Orion Launch Abort System Jettison Motor Performance on Exploration Flight Test – 1

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This paper presents an overview of the flight test objectives and performance of the Orion Launch Abort System during Exploration Flight Test-1. Exploration Flight Test-1, the first flight test of the Orion spacecraft, was managed and led by the Orion prime contractor, Lockheed Martin, and launched atop a United Launch Alliance Delta IV Heavy rocket. This flight test was a two-orbit, high-apogee, high-energy entry, low-inclination test mission used to validate and test systems critical to crew safety. This test included the first flight test of the Launch Abort System performing Orion nominal flight mission critical objectives. Although the Orion Program has tested a number of the critical systems of the Orion spacecraft on the ground, the launch environment cannot be replicated completely on Earth. Data from this flight will be used to verify the function of the jettison motor to separate the Launch Abort System from the crew module so it can continue on with the mission. Selected Launch Abort System flight test data is presented and discussed in the paper. Through flight test data, Launch Abort System performance trends have been derived that will prove valuable to future flights as well as the manned space program.

Nomenclature

ACM	=	Attitude Control Motor
AM	=	Abort Motor
CM	=	Crew Module
DM-1	=	Development Motor Test 1
DM-2	=	Development Motor Test 2
DFI	=	Development Flight Instrumentation
DOF	=	Degrees of Freedom
ºF	=	degrees in Fahrenheit
ft	=	Feet
JM	=	Jettison Motor
JSC	=	Johnson Space Center
LaRC	=	Langley Research Center
LAS	=	Launch Abort System
LASO	=	Launch Abort System Office
LAV	=	Launch Abort Vehicle
lbf	=	Pounds Force

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LM	=	Lockheed Martin
MPCV	=	Multi-Purpose Crew Vehicle
MSFC	=	Marshall Space Flight Center
NASA	=	National Aeronautics and Space Administration
PMBT	=	Propellant Mean Bulk Temperature
SA	=	Spacecraft Adapter
SLS	=	Space Launch System

I. Introduction

NASA is developing technologies that will enable humans to explore new destinations in the solar system. In the future the Orion Multipurpose Crew Vehicle (MPCV) spacecraft, launched atop the Space Launch System (SLS) heavy-lift rocket, will send a new generation of astronauts beyond low-Earth orbit to places like an asteroid and eventually Mars.

The first flight test of the Orion spacecraft, Exploration Flight Test-1 (EFT-1), was conducted on December 5, 2014. EFT-1 helps NASA to meet the President's challenge to send humans to an asteroid in 2025 and Mars in the 2030s. This flight test was managed and led by the Orion prime contractor, Lockheed Martin, and launched atop a United Launch Alliance Delta IV Heavy rocket. This flight test was a two-orbit, high-apogee, high-energy entry, low-inclination test mission used to validate and test systems critical to crew safety. This test included the first flight test of the Launch Abort System preforming Orion nominal flight mission critical objectives. The Orion spacecraft is composed of four main elements: the Launch Abort System, the Crew Module, the Service Module, and the Spacecraft Adapter (Figure 1). The Launch Abort System (LAS) provides two functions; during nominal launches, the LAS provides protection for the Crew Module from atmospheric loads and heating during first stage flight and during emergencies, provides a reliable abort capability for aborts that occur within the atmosphere. The Crew Module (CM) is capable of transporting up to four crew members beyond low-Earth orbit, providing a safe habitat from launch through landing and recovery. The Service Module (SM) provides the propulsion, electrical power, and fluids storage capability for the Orion CM. Finally, the Spacecraft Adapter (SA) provides the structural transition between the SLS and the Orion spacecraft.

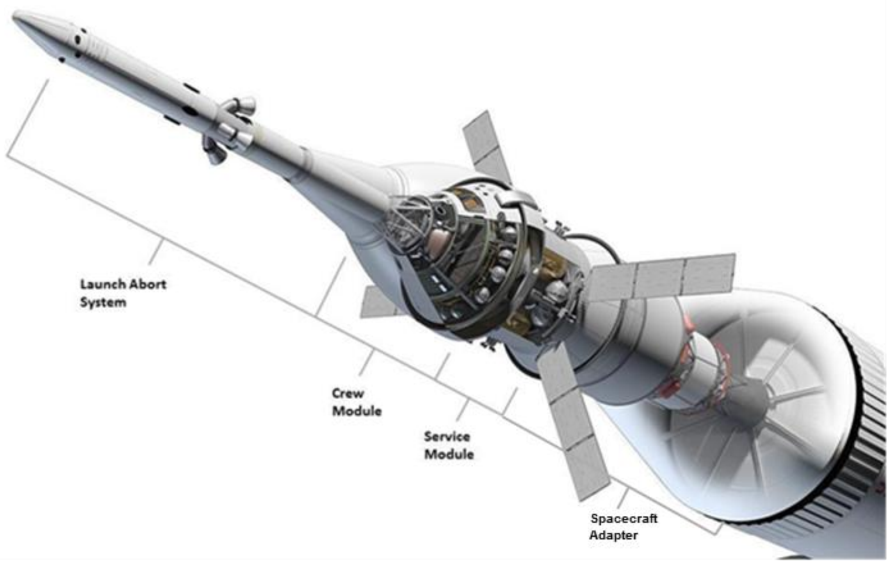

Figure 1. Orion Multi-Purpose Crew Vehicle.

II. ORION LAUNCH ABORT SYSTEM

A key feature of the Orion spacecraft design is the additional safety provided by the Orion LAS, which is mounted on top of the Orion CM. The combination of the LAS and the CM, defined as the Launch Abort Vehicle (LAV), would separate from the launch vehicle in the event of an emergency. The LAS provides a safe, dependable method of pulling the crew away from peril in the event of an emergency on the launch pad or during the ascent to Earth orbit.

The development of the Orion LAS is led by the Exploration and Flight Projects Directorate at the NASA Langley Research Center (LaRC) in Hampton, Virginia. The LAS Office (LASO) at NASA LaRC leads this effort on behalf of the Orion Project Office located at the NASA Johnson Space Center (JSC) in Houston, Texas. The NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama is a partner with LaRC in the development of the LAS. Lockheed-Martin (LM) is NASA's prime contractor for the design, development, testing, and construction of Orion, including the LAS.[1]

The LAS consists of several subsystems, three of which are solid rocket motors: the Abort Motor (AM), the Jettison Motor (JM), and the Attitude Control Motor (ACM). The primary non-propulsive subsystems of the LAS include the LAS fairing assembly, the aft interstage (AM/JM interstage), the forward interstage (JM/ACM interstage), and the nose cone. The LAS fairing consists of the fillet and ogive assemblies that protects the crew module from debris and the aero-thermal environment during ascent. Figure 2 shows an artist's rendition of the LAS, with each of the primary subsystems labeled. [1]

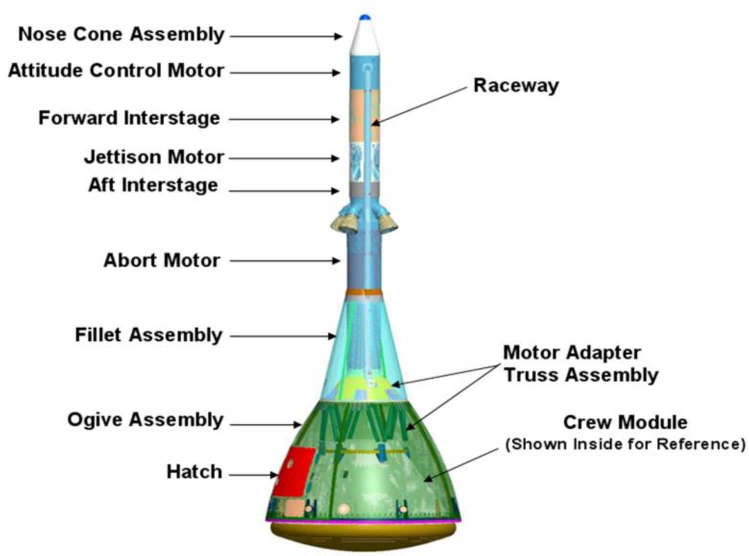

Figure 2. Launch Abort System and Crew Module.

The concept of operation and event sequencing during a LAS abort varies with altitude. An example LAS abort sequence of events is shown in Figure 3. Once an abort condition is detected, the abort motor and ACM are ignited. The LAS Abort Motor provides the primary propulsive force that is responsible for pulling the Orion CM away to safety. After the abort motor burns out (approximately 4 seconds), the vehicle continues on a controlled coast trajectory. The ACM provides steering and the control during abort motor operation and coast to maintain nose-forward flight. After the coast phase, the ACM provides the thrust force necessary to reorient the LAV in a heat-shield forward flight. While the LAV is in the heat-shield forward flight configuration, the LAS Jettison Motor is utilized to jettison the LAS, to allow CM free-flight or parachute deployment. [3]

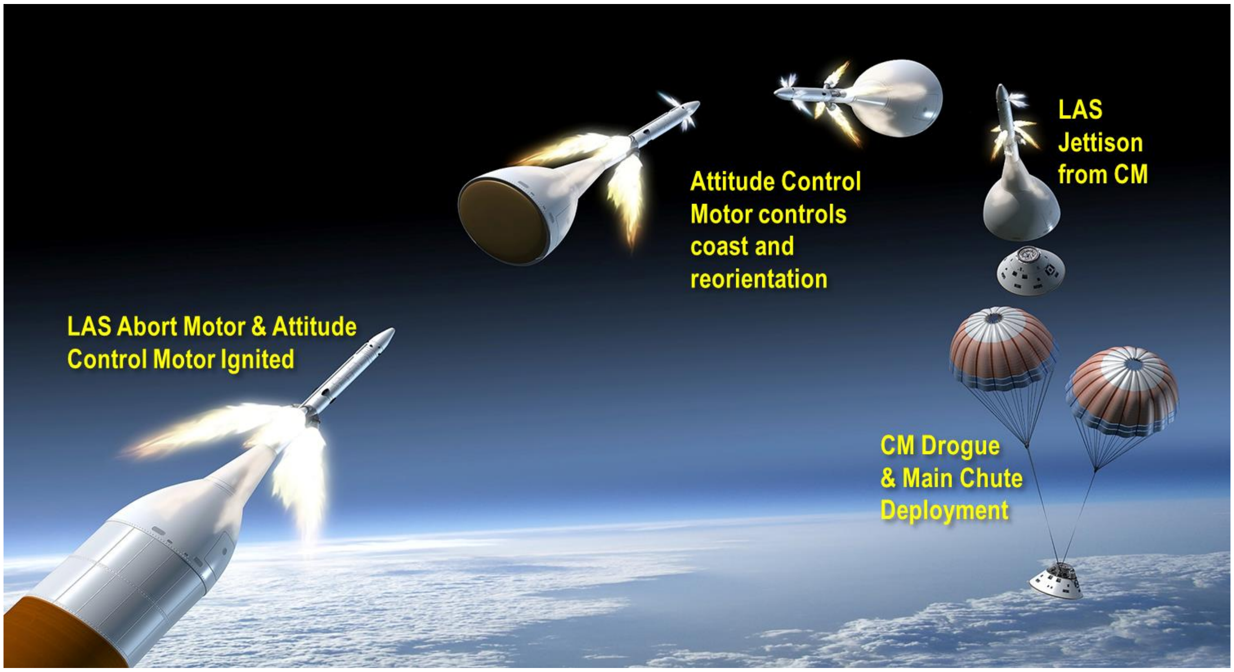

Figure 3. Example Launch Abort System Sequence of Events.

The LAS Jettison Motor is the only rocket motor of the three to be utilized on every flight, whether an aborted flight or a nominal flight. In the nominal flight scenario, the JM would be utilized to pull the LAS from the Orion. This nominal jettison of the LAS occurs approximately 30 seconds after booster separation on SLS during core stage operation..

III. EXPLORATION FLIGHT TEST -1

Orion's flight test, designated Exploration Flight Test-1 (EFT-1), was launched on December 5th atop a Delta IV Heavy rocket from Cape Canaveral Air Force Station's Space Launch Complex 37. During the two-orbit, 4.5-hour test, an un-crewed Orion traveled approximately 3,600 miles into space and reenter the atmosphere at speeds of 20,000 mph and experience temperatures of about 4,000 degrees F before splashing down in the Pacific Ocean about 600 miles southwest of San Diego (Figure 4). Orion's EFT-1 flight test was a crucial milestone in NASA's expedition to Mars. The test provided critical data needed to improve Orion's design and reduce risks to its future crews. The test stressed systems critical to safety, including the heat shield, parachutes, avionics and attitude control, to gain knowledge before Orion carries astronauts. The flight test sent Orion farther into space than any spacecraft designed for astronauts has gone in more than 40 years.

Figure 4. Exploration Flight Test – 1 Overview.

The distance Orion traveled on this test flight took it through the Van Allen Belts of heavy radiation that surround the Earth. The space station flies below the Van Allen Belts, inside the protection of Earth's magnetic field, so this will be the first time that a spacecraft built for humans has flown through the Van Allen Belts since the Apollo missions. The increased radiation tested the computers, particularly the processors, which have shrunk in size and are potentially more susceptible to effects from radiation.

Although the Orion Program has tested a number of the critical systems of the Orion spacecraft on the ground, the launch environment cannot be replicated completely on Earth. One of the key separation events tested during this flight was the nominal jettison of the LAS. For EFT-1, the LAS demonstrated functionality of the jettison motor to separate the LAS from the crew module so the CM can continue on with the mission (Figure 5). Only the jettison motor was active during the flight test.

The following sections will discuss the LAS jettison motor and analysis of the EFT-1 nominal jettison flight test results in more detail.

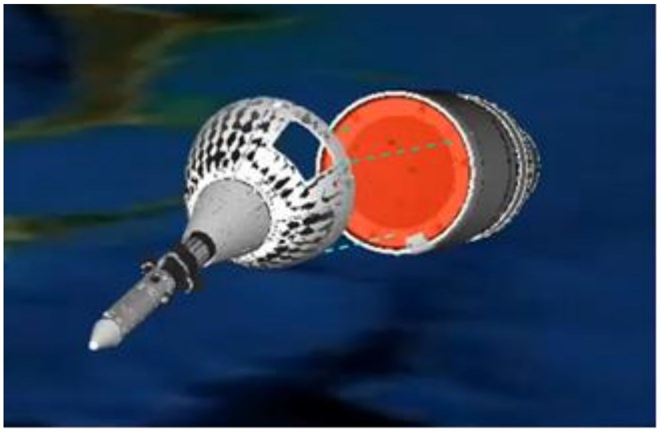

Figure 5. LAS Nominal Jettison during EFT-1.

IV. LAS JETTISON MOTOR

The LAS JM provides the thrust force required to jettison the LAS from the Orion CM, in both the abort scenario and the nominal flight scenario. In a nominal flight, the LAS JM was designed to provide the thrust required to jettison the LAS from the Orion CM, and this would occur while the SLS is ascending during core stage operation. The LAS JM is designed and manufactured by Aerojet Rocketdyne in Sacramento, California.

The LAS JM is a single solid rocket motor with an overall length of 59 inches and a case outside diameter of 32 inches. It has an architecture that includes four scarfed nozzles that are each canted 35 degrees from the primary axis of the LAS. The nominal thrust expected for the JM during EFT-1 was 46,000lbf. The JM architecture also includes three large nozzle throats and one small nozzle throat designed to offset the desired thrust vector of the overall motor to allow for adequate tip over rates. This design requirement was driven by the nominal flight scenario, to clear the LAS from the SLS flight path.

The LAS JM is a relatively high thrust motor for its short action time, a thrust profile which was driven by the requirement to quickly jettison the LAS from the Orion CM. The JM case and closure are both made of titanium. The shroud assembly is in a clamshell configuration with structural ribs, and is also made of titanium.

On May 6, 2010, the Orion program conducted a highly successful pad abort test, Pad Abort -1 (PA-1), at White Sands Missile Range in New Mexico. The JM performed as commanded. All PA-1 objectives were met. Figure 6 shows the JM separating the LAS from the CM, with the ACM commanded in a null thrust configuration at the top of the stack. There were two full scale JM static tests, or DM tests, prior to the PA-1 flight test, and the configuration of both the DM-1 and DM-2 were flight-like. The LAS DM-1 was static tested on March 27, 2008, and was tested at a nominal PMBT (~67˚F), without the shroud. [1] The LAS JM DM-2 was static tested on July 17, 2008, and was at a cold Propellant Mean Bulk Temperature (PMBT) (~21˚F). The JM DM-1 and DM-2 tests were both primary verification events for the LAS JM program, proving compliance with requirements. Both the DM-1 and DM-2 were static tested at Aerojet, in Sacramento, California. [2] Jettison Motor Development Test 2 is shown in Figure 7.).

Figure 6. Pad Abort-1 LAS Separation.

Figure 6. Pad Abort-1 LAS Separation.

Figure 7. Jettison Motor Development Test 2.

V. LAS Nominal Jettison Analysis

The LAS nominal jettison event on Exploration Flight Test-1 occurred at approximately six minutes and twenty seconds after liftoff and at approximately 600,000 ft. The Abort Motor and Attitude Control Motors were inert for EFT-1, since the mission did not require abort capabilities. A suite of developmental flight instrumentation (DFI) was included on the flight test to provide data on spacecraft subsystems and separation events. Data from this flight is being used to verify function of the jettison motor to separate the Launch Abort System from the crew module, assess the as-flown jettison motor thrust profile, and estimate LAS water impact location.

DFI measurements from the flight test being used to analyze the LAS nominal jettison separation event are relative motion measurements of the separation of the LAS from the upper stage, video of the LAS separation event, and LAS internal temperatures. Relative motion separation measurements were provided by lanyard extension displacement transducers (string pots). These sensors use a lanyard to turn a rotary potentiometer to measure extension of lanyard from lanyard drum. Three sting pots were located around the bottom of the LAS and provided relative separation measurements between the SM avionics ring and the bottom of the LAS fairing. The string pots had a maximum extension of approximately 84 inches. Video of the separation event was provided by a docking hatch window camera. Stills from the separation video are shown in Figure 8. Temperature sensors were located at a number of locations on the LAS and provided measurements prior to launch and during ascent. JM propellant mean bulk temperature (PMBT) was not directly measured. Internal LAS temperature measurements near the JM and on the JM case were constant at approximately 74 degrees F prior to launch.

A comparison of LAS jettison separation string pot flight test data to simulated LAS separation trajectories was conducted using the LAS nonlinear 6-Degree of Freedom (DOF) simulation tool. This simulation is implemented in POST2 and includes high-fidelity aerodynamic and JM motor thrust models, a GRAM atmosphere models, and an Oblate planet model. The Jettison Motor thrust model includes effects due to propellant mean bulk temperature (PMBT) variations and motor-to-motor and burn rate uncertainty. The simulation model was run with Day of Launch Mass Properties, estimated trajectory LAS Jettison initial conditions, and a constant JM PMBT equal to 74 degrees F. The JM motor model uncertainty inputs were varied to achieve a best fit least squares fit to the flight data. Best fit was at a JM model uncertainty value of approximately +1-sigma. A comparison of flight test and simulation analysis results is shown in Figure 9. As can be seen, the simulation to flight data match is very good and the results show the LAS jettison separation was consistent with pre-flight analysis.

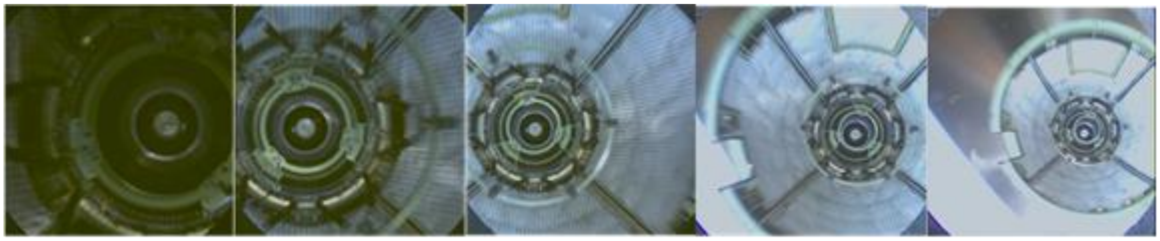

Figure 8. LAS Nominal Jettison – Stills From Separation Event Video.

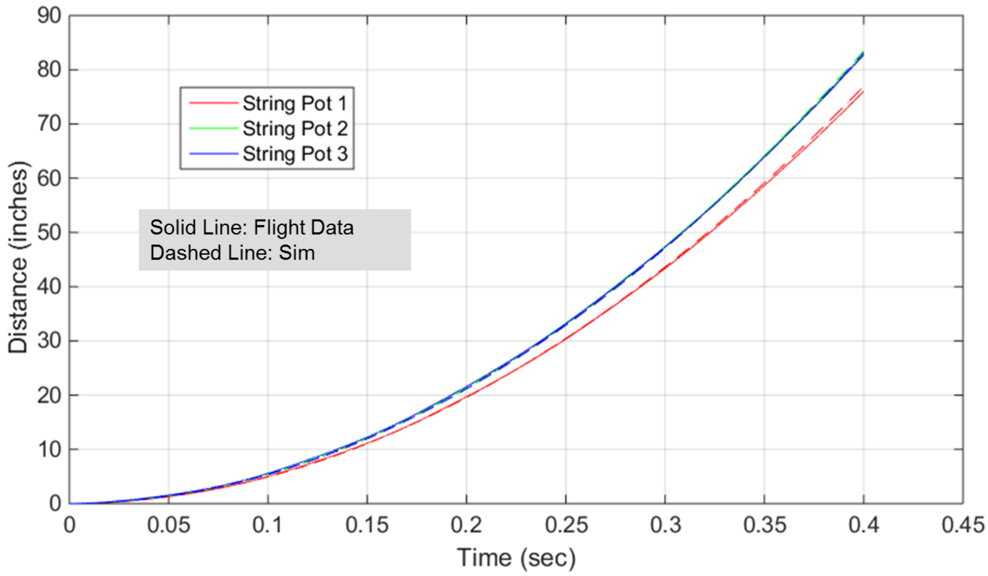

Figure 9. EFT-1 Nominal Jettison Relative Separation Data Versus Simulation Analysis Results.

During the EFT-1 flight, a key flight test objective for the LAS was to demonstrate successful LAS separation during nominal ascent. No LAS-to-CM or LAS-to-launch vehicle re-contact was detected by onboard accelerometer data. Post flight inspection of hardware, video surveillance, and data collected during flight, confirms that the LAS jettison met the EFT-1 flight test objectives.

VI. Conclusion

The Orion Multi-Purpose Crew Vehicle will serve as the nation's next generation exploration vehicle; capable of transporting astronauts on a variety of expeditions beyond low Earth orbit. The first flight test of the Orion spacecraft, Exploration Flight Test-1, was successfully conducted December 2014. This flight test was a two-orbit, high-apogee, high-energy entry, low-inclination test mission used to validate and test systems critical to crew safety. This test included the first flight test of the Launch Abort System preforming Orion nominal flight mission critical objectives. Data used from this flight demonstrated the function of the jettison motor to successfully separate the Launch Abort System from the crew module during a nominal ascent. A comparison of EFT-1 LAS jettison separation flight data with non-linear 6-Degree-of-Freedom trajectory simulation results show that the LAS jettison trajectory is consistent with pre-flight analysis. The trajectory analysis indicates that the jettison motor performance was slightly higher than predicted. Post flight inspection of hardware, video surveillance, and data collected during flight, confirms that the LAS jettison met the EFT-1 flight test objectives.

Acknowledgments

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