Testing Strategies and Methodologies for the Max Launch Abort System

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ABSTRACT

The National Aeronautics and Space Administration (NASA) Engineering and Safety Center (NESC) was tasked to develop an alternate, tower-less launch abort system (LAS) as risk mitigation for the Orion Project. The successful pad abort flight demonstration test in July 2009 of the "Max" launch abort system (MLAS) provided data critical to the design of future LASs, while demonstrating the Agency's ability to rapidly design, build and fly full-scale hardware at minimal cost in a "virtual" work environment.

Limited funding and an aggressive schedule presented a challenge for testing of the complex MLAS system. The successful pad abort flight demonstration test was attributed to the project's systems engineering and integration process, which included: a concise definition of, and an adherence to, flight test objectives; a solid operational concept; well defined performance requirements, and a test program tailored to reducing the highest flight test risks. The testing ranged from wind tunnel validation of computational fluid dynamic simulations to component ground tests of the highest risk subsystems. This paper provides an overview of the testing/risk management approach and methodologies used to understand and reduce the areas of highest risk — resulting in a successful flight demonstration test.

KEY WORDS: Testing, risk management, flight test, launch abort systems

MLAS PROJECT OVERVIEW

NASA's next generation crewed spacecraft, named Orion, is a part of the overall Constellation Program. The baseline Orion design includes a launch abort system (LAS) with tower, derived from the Apollo design. As a programmatic risk mitigation effort, the NASA Engineering and Safety Center (NESC) was tasked with designing, developing and demonstrating an alternate tower-less, statically stabilized LAS. The NESC developed the Max Launch Abort System (MLAS), named after Mercury-era engineer Maxime Faget, in less than 2 years. The successful MLAS pad abort flight test demonstration test on July 8, 2009 provided data critical to the design of future launch abort vehicles while demonstrating the Agency's ability to rapidly design, build, and fly full-scale hardware at minimal cost in a "virtual" work environment (MLAS Final Report, 2011).

Prior to the Constellation Program setting the stage for the development of a new human-rated spacecraft to replace the retiring shuttle fleet, NASA's human spaceflight program had been in an operational phase for almost three decades. Noting that many of the NASA and contractor designers of NASA's prior spacecraft, including Mercury, Gemini, Apollo and the Space Shuttle were retired, the Agency's current ability to design and build a new spacecraft was debated. The MLAS Project was conducted off-line from the Constellation Program/Orion Project and represented a unique opportunity for the Agency to: 1) collect data to assist the Orion Project; 2) engage the next generation of spacecraft designers within the Agency in a meaningful, full lifecycle project; 3) develop the capability to perform fast-paced, concurrent build and test activities for human space flight hardware using virtual teams from across multiple Centers; and 4) give the Agency experience to again become “smart buyers” of future spacecraft.

Just as important as it was to demonstrate an alternative launch abort design was the need to obtain flight test data to assess performance, validate models/tools, and support the Orion Project’s LAS design in a timely manner. As such, the MLAS Project decided early on that higher risks would be accepted for the reward of early flight test data.

MLAS Level-1 Requirements

The Level-1 requirements for MLAS were divided into three main categories as follows:

Objective System Requirements:

> The MLAS Objective System was the conceptual design of a non-towered alternate LAS that could be flown on Orion and would meet all Orion launch abort requirements and scenarios (e.g., pad-abort, maximum drag, high altitude aborts, etc.). For the MLAS project, analysis was used to show that the Objective System would satisfy performance requirements for all launch abort scenarios. Any impacts to the Orion and Ares vehicles for a nominal launch were also analyzed.

Flight Test Requirements:

> The MLAS pad abort test was used to demonstrate several of the key elements of the Objective System design, most significantly statically-stable coasting flight. The MLAS flight test performance requirements were related to Orion pad-abort performance requirements for safe parachute recovery.
>
> The Objective System design would require a purpose-built fairing with side-mounted motors. These motors would also require thrust vector control. Due to the fast-paced nature of the MLAS project, development of these new designs was not practical. Existing rocket motors were used in an aft-mounted configuration to obtain the necessary flight conditions to test MLAS static stability during coast, reorientation and forward fairing/crew module (CM) separation. As such, the boost phase was not part of the demonstration. The MLAS flight demonstration was conducted from coast phase initiation through separation of the MLAS and delivery of the simulated Orion Crew Module to prescribed flight conditions.
>
> An important component of the flight demonstration test was collecting and analyzing the data needed to verify directly the performance of design tools and to directly support the development of the objective MLAS system.

Flights of Opportunity Requirements:

> Additional development and risk-reduction tests were considered on a case-by-case basis for "flight-of-opportunity" on the pad-abort flight test demonstration. These additional objectives were not considered a part of the critical path.

MLAS Flight Test Vehicle Overview and Operational Concept

The MLAS flight fest vehicle (FTV), as shown in Figure 1, consisted of four major components (excluding the ground segment components):

- Boost Skirt – The boost skirt held four solid rocket motors and was used to propel the FTV to the proper test conditions.
- Coast Skirt – The coast skirt served as the primary structure to stabilize passively the FTV during the coast phase.
- Crew Module Simulator – The CM simulator was a full-size boilerplate of the Orion CM and had the same overall mass as the Orion CM when MLAS development began.
- Forward Fairing – The forward fairing simulated the MLAS outer mold line (OML), provided the structural load interface between the fairing and crew module for coasting flight and reorientation, and contained the separation mechanisms to release the CM for parachute recovery.

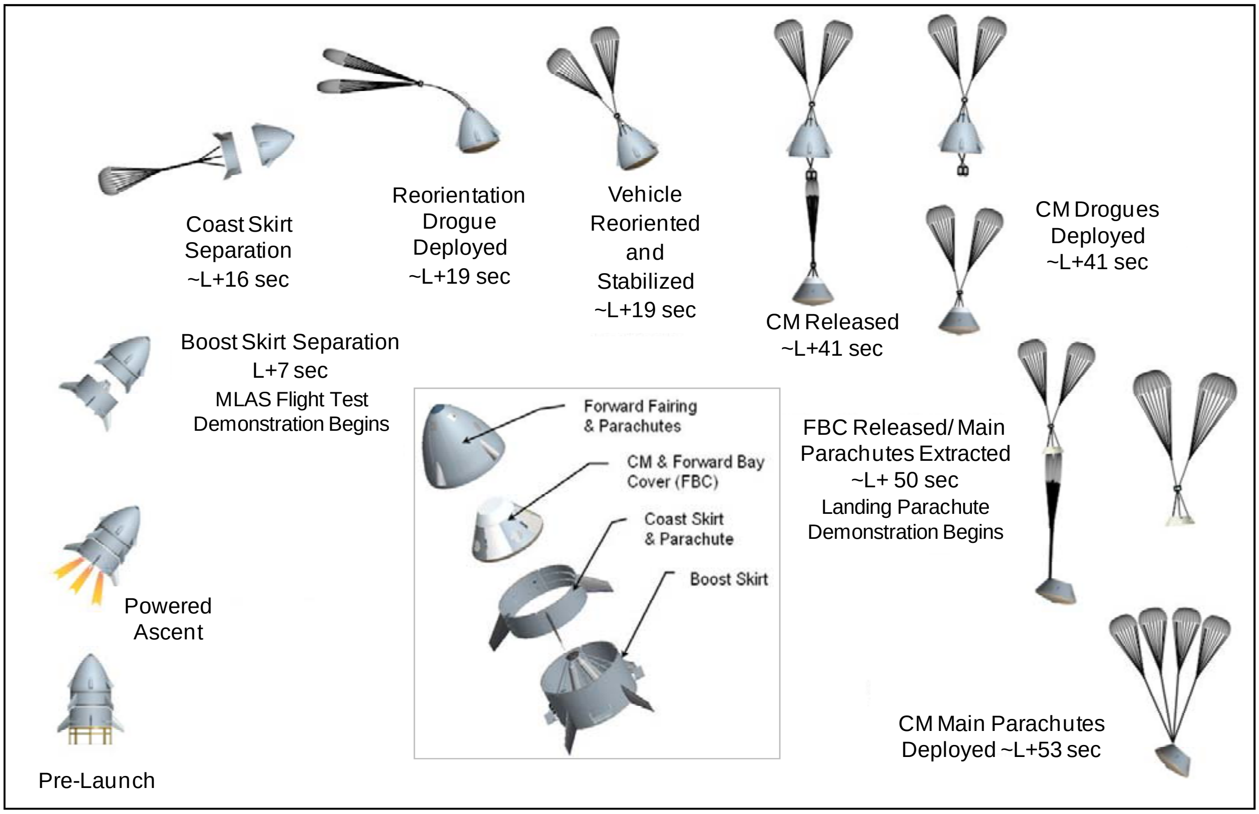


Figure 1: MLAS flight test operational concept.

The MLAS flight test concept of operations was structured to simulate a pad abort of the Orion CM from the Ares I launch vehicle. The test was divided into the major phases as outlined in Figure 1.

1) Powered Ascent – Lasts for six seconds and takes the vehicle to an altitude of about 2,200 feet.

2) Statically-Stable Coast – Begins when the spent boost skirt is discarded and takes the FTV toward an apogee of 5,800 feet.
3) Reorientation – The coast skirt is jettisoned when the dynamic pressure drops below 100 lb/ft^2 or the vertical velocity becomes negative. A drogue parachute speeds coast skirt separation. Three seconds after coast skirt separation, two drogue parachutes are deployed from the forward fairing to reorient the FTV and damp motions.
4) CM Separation – The CM is released from the forward fairing at 3,300 feet, within the conditions provided by the Orion LAS (attitude, rates, altitude and down range).
5) Main Parachute Deployment – After CM separation, two drogues are deployed from the CM to further stabilize and slow its descent. After nine seconds of descent, the four main parachutes are deployed using the CM's drogues and forward bay cover (FBC).

PROCESSES THAT DEFINED THE MLAS TEST PROGRAM

To complete the MLAS Project goals in the shortest amount of time, a rapid, concurrent design and build approach to the test article fabrication and assembly was adopted. The following management philosophies were adopted at the beginning of the project:

- Limit flight test objectives
- Establish an operational concept early
- Keep the one-off vehicle design as simple as possible
- Use conservative design margins and loads
- Streamline the systems engineering and management processes
- Maximize the use of off-the-shelf hardware and proven technologies
- Redundancy and fault tolerance provided only for system critical to meeting Level-1 requirements
- Design schedule prioritized by production and assembly sequence
- Leverage the skills and resources from across the Agency
- Seek input and guidance from experienced mentors and independent reviewers

Systems Engineering and Integration (SE&I) Approach

Even though this was an accelerated project, sound project management and systems engineering practices were still used and met the spirit and intent of NASA Systems Engineering Processes and Requirements (NASA Procedural Requirement 7123.1A, 2007). The project team was able to use a highly tailored systems engineering approach because 1) the MLAS Project was conducted off-line from the Orion Project, and 2) the FTV was uncrewed, proto-flight hardware, allowing project management to accept the higher risks associated with concurrent design, development and test, in return for a shorter project lifecycle.

The SE&I practices used were based on the following concepts:

- Systems thinking approach was everyone's responsibility
- SE&I team included the Safety and Mission Assurance representatives and a Mission Systems Engineer to lead design and trade studies
- Streamlined documentation and processes
- Utilized a 'Product Needs List' to track data deliverables between teams

- Tailored independent review process
- Streamlined configuration control process
- Safety process employed hazard analysis and risk management process without detailed failure modes and effects analysis
- Focused on developing collaborative team environment

An informal Systems Engineering Management Plan was established early in the project, and it served as a planning and communication tool for developing the final processes and documentation agreements. The processes and documentation agreements most important to MLAS testing strategy included:

Configuration Management and Control – At the beginning of the project, the team made the decision to streamline documentation by eliminating any boilerplate information and to rely on checklists if they provided the same information as a formal plan. As the project progressed, a number of formal documents were established and included requirements, interface control documents, design data book, flight test plan, operations plan and requirements verification. The configuration management processes documented in the MLAS Configuration Plan were balanced to enable a rapid prototype development project and meet the requirements in the NASA Configuration Management Standard (NASA-STD-0005, 2008) and others. Its functions were to establish the technical and associated programmatic baselines, control any necessary changes to the baselines, account for all baseline requirements, and assure those requirements had been verified as properly implemented and satisfied. Any unsatisfied requirements were noted and addressed in the Requirements Verification Matrix.

An MLAS Configuration Control Board (CCB) was established to be the authority for the project technical, cost and schedule baseline and to control engineering changes to the baseline. The MLAS Project Manager served as the MLAS CCB Chair, and the subsystem team leads and other representatives were members.

Risk Management Process – An important aspect of the MLAS SE&I approach was risk-based decision making. Each subsystem team identified their top risks, along with mitigation plans, early in the project and regularly updated the risk matrix. Each identified risk was quantified on the standard 5×5 matrix in terms of likelihood and consequence. Consequence was evaluated separately for cost, schedule, safety, performance, and priority. The SE&I team acted as the project risk manager by tracking project risks, but also identified system and project-level risks, or risks that crossed subsystems. The SE&I team also tracked each subsystem's progress in executing their mitigation plans and keeping a watch for where targeted tests on components or parts of a subsystem might have a large payoff in mitigating risk, or retiring it all together. Some risks were managed by the subsystem teams; others were managed at the project level. The risk information was updated and reviewed throughout the project's lifecycle and the team used the information in prioritizing work and developing testing plans.

MLAS Testing Approach

Because the MLAS flight test was a demonstration and off-line from the Orion Project, decisions on testing were based on a rapid prototype, higher risk tolerance philosophy. A two-step approach was used in determining where to invest in significant testing: 1) look for areas where a high risk was primarily due to reliance on new and unproven concepts; and 2) of those high risks, target those having a consequence of failure that was either loss of mission if occurring early in the flight or loss of mission objectives if occurring later in the flight.

A strong design and analysis approach, which applied significant conservatism in the FTV design, reduced or eliminated much of the traditional testing. In many cases, design margins were double or triple those typically used in operational spacecraft or launch vehicles. Analysis was performed with worst-case loads; proto-flight structural margins were used including additional uncertainty factors and aerodynamic uncertainties that were conservative because the uncertainties had not yet been reduced by extensive component or subsystem tests. This design and testing approach enabled the SE&I and subsystem teams to more readily identify testing requirements.

While each subsystem team attempted to build in sufficient margin to reduce testing, they also used testing as mitigation for lower margins if it was the most effective approach. When the SE&I team or a subsystem team believed test was the best method to sufficiently mitigate a risk with a reasonable cost and schedule impact, the test was planned and documented in the MLAS Integrated Test Plan. This test plan was developed to define all ground tests to be accomplished prior to the MLAS flight demonstration test. The document contained three sections: planned tests (critical test list), test flow, and other tests considered (to document the rationale for not performing certain tests). The team also focused on the MLAS test flight objectives when making decisions on testing, to minimize requirements creep.

SUMMARY OF MAJOR TESTS

Over the course of the project, testing of several new concepts and key components used in the MLAS design were placed on the critical test list. These tests were performed to either validate the concept or collect sufficient data to increase confidence that the concept had a high likelihood of functioning as intended and make corrections to reduce risk where possible. Tests were also conducted to better understand the probability of failure of commercial components. In every case, the test results were presented to the MLAS CCB to allow the project team to evaluate the results and concur that the concept or component should go forward to the flight test.

The testing effort concentrated on the following risk areas:

- Aerodynamic Design Methodology – There was a nearly complete reliance on computational fluid dynamics (CFD) to design an aerodynamically stable FTV during the boost and coast phases of flight
- Mass Properties Measurement – The trajectory design depended on knowledge of and locating the FTV center-of-gravity (c.g.) relative to the propulsion thrust vector, while still maintaining the FTV's aerodynamic stability, i.e., relative positioning of c.g. to the aerodynamic center-of-pressure

- Use of Commercial-off-the-Shelf (COTS) Instrumentation – Commercially available data collection instrumentation was considered for use in a high-vibration launch environment
- Reorientation and Separation Events – Reorientation and stabilization of the FTV using drogue parachutes, including passive separation of the CM from the forward fairing was a new concept
- Landing Parachute Demonstration (LPD) Drop Test – The CM main parachutes were to be deployed using a new deployment method for crewed vehicles
- Solid Rocket Motor Test – The selected motors were in excess of 20 years old and near the end of their certified life.

The major tests employed to reduce risk and/or validate the concepts are described below.

Aerodynamic Design Methodology Validation – The rapid-prototype nature of the flight test dictated that the aerodynamics design rely heavily on CFD models and handbook aerodynamics methods to conceptualize, estimate vehicle performance from boost through reorientation and finalize the FTV OML design. While this heavy reliance on CFD initially added risk to the MLAS Project, the approach enabled the MLAS team to rapidly cycle through a large number of concepts and arrive at a final OML design with predicted performance much faster than if they had conducted concept verification wind tunnel tests along the way. Thus, a draft aerodynamics performance database generated by CFD was developed for use by other subsystem designers very early in the design process.

Examples of several OML designs developed and evaluated with CFD are shown in Figure 2.

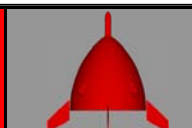
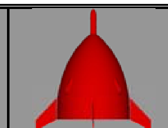
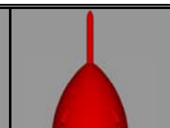
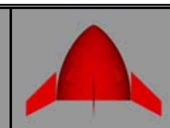
Coast Stability					
Configuration	D2-1A Short Fairing	D2-1A	D2-4A	D2-6A	D2-7

Figure 2: Examples of preliminary FTV shapes quickly evaluated with CFD.

With initial design completed, a series of wind tunnel test were conducted to 1) validate the CFD modeling results with actual test data, given to the unusual shape and stability requirements; 2) investigate reorienting the FTV using dual reorientation drogue parachutes; and 3) evaluate the separation aerodynamics, which were too complex to model in CFD in the allotted time. Wind tunnel models used during the tests are shown in Figure 3.

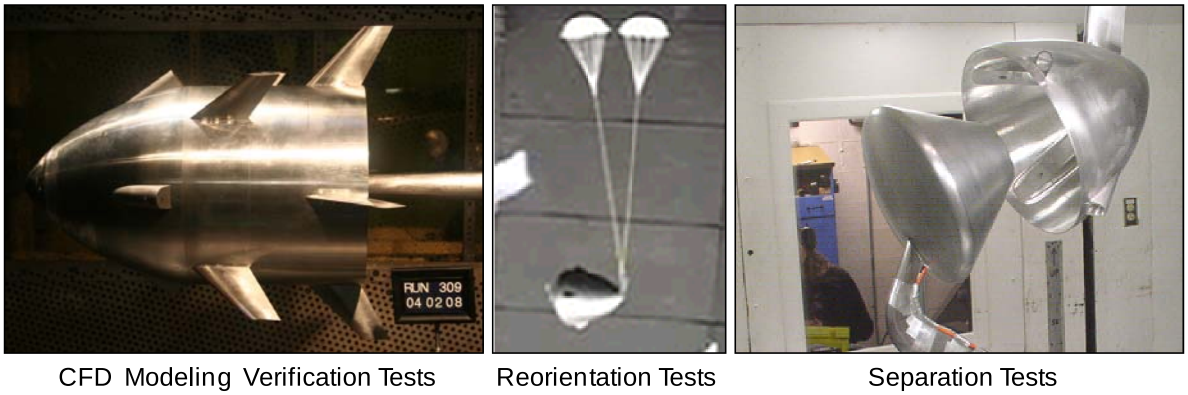


Figure 3: Wind tunnel models used to validate CFD results, reorientation and separation concepts.

Wind Tunnel Tests to Validate CFD Modeling Results – The first model, at far left of Figure 3, was used in the Calspan 8-foot Transonic Wind Tunnel to validate the CFD aerodynamic performance database. Tests were conducted of the FTV model in the boost, coast and reorientation configuration to collect aerodynamic pressures, forces and moments. A correlation effort of the wind tunnel test data to the CFD results showed the two datasets compared very well, as plotted in Figure 4, and that manufacturing of the FTV OML composite structure could begin. This agreement between the model and test data also allowed the MLAS team to continue to leverage CFD as a primary source for aerodynamic predictions, particularly as the FTV configuration evolved past the baseline tested in the wind tunnel as shown in Figure 5.

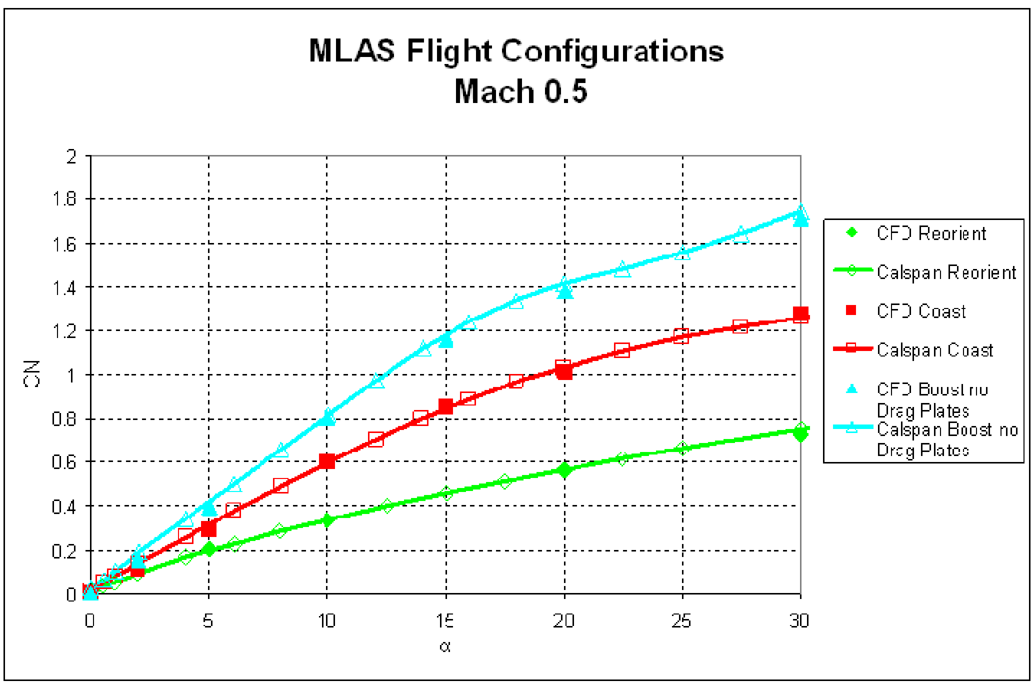


Figure 4: Sample CFD comparison with wind tunnel data at Mach 0.5.

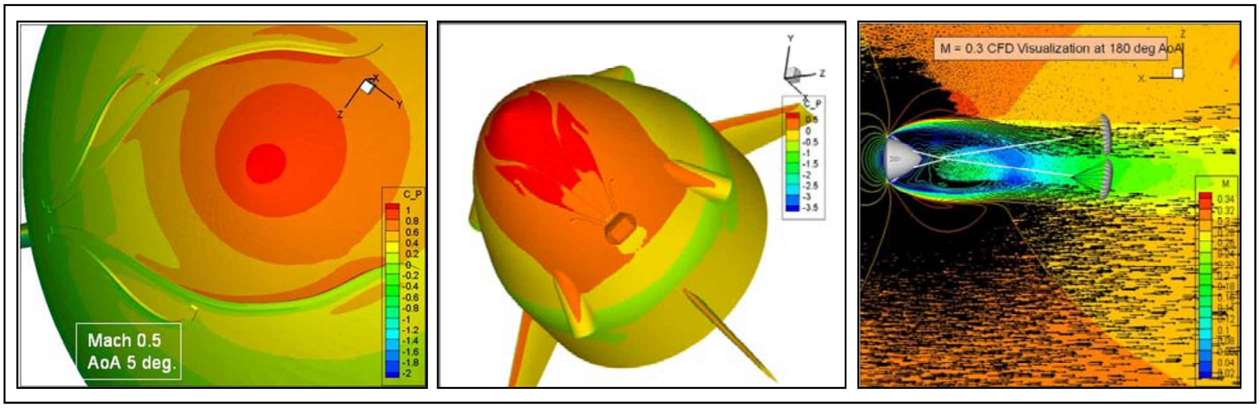


Figure 5: CFD investigation of aerodynamic effects due to changes in FTV OML.

The validated CFD models of Figure 5 were used to investigate the aerodynamic effects of the reorientation parachute harness routing on the OML and the parachute harness storage bay. The CFD model at the far right was used to visualize the wake behind the FTV in which the reorientation parachutes would deploy. The use of validated CFD was an important efficiency realized by the team and was central to managing cost and schedule by not having to conduct additional wind tunnel testing as the vehicle design evolved.

Reorientation Concept Validation Testing - A high-level validation of the reorientation concept was derived from using the model shown in the middle of Figure 3 in the NASA Langley Research Center Spin Tunnel. While only qualitative, the test did indicate that the proper amount of drag area was being deployed to reorient the FTV and dampen its motions in the required amount of time so that separation of the CM without detrimental recontact against the forward fairing could be achieved. Extraction of damping coefficients from the test data was attempted but eventually was abandoned for a number of reasons that indicated they would not scale to the FTV flight conditions.

Reorientation and Separation Concept Tests - The model shown on the right of Figure 3 was used in the University of Washington Aeronautical Laboratory Kirsten Wind Tunnel and provided critical insights and understanding into the relative behavior of the CM and forward fairing during the critical separation event. Data obtained from this test were used to increase the fidelity of an analytical model of the separation to bound the forces resulting from low pressure in the forward fairing that were predicted to slow the separation event. Results from the improved model and wind tunnel tests compelled the project to re-evaluate the separation concept because the data indicated the possibility of a separation retarding force sufficient enough to greatly lengthen the separation time, thereby reducing the altitude remaining after separation to successfully deployment of the CM parachute landing system. Additional analysis as a part of an independent peer review allowed the project to classify the risk of a slow separation as acceptable when traded against developing a new reorientation concept that would improve the separation time.

Mass Properties Model Verification Testing –Demonstrating an aerodynamically stable FTV during the boost and coast phases was a main pad abort flight test objective. Early analysis indicated that a "rule of thumb" static margin of 10 percent body diameter (difference between c.g. and aerodynamic center-of-pressure locations) would be sufficient to provide aerodynamic stability in the face of numerous perturbations to the FTV during flight. The static margin requirement drove the sizing of the eight identical fins and the development of a vehicle ballasting strategy to manage c.g. location to ensure static stability. Location of the c.g. relative to the propulsion thrust vector was the primary method used to design the flight test trajectory. A slight radial offset in c.g. was required to develop the turning moment needed to pitch the FTV to a down-range trajectory early in the six-second boost phase.

An analytical mass properties model, which tracked c.g. location, was developed early in the design phase and was continuously updated with actual component weights as they became available. In addition, two major mass properties test were conducted because the trajectory design relied on accurate knowledge of the FTV mass properties. The mass properties tests were conducted by making direct measurements of major FTV subassemblies and the fully assembled FTV vehicle. Measurements included weight, c.g. and radial moments of inertia. Various techniques were used to make the measurements, post-process the data, and assess the residual uncertainty in the measurements. The principles utilized for c.g. determination are shown in Figure 6 for a planar system and were extended for application to the three-dimensional FTV geometry.

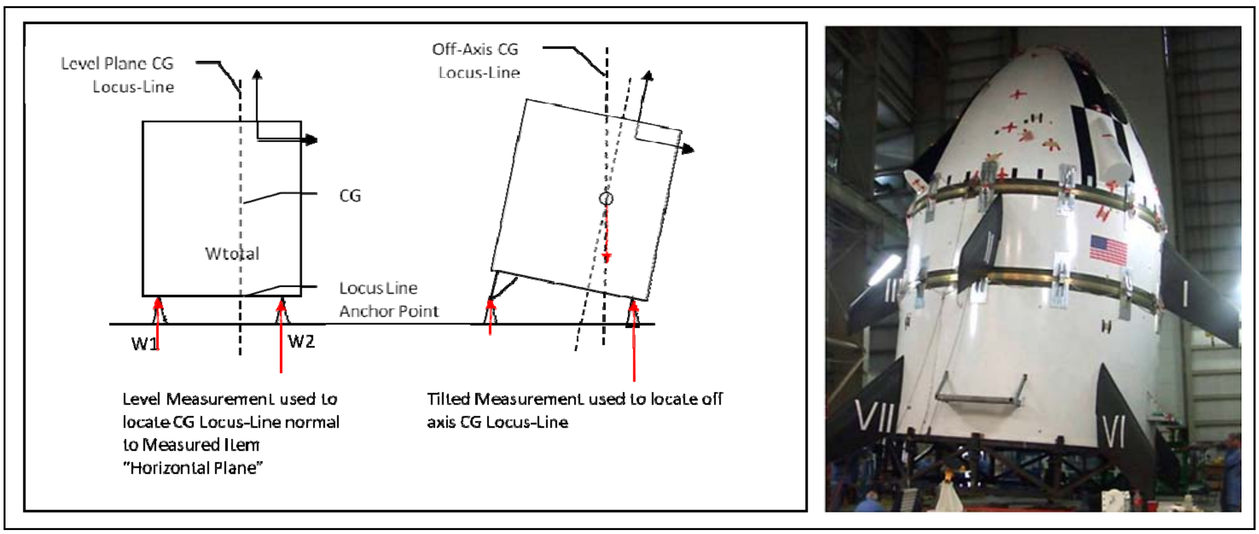


Figure 6: Principles of weight and c.g. measurement (left) and off-axis FTV axial c.g. measurement.

The component or full vehicle c.g. location was defined by the intersection of the level plane c.g. locus-line with the two orthogonal off-axis c.g. locus-lines as depicted in Figure 6. Weight and c.g. measurements generally correlated well with the analytical mass model.

The predicted ballast required to shape the flight trajectory were verified after the first mass property test. This was a critical milestone because no active control system was available during flight to correct the trajectory. Residual uncertainty in the modeling and tests ultimately resulted in a range safety required 4-degree tilt in the launch stand to ensure the FTV would fly away from range facilities. The second mass properties test was conducted on the fully assembled FTV, after which it was placed on a strict regimen of mass control. A mass log was established by SE&I and its use was maintained and enforced by the FTV integration manager and mass properties analyst.

Testing of COTS Instrumentation – The vibration levels during launch and the impulse during splashdown were significant design drivers for the instrumentation system and the avionics in general. An added difficulty regarding these design drivers was the concurrent nature of the development. Mechanical design of the avionics assemblies, including isolation devices, occurred simultaneously with the analysis required to predict the vibration levels. Several final vibration levels came late in the integration process, necessitating the acceptance of higher levels of risk than may otherwise be customary.

Vibration table testing was performed on all avionics and instrumentation to ensure operation during the flight test. An example of a key trade was to determine if the signal conditioners and amplifiers required for the various sensors should be purchased as COTS or designed specifically for the FTV flight environments. COTS instrumentation amplifiers were readily available for the strain gages located throughout the FTV structure and reorientation parachute harness load cells. The COTS strain gage amplifiers came sealed and could not be inspected for quality without destroying the unit. As vibration testing of the amplifiers progressed, numerous failures occurred, even after significant efforts to isolate the failures and improve the design and packaging. Eventually this COTS product was abandoned in favor of a proven in-house amplifier design. This decision created some delay in the avionics development schedule.

Ultimately, all sensors deemed critical to proving whether or not the key flight test objectives had been met used proven in-house amplifier designs that could survive the expected vibration environment. Some COTS components, like high-speed custom video recorders, were successfully repackaged and performed well. Had the development of vibration environments started earlier in the project, the conservative design factors initially applied to the vibration environments may have been reduced, thus allowing a wider use of COTS sensors and instrumentation.

Reorientation and Separation Events – Two key steps were involved in delivering the CM to the same safe CM recovery initialization conditions provided by the Orion LAS. First, dual drogue parachutes had to be deployed from the forward fairing along with the reorientation harness that fastened the drogues to the forward fairing. Second, the CM had to be separated from the forward fairing without detrimental recontact. Both events were identified as risks because they were unique concepts and systems without flight history.

A risk mitigation plan was developed for the reorientation event and called for a series of low-speed and high-speed ground deployment tests and a parachute mortar firing test to increase confidence in the drogue deployment and gain experience in rigging of the parachutes. Because the parachute rigging had also not been tried or tested previously, a full-scale mock up of the forward fairing was built at the parachute supplier’s facility to perform both the extraction tests and gain experience with the rigging. The mock-up is shown at lower left in Figure 7, the rigging in the middle photo and a drawing of the reorientation drogue harness legs in the right frame of Figure 7.

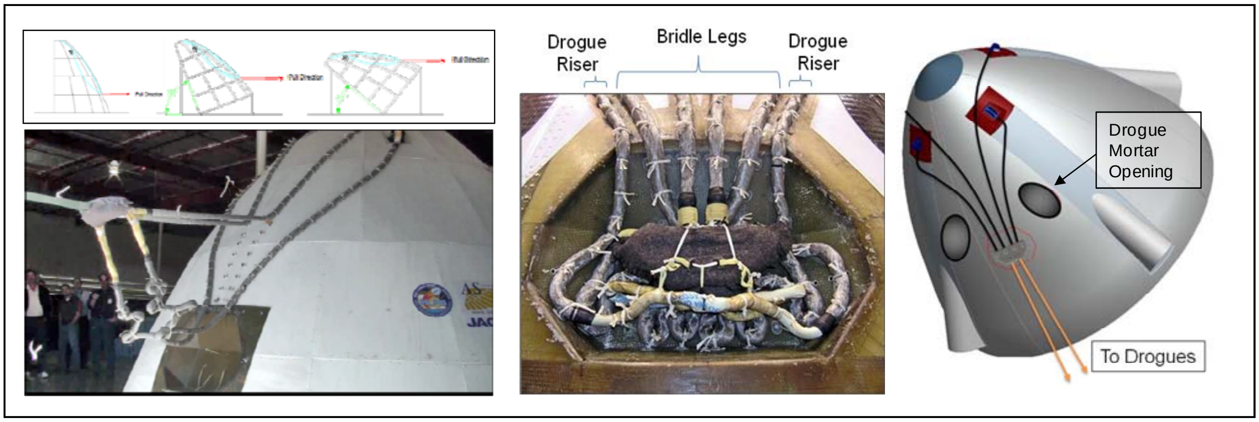


Figure 7: Full-scale mock-up of forward fairing used for reorientation harness deployment tests.

The reorientation and separation event testing programs can be summarized as follows:

- Low-Speed Extraction Tests – A limited test matrix was developed that enveloped the extremes of the FTV's predicted attitude at drogue deployment due to cost and schedule limitation. A design of experiments approach was used to help define the test matrix. To execute these tests, a pulling force was applied to the dual drogue riser ends indicated by the arrows in the upper left drawing of Figure 7 and the test was videotaped for analysis. After each test, the reorientation system was completely re-rigged. However, only one drogue riser was pulled to simulate the worst-case deployment conditions that occur when one parachute begins to pull before the other, creating imbalance that must be compensated for by the rigging. All tests were successful and increased confidence of a clean deployment without entanglements over the attitude extremes during the flight test. Minor changes were made to the rigging at the conclusion of the tests.

- High-Speed Extraction Tests – Only two extreme FTV attitudes were investigated, again due to cost and schedule restrictions. In these tests, an impulsive pulling force was applied to only one of the dual drogue riser ends. This simulated the initial force of a single parachutes reaching line stretch, just prior to parachute inflation, to test worst-case deployment conditions. If functioning properly, the rigging would deploy cleanly without entanglements or failures. Each test was recorded by a high-speed video camera to allow detailed analysis of the deployment as shown in the left photo of Figure 7. Both tests were completed and one test at a 10-degree angle of attack turned out to be almost identical to the flight test deployment conditions. Minor changes were made to the rigging due to minor surprises that materialized from these two valuable tests.

- Mortar Firing Test – It was felt that insufficient test data existed for firing of the MLAS drogue parachute through the 14-inch thick layer of foam and closeout tape used to preserve the FTV OML over the 18 × 30-inch mortar openings (refer to right drawing in Figure 7). This was an identified risk because the mortar openings on the FTV were already closed out with no test data to prove the parachute packs would penetrate the OML with no damage or loss of velocity. There was also interest by the parachute manufacturer in this test because at that time the Orion Project was considering deploying their CM drogue mortars through a thick layer of thermal protection material.

A test program was developed that would help gain confidence in the parachute deployment velocity and the mortar's ability to propel the parachute pack out to line stretch — a minimum success criteria for parachute deployment. A spare flight mortar was mounted in a section of scrapped forward fairing so that the OML closeout planned for the flight could be tested. To achieve the worst-case condition available on a ground test firing, the mortar was aimed vertical so that gravity would help to slow the parachute pack speed. High-speed video was successfully used to analyze the deployment as shown in Figure 8.

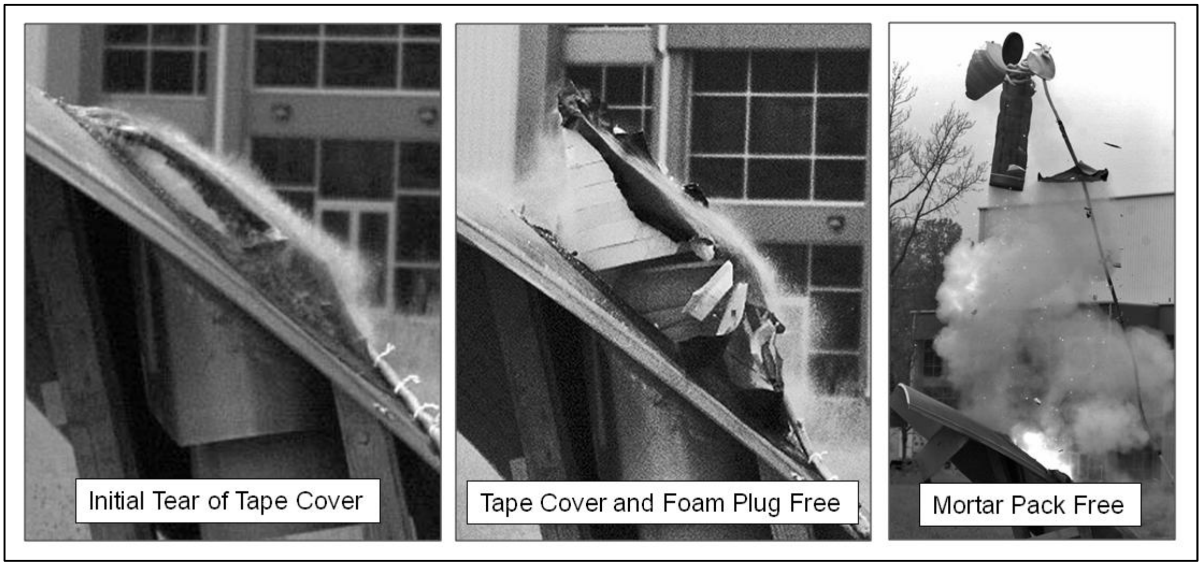


Figure 8: Reorientation drogue parachute mortar ground firing test through OML closeout.

This test allowed the parachute deployment models to be updated with measured initial parachute pack velocity after breaking through the OML close out. More importantly, the test indicated that the OML closeout would not prevent the parachute pack from reaching line stretch. No alterations were required to the existing OML mortar closeouts on the FTV.

- Separation Event Test - The separation event of the CM from the forward fairing was the subject of much analysis that was backed by limited wind tunnel testing as was discussed earlier. Data collected from the wind tunnel test was used to improve the analysis models and bound the low pressure force which, was expected to slow separation of the CM from the forward fairing. The test and analysis showed the reorientation parachutes created sufficient drag to ensure the separation event. The combination of the reorientation tests and the separation event tests in the wind tunnel revealed valuable data at minimum cost and schedule impact and reduced the estimated risk of this unproven concept to a level acceptable to the project.

Landing Parachute Demonstration (LPD) Drop Test – The highest risk event after separation of the CM from the forward fairing was considered to be the LPD. The LPD began as a flight of opportunity experiment on the MLAS. The LPD used the CM FBC and the CM drogues to simultaneously deploy the four main parachutes and achieve synchronous inflation with the goal of more consistent load sharing among the main parachutes. The LPD concept was part of the Orion CM baseline design when the MLAS Project started. Even though the deployment concept was used routinely to deploy the main recovery parachutes on the space shuttle solid rocket boosters, the MLAS Project required a full-scale drop test, shown in Figure 9, to prove the concept in this application and reduce risk. The consequences of an LPD failure on the flight test would include loss of mission-critical engineering data and video footage recorded on-board the CM. The LPD drop test was the most formal of the MLAS ground tests, requiring a detailed test plan in addition to the standard test readiness reviews. To preserve the project's flight test schedule, two identical flight test FBCs were designed, built and rigged simultaneously. One FBC was attached to a weight tub having a mass identical to that of the CM as shown in the left of Figure 9. The test article was dropped from a CH 53 helicopter and was allowed to descend on a single drogue parachute until reaching the dynamic pressure conditions predicted for the actual flight test. At that point, the weight tub was released from the FBC and the weight tub descended on the four main parachutes as shown on the right of Figure 9.

Figure 9: LPD drop test.

The successful drop test demonstrated that the main parachutes could open properly and withstand the loads imposed by the flight weight CM. Deployment conditions during the drop test occurred at nearly the upper bound in capability of the main parachutes. Some damage to the main parachute suspension lines were noted, which resulted in minor alterations to the parachute rigging in the remaining FBC. An additional benefit of the drop test was the lessons learned in capturing the real-time video of the dynamic events that were applied to the MLAS pad abort test flight.

In retrospect, significant cost savings were realized during the drop test from: 1) simultaneous development of identical configured FBCs; 2) use of a helicopter rather than the typical drop test cargo aircraft; and 3) use of the Wallops Flight Facility test range, which kept the drop test team and hardware co-located with the FTV and project team.

Solid Rocket Motor Test – The MLAS used four solid rocket motors obtained as surplus from the U.S. Navy Standard Missile Program. Historical performance data from the motors provided verification of their initial performance. Because the motors were at the end of their 20-year certification life, it was unknown if the historical performance data was still valid. A second inservice surveillance evaluation performed in 2008 certified the useful lifetime of the motors to 25 years.

Recertification testing was conducted by the Naval Weapons Center at Indian Head, Maryland as shown in Figure 10. The results indicated that the motors tested were still performing within original specifications. This test reduced the risk of using the historical performance data as direct inputs to the overall trajectory design and modeling effort.

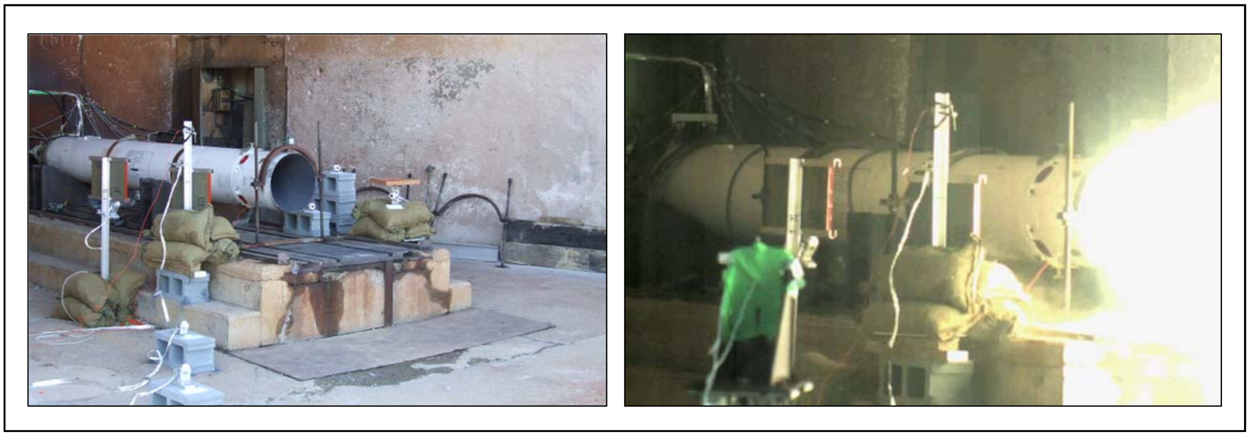


Figure 10: Static rocket motor firing to collected thrust, thermal, and acoustic data from similar age motor.

FLIGHT TEST RESULTS

Overall, the MLAS flight test was considered a resounding success. The FTV flew well within the predicted trajectory dispersions. Stability predictions made for the FTV through the use of CFD and validated through wind tunnel testing and mass properties testing correlated well with the actual flight test data. Aerodynamic pressure data were measured on the forward faring during flight and showed excellent agreement with the prefight CFD and wind tunnel data. Additionally, the CM successfully separated from the forward fairing with no significant delay between firing of the release mechanism and initial motion of the CM.

The two critical parachute events, reorientation and the LPD, were nominal and as predicted. Flight test data from on-board and ground high-speed video cameras allowed the parachute deployment events to be analyzed (Figures 11-13), with the results comparing well with the pre-flight predictions.

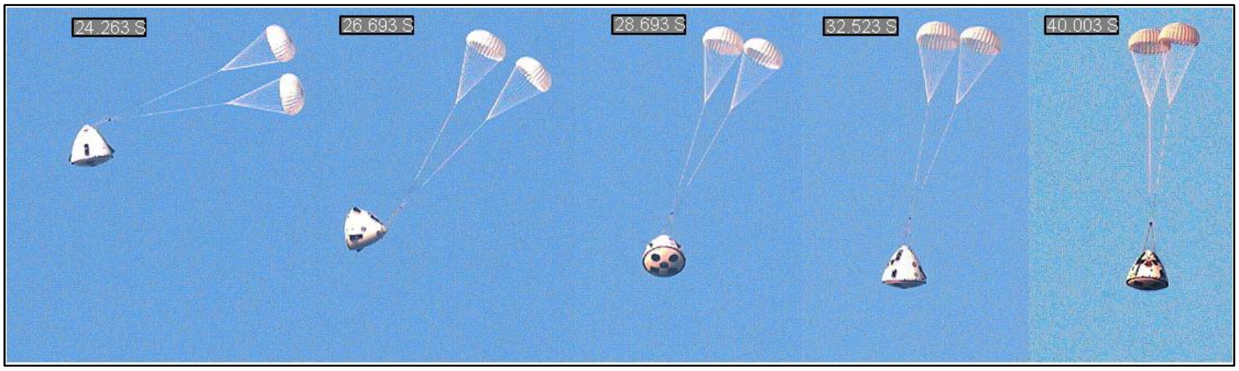


Figure 11: MLAS successful reorientation event.

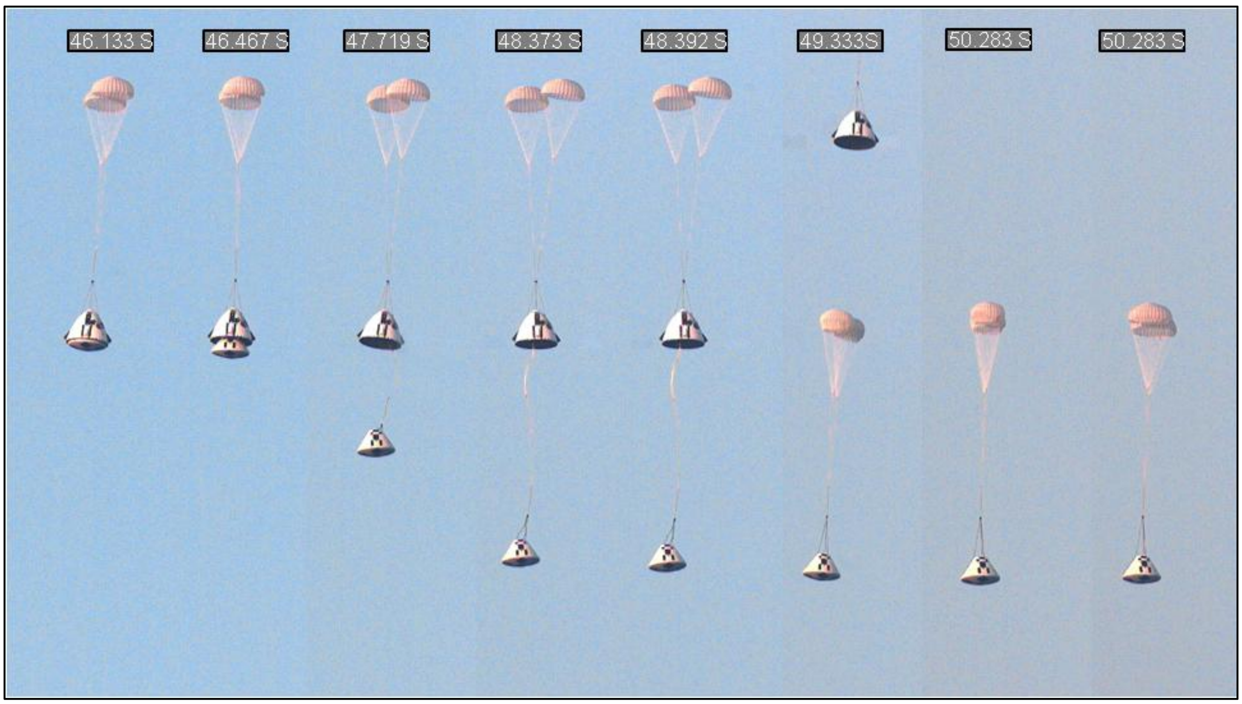


Figure 12: MLAS successful separation event.

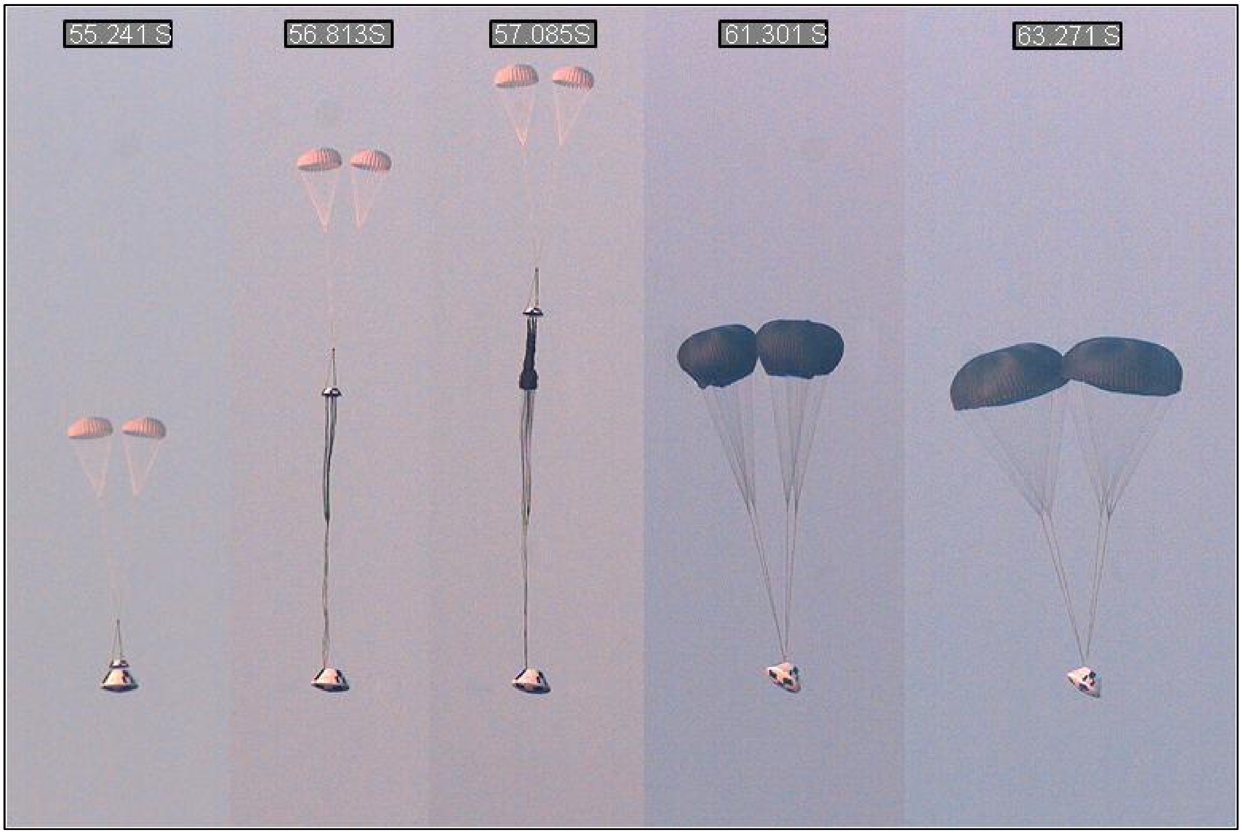


Figure 13: MLAS successful LPD.

CONCLUSIONS

The rapid-prototype, low-cost MLAS Project relied on conservative design margins and uncertainty factors to reduce or eliminate much of the testing typically required by a flight project. A targeted set of verification and validation tests were undertaken to reduce risk in the highest risk areas. The primary characteristics of the highest risk areas included unproven concepts with little or no flight data and mission critical events and subsystems.

In the end, the accepted risk to rely so heavily on CFD was appropriate as wind tunnel testing and ultimately flight data demonstrated that the computational methods provided a highly accurate picture of the vehicle performance. Additionally, both ground and drop tests verified unproven parachute deployment concepts and provided the MLAS Project with the confidence to fly the previously unproven deployment methods. The successful MLAS flight demonstration test on July 8, 2009 is providing data critical to the design of the Orion spacecraft and future LAS vehicles. Furthermore, it demonstrated the Agency's ability to rapidly design, build, and fly full-scale hardware at minimal cost in a "virtual" work environment.

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BIOGRAPHIES

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Ms. Dawn Schaible is currently the Manager of the Systems Engineering Office for the NASA Engineering and Safety Center (NESC) at the Langley Research Center. Ms. Schaible began her career with NASA at the Kennedy Space Center (KSC) in 1987, where she served as a Space Shuttle Orbiter Environmental Control and Life Support Systems (ECLSS) Engineer. In this role, she led the ECLSS ground processing activities for the Orbiter Endeavour. In 1996, Ms. Schaible joined the International Space Station (ISS) Hardware Integration Office, where she served as the Lead Test Engineer for the "Unity" Node and U.S. Laboratory "Destiny" modules. In 2000, Ms. Schaible was selected to serve as Chief, Integration Branch for the ISS/Payload Processing Directorate. Ms. Schaible completed the Systems Design and Management Program at the Massachusetts Institute of Technology, where she earned an M.S. degree in Engineering and Management. Ms. Schaible also holds a B.S. degree in Mechanical Engineering from Bradley University and a M.S. degree in Space Systems Operations from the Florida Institute of Technology.

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Mr. Daniel Yuchnovicz is currently a systems engineer in the Systems Engineering Office for the NASA Engineering and Safety Center (NESC) at the Langley Research Center. Mr. Yuchnovicz spent over 20 years as a systems engineer to the U.S. Department of Defense in the areas of data communications, simulation and avionics development and certification, and worked for companies including TRW, Unisys, Computer Sciences Corporation and RTI International. Mr. Yuchnovicz joined NASA in 2001 as a reliability and safety engineer and then joined the NESC in 2004 as a systems engineer. Mr. Yuchnovicz received the 1993 Computer Sciences Corporation Technical Excellence Award for Systems Integration and the NASA Exceptional Engineering Achievement Medal in 2010. Mr. Yuchnovicz holds a B.S. Degree in Electrical Engineering from Western Michigan University.