CEV) studies. The Lessons Learned from those experiences has formed the basis for changes to the Atlas launch vehicle to provide passenger transportation to Earth orbit. Over the past two years, Lockheed Martin has been refining concepts for a capsule-based commercial transportation system. The study established a baseline capsule-shaped vehicle, which is less complex and less expensive than a winged vehicle, and easier to integrate onto a launch vehicle. The capsule shape draws on Lockheed Martin's experience building reentry vehicles for Genesis, Stardust, and several Mars missions. The passenger transfer vehicle has a gross mass of approximately 20,000 lbs and is capable of carrying several passengers to a low Earth circular orbit of 265 nmi at a 41 deg inclination. The capsule includes an Abort/Orbital Maneuvering System mounted below the heat shield to provide the required delta V and impulse for either launch aborts or the final orbital maneuvering system function.

The Atlas V 401 launch vehicle was selected for its low cost and high intrinsic reliability. However, an Atlas V 402 (with two Centaur engines) could also be used for higher performance. An expanded view of the entire launch stack is depicted in Figure 1.

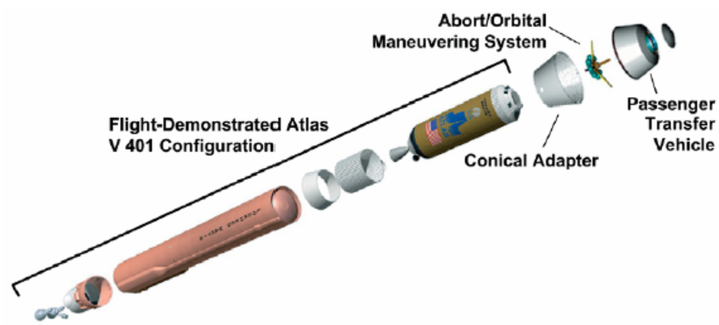

Figure 1. With Minor Modifications, the Atlas V/401 Launch Vehicle Can Support Passenger Transportation to Space.

Performance for this configuration was determined using TRAJEX simulations which are anchored to actual flight data. All simulations indicate that the flight environments are well within our current experience. Figure 2 and Figure 3 depict the maximum dynamic pressure and acceleration curves, respectively. A unique benefit of the Atlas

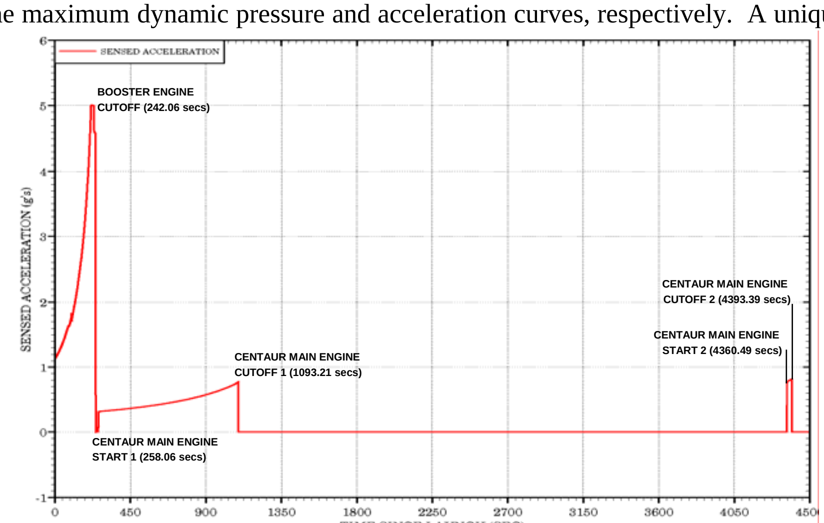

Figure 2. This Atlas V/401 Passenger Transfer Vehicle Acceleration Profile Demonstrates That the System Can Meet Passenger Requirements.

is that the peak acceleration, shown in figure 3, can be tailored using the throttle capability of the RD-180 engine.

An Atlas 401 vehicle is well suited for this mission as it utilizes only two engines (one RD-180 on the Common Core Booster™ and one RL10 on the Centaur Upper Stage). This flight proven configuration is the simplest, most reliable system currently available to safely fly a commercial passenger vehicle to low Earth orbit (LEO).

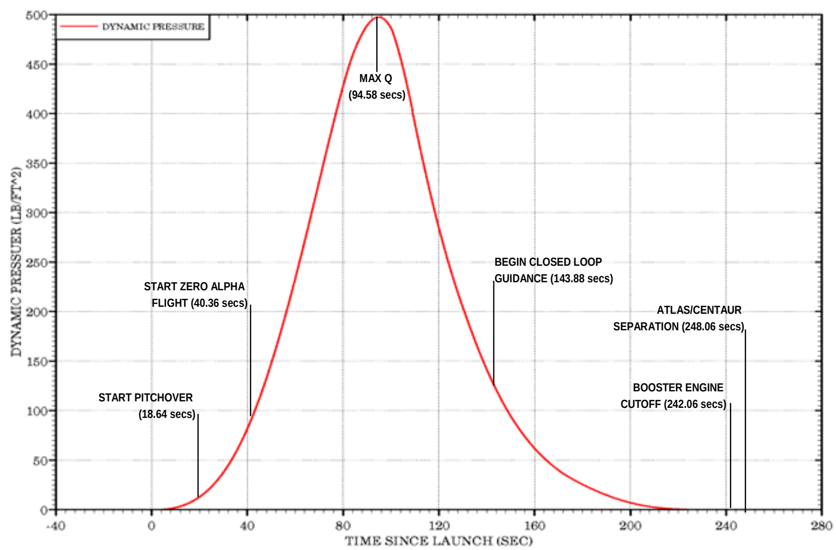

Figure 3. The Atlas V/401 Launch Vehicle Provides a Benign Maximum Dynamic Pressure Environment While Minimizing Ascent Loads and Enhancing Abort Conditions.

III. Atlas/Mercury Manrating History

The Atlas ICBM was selected to launch the first American into orbit during the Mercury Program. The early days of launch vehicle development were fraught with challenges as engineers struggled to design a vehicle that could perform reliably, *and* have the necessary systems on-board to ensure the safety of the astronaut. The first two unmanned Atlas/Mercury vehicles resulted in failure (Vehicle 10D on 9/9/59 and Vehicle 50D on 7/29/60). It wasn't until February 21, 1961 that the program realized its first success (Vehicle 67D). Prior to the first manned mission, the Program suffered 3 failures in 6 launch attempts.

"Manrating" for Mercury followed a simple, common sense approach that concentrated in two areas: hardware and people. Hardware changes to the baseline Atlas ICBM focused on improving vehicle redundancy, propellant utilization and control, and structural factors of safety. These changes were based on flight data and on one single critical factor: *time:* *time* to sense a system problem, *time* to evaluate the impact of that problem, and ultimately, *time* to execute an abort. The involvement of design, test, production and operations people, working hand in hand with the astronauts, was the single most important activity to ensure a successful mission. Hardware for manned missions was uniquely identified, and required meticulous data keeping on each component. There were exhaustive data reviews of the components, subsystems and systems. Everyone realized that the results had real life or death ramifications.

Finally, an "Abort Sensing and Implementation System ("ASIS") was developed to sense the development of any possible catastrophic failure of the booster, accomplishing what is currently commonly referred to as Vehicle Health Management. Engineers performed exhaustive data analysis and review of all Atlas Series D flight failures to look for indications of failures. A set of 11 parameters and tolerances were selected as tell tale items to be monitored by the ASIS system. If one or more of the monitored parameters deviated from the pre-established limits, the control unit generated an automatic abort command.

These simple common sense human rating approaches to hardware, people, and health monitoring served the program well, as the 7 Atlas/Mercury manned missions were 100% successful.

IV. Requirements

Atlas has used a wide variety of Specifications, Standards, Handbooks, FAA and NASA requirements, and 50 years of unparalleled launch vehicle experience to provide the basis for the changes we believe are required to safely and reliably transport commercial passengers to LEO. Atlas engineers have performed detailed assessments of their systems' ability to meet those human rating standards. A key study groundrule was to minimize modifications to the Atlas system in order to leverage the demonstrated reliability benefits of a common fleet while maximizing safety for the passengers. The following sections describe approaches and requirements that drive unique changes to Atlas, or requirements that have significant adverse impacts that, if incorporated, would reduce reliability and/or passenger safety.

A. Factors of Safety

Atlas/Mercury and NASA experience determined that hardware for human missions should be designed – or redesigned - to meet a higher Factor of Safety (FS) than had historically been used on unmanned launch vehicles. The same need exists today for any existing system that will carry passengers. For example, NASA Standard 5001 "Structural Design and Test Factors of Safety for Spaceflight Hardware" requires a 1.4 FS for use in the analytical assessment and test verification of ultimate loads on launch vehicles, including their propellant tanks and solid rocket motor cases, and payloads. It is important to note that *excluded* from this Standard (i.e. not subject to the 1.4 FS requirements) are design loads determination, fracture control, pressure vessels, pressurized components, engines, rotating hardware, solid propellant, insulation, ground support equipment, and facilities.

Because Atlas V is designed to use common vehicle elements for all configurations, each component on the vehicle is designed to the worst case conditions that it would experience in flight. The worst case conditions are driven by multi-body vehicles configurations (e.g. HLV, and vehicles with SRBs). These configurations experience higher dynamic pressure, produce higher thrust, and carry heavier payloads. When qualification margins are added on top of the driving missions, the result is that the structure has considerable margins for the relatively benign loads of a passenger mission on an Atlas 401 or 402 vehicle. This approach to Atlas design robustness is depicted in Figure 3.

This is particularly evident with the structural FS (ultimate) requirements. All Atlas 401 flight structural loads were assessed to determine the *actual* margin

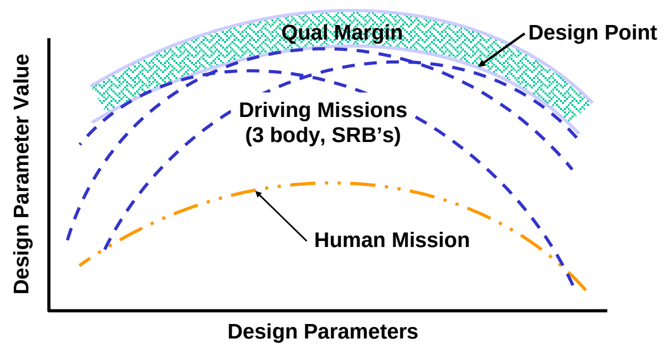

Figure 3. Atlas Common Element Design Leads to Large Margins for Passenger Missions

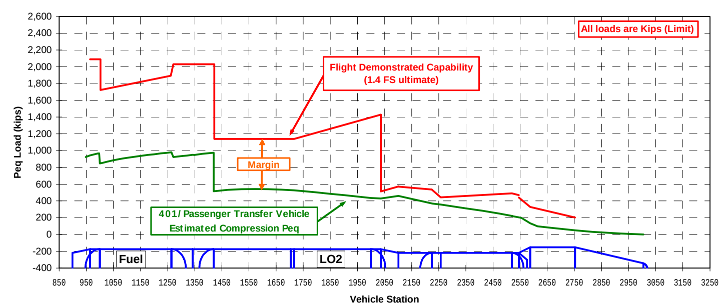

Figure 4. Atlas V/401 Passenger Transfer Vehicle Predicted Compression Loads vs Flight Demonstrated Capability.

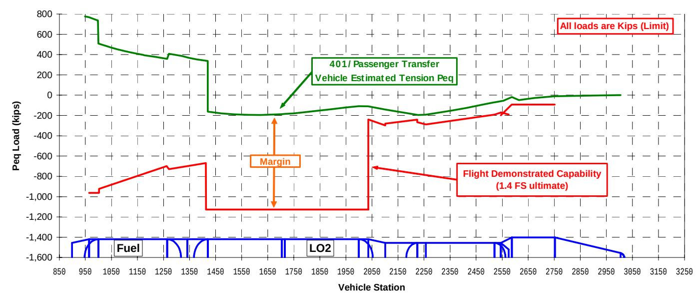

Figure 5. Atlas V/401 Passenger Transfer Vehicle Predicted Tension Loads vs Flight Demonstrated Capability.

experienced for the baseline passenger vehicle. Figure 4 through Figure 6 depict the peak compression, tension and shear loads as a function of vehicle station. In all cases, the predicted loads are below the flight demonstrated load capability corrected for a 1.4 ultimate FS, with adequate margin. Therefore, Atlas primary structures meet the 1.4 Factor of Safety requirements for this application

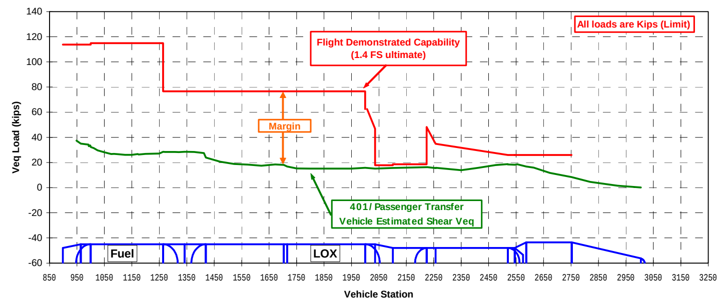

Figure 6. Atlas V/401 Passenger Transfer Vehicle Predicted Shear Loads vs Flight Demonstrated Capability.

Even though the requirements in the Standard do not extend to engines, the RD-180 and RL10 propulsion systems were also assessed for their compliance to an ultimate FS requirement of 1.4. As with the majority of Russian-built hardware, the FS is typically much greater than the requirement. A detailed RD-180 component review revealed only one component that was designed to a 1.38 FS. Preliminary review of RL10 strength summaries indicates that the majority of components satisfy the 1.4 ultimate FS requirement.

These results, anchored in flight data, demonstrate that the Atlas 401 vehicle provides margin for the requirements for a 1.4 FS for ultimate loads.

B. Dual Fault Tolerance

A common theme to human transportation is that systems should be designed so that no two failures result in a loss of life. Adding *complete* dual-failure tolerance to a system is not practical, and potentially counter-productive. In many cases the benefit of increased redundancy is negated by the increase in complexity. Therefore, waivers to this requirement are typically allowed on a case-by-case basis. Common sense and experience should be the driving considerations to implementing dual fault tolerance.

Atlas philosophy indicates that the passenger transportation system should approach dual fault tolerance at the system-level. This means using a synergistic approach to maximize the capability of the launch vehicle *and* the capsule. For example, our analysis indicates that dual fault tolerance for the main propulsion system is best accomplished by providing for engine-out capability rather than adding redundancy and complexity at the component level. However, no current ELV has the capability to lose an engine and continue to orbit. Instead the baseline Atlas approach allows the capsule abort/escape system to be used as the second leg of abort in cases such as this where two fault tolerance isn't practical.

The Atlas V design approach was one of fault avoidance and fault tolerance. Fault avoidance focuses on component selection, reduction in number of critical systems, designing out single point failures (SPF), and applying lessons learned from our extensive history in launch vehicle development and operations. Fault tolerance focuses on designing the vehicle such that it will achieve mission success despite the existence of faults. Atlas V was a significant improvement in fault tolerance compared to other comparable launch vehicles. For example, the Titan IV B booster had approximately 150 SPFs as compared to the Atlas V Common Core Booster™ which has 44 SPFs. The program has performed Fault Assessments of the entire system utilizing Fault Tree Analysis, FMEAs, and Fishbones at the component, system, and operational level to identify system interactions and failures modes. All SPFs were identified using the Computer Aided Fault Tree Analysis (CAFTA) Software and, where practical, designed out. All other failure modes were analyzed and assessed for likelihood of occurrence and mitigation plans were implemented. As detailed in Figure 7 there are only 30 active SPFs for the baseline mission. ("Structural" SPFs include items such as propellant tanks, pressure vessels, orifices, etc. "Active" SPFs include items such as engines, solenoid valves, batteries, etc.) The Structural SPFs were mitigated by increasing margins and FSs, where applicable. The Active SPFs were

System	Total SPF	Structural SPF	Active SPF
Common Core Booster ™	44	38	6
Centaur	51	29	22
Centaur Separation	2	0	2
MLP Interface	6	6	0
Avionics (Block 2)	0	0	0
Total	**103**	**73**	**30**

Figure 7. Atlas Significantly Reduced SPFs Relative to Heritage Systems.

mitigated by using tested, proven, heritage systems that have a high degree of confidence associated with them. Finally, the integrity of those Active SPFs are monitored and verified prior to liftoff.

Atlas successfully designed and demonstrated Block 2 Fault Tolerant Avionics on the Pluto New Horizons Launch in January of 2006. Block 2 Avionics was specifically designed to provide single fault tolerance while managing the increased system complexity caused by redundancy management. Redundancy management is primarily hardware-based and utilizes a simple, self-checking architecture without complex arbitration schemes. The Block 2 architecture focuses on strong fault containment to assure that failures do not propagate. The system includes a block redundant Fault Tolerant Inertial Navigation Unit (FTINU), a single fault tolerant box design and power system, and separation of redundant paths. Block 2 Fault Tolerant Avionics will fly on all future missions.

Atlas has a common sense approach to addressing Fault Tolerance that involves the identification, redesign, and mitigation of SPFs without unnecessarily increasing the complexity of proven systems. Most importantly, Atlas has ongoing product improvement programs to further reduce Single Point Failures.

C. Software Common Cause Failures

The Space Shuttle uses backup flight software to prevent or mitigate the effects of common cause failures in time-critical software. This has resulted in an independent STS Backup Flight Software (BFS) System that increased nonrecurring flight software development costs by at least 20%. The Space Shuttle BFS was originally intended to fly only on the first three STS development missions to gain confidence in the primary flight software, but has been retained for operational flights. This approach results in significant overhead from multiple software development organizations using multiple development environments and tools. It also increased system complexity, resulting in unique systems which increase system costs without an obvious benefit to safety. The benefits of BFS are virtually impossible to quantify. Certainly the theoretical software reliability increases due to BFS; however the degree of independence under which the system was developed and how it operates is critical to determining SW failure modes. Simply put, complex system requirements result in complex flight software and common errors. Also, common requirements errors lead to common implementation errors.

Atlas Program experience has determined that the root cause of software failure is human error caused by 1) requirements or coding errors or 2) a misunderstanding of the interaction between the hardware and software. Atlas has mitigated software errors by eliminating the potential for single human error opportunities. In addition, the Program recognizes that reliable Flight Software products depend upon several factors; a software development and integration team that is intimately familiar with the requirements; rigorous development, test and maintenance processes; and finally independent Verification and Validation (iV&V) of mission critical software modules.

As such, rather than developing a BFS system, the Atlas Program utilizes a rigorous software/hardware development and testing process that results in a thoroughly tested, flight proven, highly reliable, robust flight control system. Key to the demonstrated success of this approach is 1) an independent review and testing of critical software modules by an iV&V organization (including independent requirements development), and 2) independent analysis of software test results by the hardware principal engineers.

D. Passenger Ingress/Egress

Getting passengers in and out of the capsule offers some unique challenges for the current Atlas V Launch Complex 41 (LC-41), which is essentially a "clean pad." The "clean pad" concept means that there is no on-pad processing of the vehicle, and as such, limited access once it rolls out of the Vertical Integration Facility (VIF). However, there are several concepts to accommodate passenger ingress and egress at LC-41.

The mast on the existing Mobile Launch Platform (MLP) currently has a small man-lift to transport a limited number of workers to levels above the deck of the MLP. The most promising access concept is to modify this man-lift to be capable of hoisting up to 5 ground crew and passengers up to the capsule door level of the stack. In addition, a series of removable decks and railings would provide a level surface from the man-lift to the capsule door. After cryogenic tanking has completed and the vehicle is in a safe and stable condition, passengers would be transported up the man-lift in groups of 2 or 3, along with a small

Figure 8. Passengers Can Access the Capsule via the Mobile Launch Platform Currently Used at LC-41.

ground crew to assist in ingress. After all passengers are seated and secured in the capsule and the capsule door latched, the decks would be retracted, and the ground crew would leave the MLP using the man-lift. This concept (depicted in Figure 8) is the most cost effective and simplest technical solution.

A second option would be to use an industrial-grade tower crane that is typically used in the construction of high-rise buildings. These cranes can be simply converted to incorporate elevators in the vertical sections, and walkways to allow access to the capsule. The crane would be secured adjacent to LC-41 (outside of the catenary towers), and the jib would be remotely moved into position next to the capsule door. The passengers and ground crew would use the elevator to access the jib, then walk across to the capsule door. Once the passengers are secure in the capsule, the jib would be rotated to its safe position for launch. After launch, the crane could be left in place, or moved to a secure area.

Finally, a Passenger Access Tower (PAT) could be permanently constructed next to LC-41. The PAT would be outfitted with staging areas, several elevators, a retractable access arm and options for emergency passenger egress. A permanent structure such as the PAT would be the most expensive of the options currently being considered.

In all cases, a driving consideration for passenger safety is emergency egress in the unlikely event of a catastrophic on-pad emergency. In order to understand the likelihood of this emergency, the Atlas Program reviewed all fishbones, fault trees, FMEAs, and pre-launch timelines to identify any failures that would require emergency passenger egress. The results of that analysis indicate that there are no credible pre-launch failures that would result in a catastrophic condition. In the highly unlikely event of an on-pad catastrophic event, the Program feels that it would be safer to utilize the capsule's abort/escape propulsion system to extract the capsule from the launch vehicle rather than attempt to remove the passengers from the capsule. This scenario offers a greater chance of passenger survival, rather than having individuals with limited training attempt to quickly exit the capsule, descend to the ground level, and move a safe distance away from the pad.

E. Emergency Detection System (EDS)

Similar to the Atlas/Mercury Program, the current Atlas V will require a system to detect imminent vehicle failures and to initiate an abort. An Emergency Detection System (EDS) has been conceived to accomplish this function by monitoring critical system parameters, detecting out of family conditions (or early indication of failure), placing the vehicle in the optimum state for safe capsule separation, and then allowing an abort capability that is optimal for the current situation. Key to this approach is that the EDS would not significantly change the proven Atlas V vehicle design.

The EDS would perform general data collection and telemetry functions, and would be flown on all Atlas missions to better characterize system performance. EDS would monitor key parameters and instrumentation in order to provide launch vehicle health status to the passenger capsule and to perform emergency detection of sensed or measured system failures. The EDS would be dual fault tolerant at the system level, meaning that the abort capability would be maintained in response to second failure within the EDS system.

Similar to the Atlas/Mercury Program experience, Atlas has performed a detailed fault coverage assessment that identified potential failure modes of Atlas/Centaur subsystems, and identified if the current design met requirements to fly commercial passengers, or if any design change was required. As part of the same analysis, safety critical failure modes were identified, along with the time for that failure to manifest itself in a catastrophic situation. Also identified were the primary measurements that would be monitored for those failure modes, and backup or corroborating measurements.

The Atlas launch vehicle currently incorporates some elements of an EDS. An engine health check is used to abort the liftoff if the RD-180 engine does not achieve the desired turbine pump speed at engine start. Atlas also incorporates a pogo detection algorithm that monitors acceleration, and if a threshold is exceeded, the engine is throttled down proportionally to the exceedance. The propellant utilization system commands are monitored, and mixture ratio valves are positioned at pre-determined angles to compensate if thresholds are exceeded. Lastly, the flight software incorporates a tumble check that delays spacecraft separation if the attitude or attitude rate thresholds are exceeded.

Clearly, the building blocks of an EDS system for Atlas are flying today. In keeping with the Atlas Human Rating philosophy, an upgraded EDS would be flown on *every* Atlas mission, thus subjecting it to proven design, test and validation processes, and providing vehicle and system characterization *before* the first passenger flight.

F. Ascent Survival Modes and Acceleration Limits

A launch escape system, such as the type built for Apollo and Soyuz, can remove astronauts from the vicinity of a failing rocket during ascent. This reduces the threat from explosive blast waves or fragments. However, under some conditions the subsequent reentry from this ascent abort can be too fast or too steep. In these cases the passenger vehicle reaches the lower, denser atmosphere while still at high velocity, causing rapid deceleration and high dynamic pressure and heat rates. These steep reentries may exceed human tolerance for acceleration or violate vehicle design constraints for structural loads or heat rate. The periods during nominal ascent when an abort would be unsafe are called “black zones.” These black zones must be identified and then minimized or eliminated in order to launch passengers safely.

Black zones are strongly influenced by the shape of the launch vehicle’s trajectory. In the event of an abort, the passenger vehicle will continue on a ballistic trajectory up to an apogee altitude determined by the instantaneous velocity, altitude, and flight path angle (the angle of the velocity vector above the horizontal) of the nominal launch trajectory at the time of the abort. It will then fall back to Earth, entering the upper atmosphere at an angle which is likewise determined by the velocity vector at the start of the abort. During the beginning of the ascent, the speed and altitude are low and slow enough that an abort would not result in high g deceleration. During the final portion of ascent, the vehicle velocity and altitude are very high, but because it is at near-orbital speed it would reenter at a very shallow angle, allowing it to decelerate more gradually in the thin upper atmosphere. Black zones typically occur during the middle of the ascent timeline, when the vehicle is high and fast enough for reentry to be dangerous, but not yet fast enough to enable a flattened reentry trajectory. Lofted trajectories – those which climb higher early in flight – generally have worse black zones than depressed trajectories. To use a diving metaphor, the trajectory must be re-shaped to change a belly flop off a high diving board into a racing dive from a low platform. Trajectory lofting is frequently associated with vehicles which have a low upper stage thrust to weight ratio (T/W). Black zones are also typically longer and more severe for passenger vehicles such as capsules which have low lift to drag ratios (L/D). In contrast, winged vehicles have higher L/D and can use their lift to stay higher in thinner air longer and decelerate more gradually.

Lockheed Martin developed methods for analyzing and eliminating black zones during the Orbital Space Plane program, and has studied black zones extensively for several manned spacecraft and a wide variety of launch vehicles from different manufacturers. Past studies of Atlas concluded that it is easy to eliminate black zones when using the Dual Engine Centaur (DEC), especially for launches on larger versions of the Atlas V, such as the HLV and Atlas 552. These vehicles achieve high staging velocity with the Common Core Booster before the lower-thrust Centaur takes over, and the twin engines on the Dual Engine Centaur provide reasonable thrust to weight. However, studies of commercial passenger systems pointed to the Atlas V 401 as a preferred launch vehicle because it is the simplest configuration in the Atlas V family, and therefore the lowest cost and most reliable. With its low staging velocity and single RL10 engine, eliminating black zones from the Atlas V 401 trajectory is much more challenging. Therefore, special effort was put into validating the feasibility of safe passenger launches on the Atlas 401.

Lockheed Martin’s method for analyzing black zones involves generating thousands of abort trajectories for the passenger vehicle under consideration, starting from a wide range of initial velocity, altitude, and flight path angle conditions. Each of these trajectories is analyzed to determine the g load vs duration and margin or lack of margin against the human factors requirement. Peak dynamic pressure and heat rate are also recorded. These data are then processed to create lookup tables which indicate the abort g load margin for any set of initial conditions. A trajectory program such as POST II (Program to Optimize Simulated Trajectories) can then use these lookup tables to instantly determine the g load, dynamic pressure, and heat rate that would result from an abort at any time during a simulated ascent trajectory, without re-running the abort trajectories themselves. This enables the trajectory designer to rapidly identify problems and to apply abort environments as constraints which must be met by POST II in targeting and optimizing the trajectory. Once a suitable (or nearly suitable) trajectory is developed, the worst abort trajectories are simulated again to verify compliance, including factors for trajectory dispersions. Additional parameters, such as the seat angle, can be adjusted to fine tune the loads experienced by the passengers.

Figure 9 shows three steps in the development of a safe Atlas V 401 trajectory. The initial trajectory (shown as the upper red line) utilized a single-burn direct injection into the final target orbit of 264 nmi circular at 41 degrees inclination. This resulted in a lofted trajectory during the middle phase of flight, and a severe black zone. The second step (the middle blue line) shows a trajectory which used two-burn injection, with an elliptical transfer orbit between the burns. The thin lines in Figure 9 after 100 seconds indicate the beginning of the un-powered coast phase between the two burns. The final circularization burn could be performed either by restarting the Centaur upper stage, or by using the spacecraft’s onboard propulsion system. The two-burn trajectory greatly reduced the severity of the black zone, but did not eliminate it. For the third trajectory (the lowest green line), the steering was further adjusted to reshape the trajectory with a flatter initial rise which fully closed the black zone. The perigee altitude was also raised to meet launch vehicle ascent trajectory design criteria for dynamic pressure and heating. There is a moderate performance penalty (on the order of 5-10%) associated with the trajectory adjustments required to eliminate the black zone, but the Atlas V 401 can still deliver in excess of 20,000 lbs to the targeted elliptical transfer orbit.

In the absence of an accepted commercial or FAA standard for passenger abort g loads, requirements from NASA-STD-3000 "Man-Systems Integration Standards" have been used. These standards do not provide a single value of acceleration, but rather a curve (shown in red in Figure 10) which defines combinations of acceleration and duration. High accelerations can be tolerated for short periods of time, while longer durations require lower accelerations. It is also important to note that for rare emergencies such as abort reentry, the allowable acceleration limits are higher than for routine flight. Figure 10 shows the acceleration vs time curve for an abort at the worst time during the ascent trajectory. It meets the requirement with 10% margin. If the abort were to occur earlier or later in flight, the margin would be even larger.

Since trajectories with tolerable abort environments have been developed for the most challenging scenario, – an Atlas V 401 with a low L/D passenger capsule – and since previous analyses have indicated similar successful results for several other Atlas configurations, it is expected that safe trajectories are feasible for most types of passenger vehicles on most Atlas configurations going to most LEO orbits. Additional analysis can be performed on a case-by-case basis for potential customers.

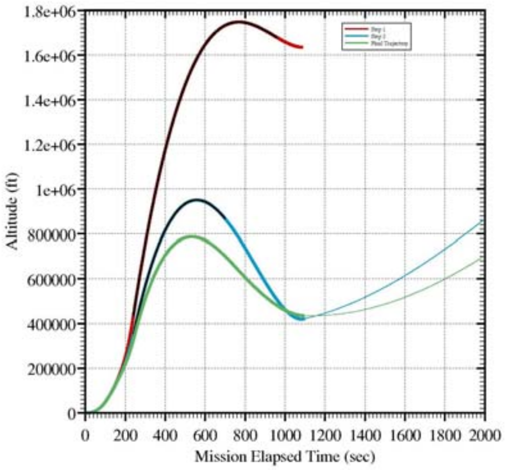

Figure 9. Three Iterations of the Atlas V 401 Trajectory Design, with Black Zones Indicated. The Final (Green) Trajectory has No Black Zone and is Safe for Passengers.

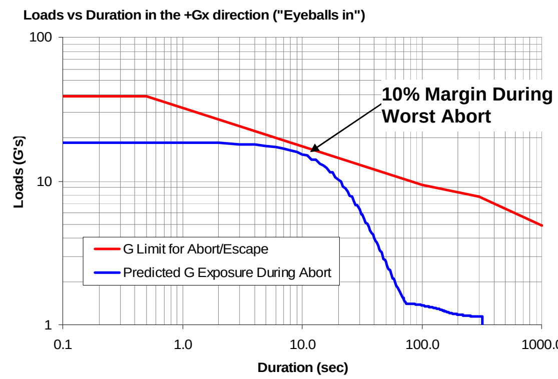

Figure 10. Atlas V 401 Trajectory Meets Loads vs Duration Limit for Emergency Conditions.

V. Summary

Providing safe, reliable and robust Earth to Orbit transportation is critical for the success of the emerging orbital space tourism market. Atlas is the only existing launch vehicle that meets or exceeds the identified Specifications, Standards, Handbooks, FAA and NASA requirements for providing commercial passenger transportation. An Atlas 401 vehicle is uniquely suited for commercial passenger missions as it is a flight proven system, including the highly reliable and robust RD-180 and RL10 propulsion systems. The Atlas currently has flown 79 consecutive successful missions, including 8 Atlas V's, providing an unparalleled demonstrated history of successful launches. The Atlas 401 is the simplest, most reliable launch vehicle system currently available to safely fly a commercial passenger vehicle to LEO.

References

[1]Bonesteel, H.M., ""Manrating" Atlas ICBM for Mercury," Human Rating Workshop, November 19 – 22, 1991, hosted by the NASA/JSC Systems Engineering Division