IAC-08-D2.6.7

ARES I-X FLIGHT TEST VEHICLE SIMILITUDE TO THE ARES I CREW LAUNCH VEHICLE

Lawrence D. Huebner
NASA Langley Research Center, USA
Lawrence.D.Huebner@nasa.gov

R. Marshall Smith
NASA Langley Research Center, USA
Marshall.Smith@nasa.gov

John R. Campbell, Jr.
NASA Marshall Space Flight Center
Ricky.Campbell@nasa.gov

Terry L. Taylor
NASA Marshall Space Flight Center
Terry.L.Taylor@nasa.gov

ABSTRACT

The Ares I-X Flight Test Vehicle is the first in a series of flight test vehicles that will take the Ares I Crew Launch Vehicle design from development to operational capability. The test flight is scheduled for April 2009, relatively early in the Ares I design process so that data obtained from the flight can impact the design of Ares I before its Critical Design Review. Because of the short time frame (relative to new launch vehicle development) before the Ares I-X flight, decisions about the flight test vehicle design had to be made in order to complete analysis and testing in time to manufacture the Ares I-X vehicle hardware elements. This paper describes the similarities and differences between the Ares I-X Flight Test Vehicle and the Ares I Crew Launch Vehicle. Areas of comparison include the outer mold line geometry, aerosciences, trajectory, structural modes, flight control architecture, separation sequence, and relevant element differences. Most of the outer mold line differences present between Ares I and Ares I-X are minor and will not have a significant effect on overall vehicle performance. The most significant impacts are related to the geometric differences in Orion Crew Exploration Vehicle at the forward end of the stack. These physical differences will cause differences in the flow physics in these areas. Even with these differences, the Ares I-X flight test is poised to meet all five primary objectives and six secondary objectives. Knowledge of what the Ares I-X flight test will provide in similitude to Ares I—as well as what the test will not provide—is important in the continued execution of the Ares I-X mission leading to its flight and the continued design and development of Ares I.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) has been carefully planning a series of test flights to ensure that the Constellation vehicles that are being developed are safe, affordable, and reliable. The first flight test for the Ares I Project, scheduled for April 2009, is the Ares I-X Flight Test Vehicle (FTV), an ascent development flight test that will acquire flight data early enough to impact the design and development of the Ares I. The primary stakeholder organizations within Constellation are the Orion Crew Exploration Vehicle Office at Johnson Space Center in Texas, the Ares Projects Office at Marshall Space Flight Center (MSFC) in Alabama, and the Ground Operations Office at Kennedy Space Center (KSC) in Florida. The Ares I-X FTV is being developed in accordance with the requirements set forth in the Ares I-X System Requirements Document,[1] which flow out of the Constellation Ares I-X Flight Test Plan.[2] The Ares I-X characteristics and performance are enough "like" the Ares I to meet the test flight objectives and provide significant data that will improve the Ares I design. This paper describes the similitude between the Ares I-X FTV and NASA's Constellation Program integrated launch vehicle comprising of the combined Orion/Launch Abort System (LAS) and Ares I Crew Launch Vehicle, hereafter called Ares I, and is a subset of the project similitude document.[3] Comparisons between the two vehicles are made addressing similarities and differences in Outer Mold Line (OML), aerosciences, trajectory, structural modes, flight control architecture, separation sequence, and relevant element differences. No discussion of similitude with ground systems and ground operations is provided.

DISCUSSION OF SIMILITUDE COMPARISONS

This section captures the particular Ares I quality or performance measure that Ares I-X is matching (or not matching) with Ares I. Items included are defined by an Ares I-X FTV requirements document and have the nature of making Ares I-X "like" Ares I. Similitude details describe the similarities and differences in and due to external configuration details, trajectory, structural bending modes, ascent flight control system architecture, separation, and relevant element differences.

<u>Top-Level Vehicle Comparison</u>

Figure 1 presents a top-level comparison of the elements between the Ares I-X and Ares I. Five major hardware elements comprise the Ares I-X. These include the First Stage (FS), the mass and OML simulators of the Upper Stage (US) and Crew Module (CM)/LAS, the Roll Control System (RoCS), and the avionics (parts of which are located throughout the vehicle). A team led out of the Langley Research Center in Virginia is responsible for executing the Systems Engineering and Integration function for Ares I-X. The launch vehicle elements for Ares I include the First Stage, Upper Stage, and Upper Stage Engine, that, along with the Vehicle Integration function (led at MSFC), provide the ascent requirements to place Orion into low Earth orbit.

<u>Comparison of Ascent Flight Scenarios</u>

It is important to understand the differences in the Ares I and Ares I-X ascent flight scenarios. The Ares I ascent flight scenario is shown in Figure 2. Ares I with the Orion Crew Exploration Vehicle is launched from Launch Complex 39B at KSC. Approximately two minutes after ignition, the FS

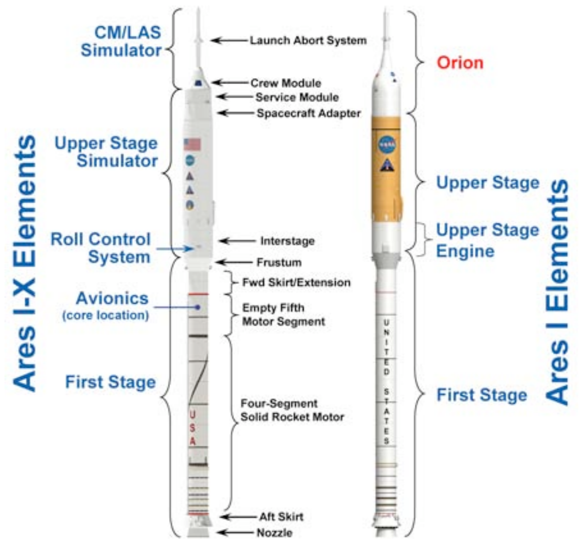

Figure 1. Ares I-X element comparison to Ares I.

Reusable Solid Rocket Motor (RSRM) burns out, and the FS and interstage are separated from the US. Following the staging event, the RSRM sheds the interstage and frustum combination and descends, splashing down in the Atlantic Ocean where it is recovered. Meanwhile, one second after staging, the J-2X Upper Stage Engine starts and fires for approximately eight minutes. Orion then separates from the spent US and continues toward low Earth orbit. The expendable US proceeds to breakup in the atmosphere during reentry and the surviving pieces descend and impact the Indian Ocean.

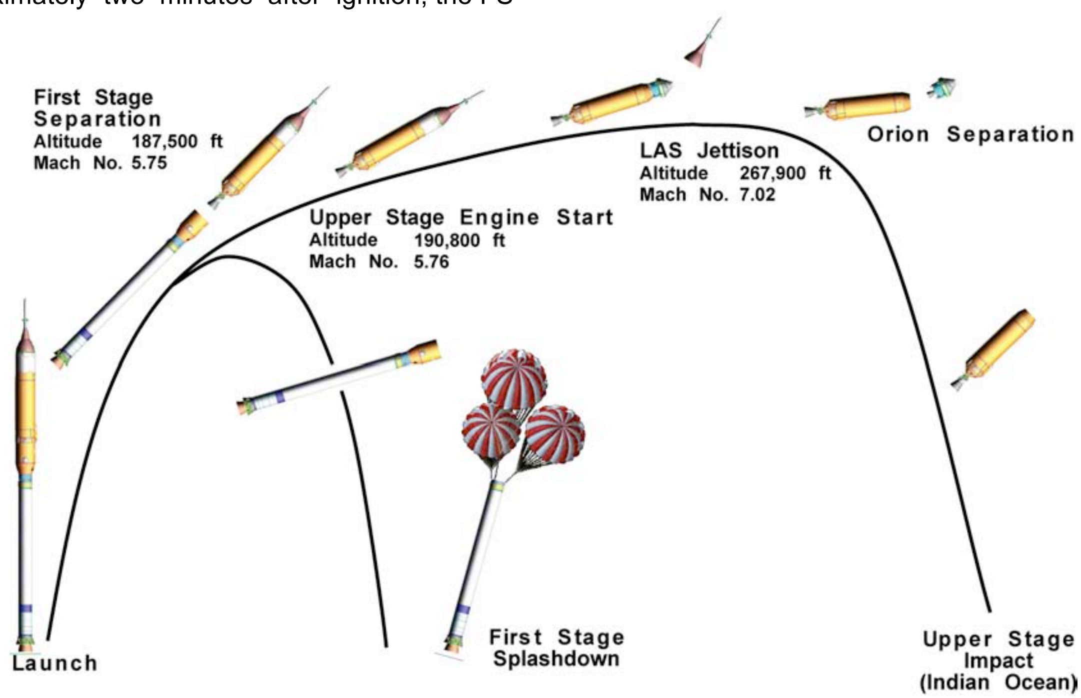

Figure 2. Ares I ascent flight scenario.

The Ares I-X flight, on the other hand, is a suborbital flight, and its ascent flight scenario is shown in Figure 3. Like Ares I, the FS fires for approximately two minutes prior to separation. The FS will then descend and splashdown in the Atlantic Ocean. Meanwhile, the simulator comprised of the CM/LAS, the Upper Stage Simulator (USS), the interstage, and the FS frustum continues in an uncontrolled, ballistic trajectory until impact in the Atlantic Ocean farther downrange.

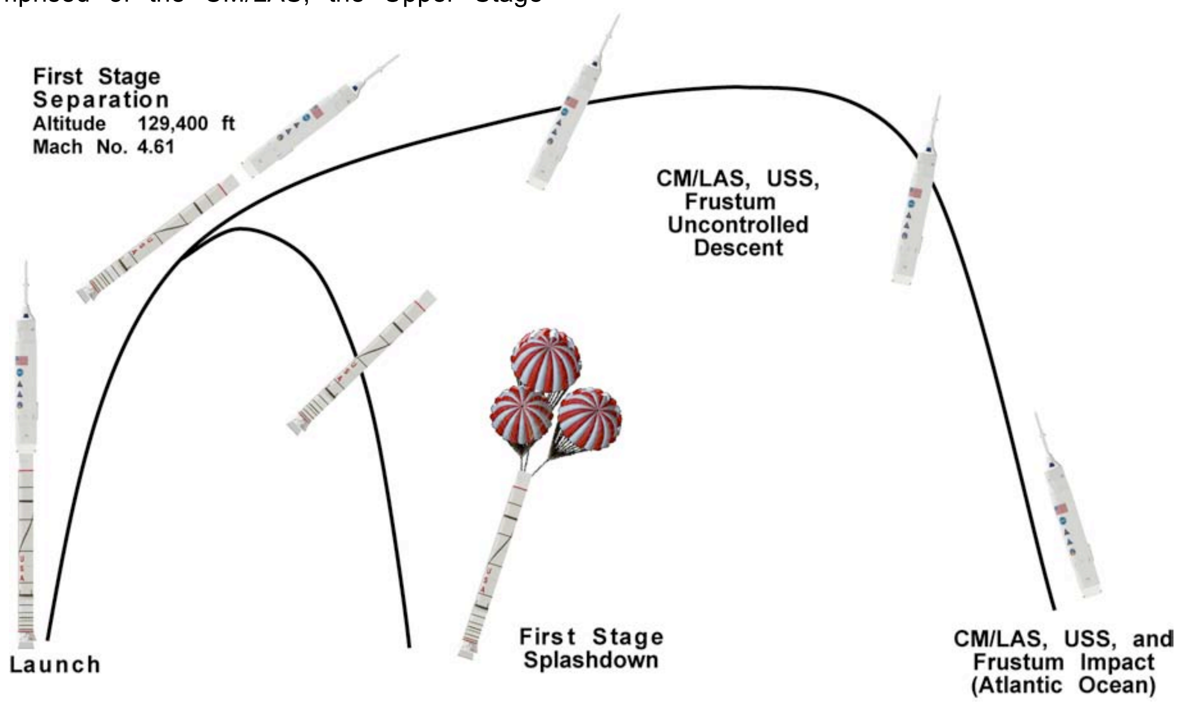

Figure 3. Ares I-X ascent flight scenario.

<u>Outer Mold Line Comparison</u>

The Ares I-X OML was to conform to the Ares I OML as closely as possible. Matching OML minimizes the differences on ascent due to aerodynamics, aeroelasticity, aeroacoustics, etc. Since the Ares I-X OML was "frozen" to allow analysis to be completed and fabrication to begin,[4] NASA is fully documenting the OML differences as the Ares I design continues to mature from the baseline that was used as a reference for Ares I-X. Most of the OML differences present between Ares I and Ares I-X are minor and will not have a significant effect on overall vehicle performance. The most significant impacts are related to geometric differences in Orion in the forward end of the stack that will cause differences in the flow physics in these areas.

Overall, the Ares I-X total length is slightly more than 26 inches longer than the current Ares I length. The differences are primarily due to changes in the Ares I LAS and US design, as well as a FS nozzle extension on Ares I-X that is shorter than what is expected for Ares I. Structural diameters for the US and FS aft skirt base are identical, and the FS diameter of the Ares I-X is nearly identical (differences due only to variations of 0.00 to 0.04 inches in the manufacturing of the five FS motor segments). As expected, with the FS nozzle extension length difference, the Ares I-X FS nozzle exit diameter is about 3 inches smaller. Ares I-X OML will exhibit external flanges (or simulations thereof) in corresponding locations to the height and thickness of exposed Ares I flanges. In particular, flanges located on the Ares I US will be replicated because they have an effect on the local buffet downstream of their locations.

<u>Orion/LAS</u>

The largest differences between the Ares I-X and Ares I OMLs are the changes to the LAS and Orion, as shown in Figure 4. The Ares I

OML design has an ogive fairing to shroud the CM and docking adapter with a fairing that extends to the base of the spacecraft adapter, eliminating one compressive surface (albeit small) from the Ares I configuration. Furthermore, the forward conical fairing extends farther up the LAS to minimize separated flow that can develop in regions of large geometric variation. The LAS has similar attributes between the two vehicles (lengths, location of abort motor nozzles, nose cone angle), but the design of the LAS has been refined for Ares I to include better fidelity of the abort motor nozzles.

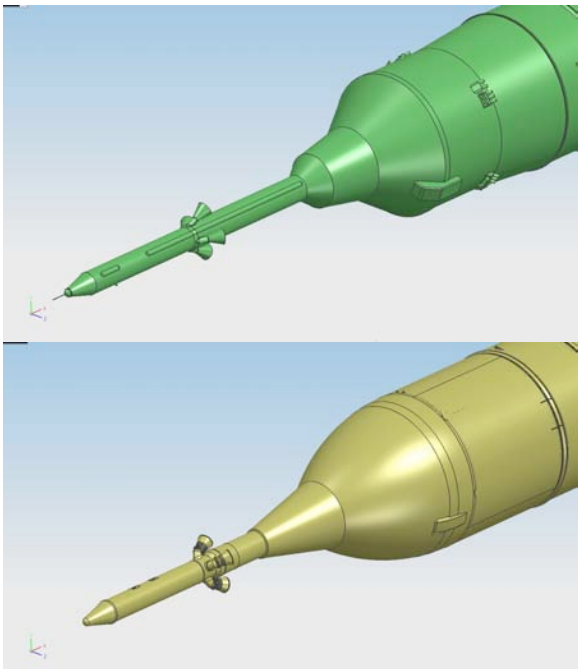

Figure 4. Comparison of Ares I-X (top) and Ares I (bottom) Launch Abort System and Orion Outer Mold Lines.

Protuberances

The initial intent was to model all of the Ares I protuberances on Ares I-X. As the design of the Ares I continued to mature following the establishment of the baseline Ares I-X OML, and as changes to Ares I-X matured, updates have been made to protuberances on both vehicles. Some of the Ares I protuberances that do not have significant flowfield effects are not incorporated on Ares I-X. For the LAS, the Ares I-X includes the following protuberances that are not part of the Ares I design: an air-data probe, angle-of-attack and angle-of-sideslip vanes (Figure 5), and a multi-part systems tunnel. As seen in Figure 4, the Service Module (SM) reaction control system nozzles are exposed for Ares I-X, but they are within the shroud of the ogive fairing for Ares I. While an umbilical fairing between the CM and SM are evident in both configurations, the Ares I design is now partially submerged in the shroud and is more aerodynamically favorable.

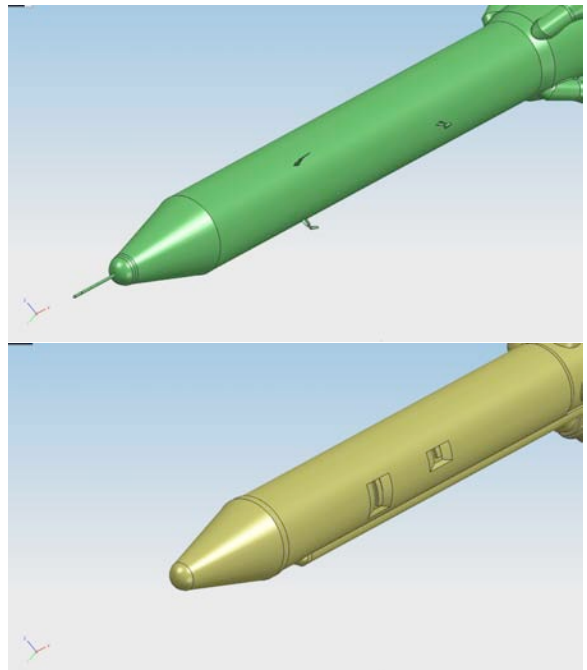

Figure 5. Comparison of Ares I-X (top) and Ares I (bottom) Launch Abort System tips.

Comparing the Ares I-X USS and the Ares I US (Figure 6), there are minor differences in the front fairing, height, and closeout of the US systems tunnel. The Ares I camera and antenna fairings on the Instrumentation Unit (IU) are both included on Ares I-X. For Ares I, the four pairs of ullage motors are now contained in fairings, and the US Reaction Control System and RoCS fairings for Ares I are more aerodynamically smooth compared to the flat ramp surfaces on the respective Ares I-X fairings. Furthermore, the Ares I-X RoCS OML was designed to house existing operational flight hardware that is different from the hardware in the Ares I RoCS design. For Ares I-X, a camera fairing is located just below the IU. Minor differences exist in the respective Liquid Hydrogen (LH_2) feedline fairings. The LH_2 fill-and-drain line fairing and the additional flange from the common bulkhead between the LH_2 and Liquid Oxygen tanks on Ares I were late additions to Ares I and are not represented on Ares I-X.

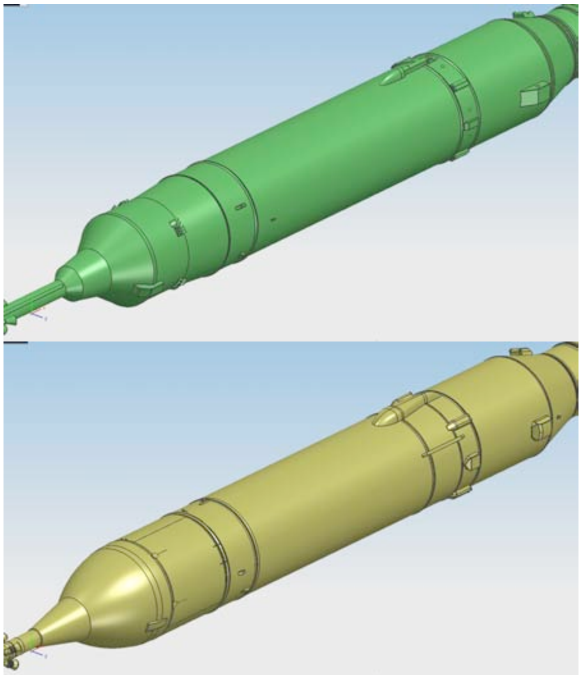

Figure 6. Upper Stage protuberance comparison (270ϒ deg clocking angle up), (Ares I-X, top).

On the FS frustum (Figure 7), Ares I-X includes a small fairing that houses an Ares I-X-specific camera that will provide visual data to be telemetered and recorded during ascent. Although the Ares I-X Booster Tumble Motors (BTMs) have been moved from the frustum to the FS aft skirt, simulated BTMs are incorporated on the Ares I-X OML, albeit slightly downstream from the current BTM location for Ares I. An additional dissimilarity that is found on Ares I-X is a small faring located just below the base of the frustum covering the linear shaped charge used for separation.

For its FS, Ares I-X will use an existing Shuttle four-segment RSRM that is partially capable of replicating the five-segment Ares I RSRM design. The functions of components in the region from the frustum through the forward FS segment are different in Ares I and Ares I-X. In Ares I, this area houses the forward propellant segment in the five-segment booster and the FS recovery systems. In Ares I-X, the forward segment replicates the OML of the five-segment booster forward segment and contains FS recovery systems as well. Additionally this region includes the First Stage Avionics Module (FSAM), which brings about a number of protuberance differences in this area. For example, near the top of the Ares I-X forward skirt extension, two mounting brackets are included for stabilization while on the pad. Just aft of one of the mounting brackets, another Ares I-X-specific camera fairing is seen. This camera faces forward and will be used just after the main separation event until splashdown to provide visual data for the events of FS recovery, supporting one of the Ares I-X objectives.

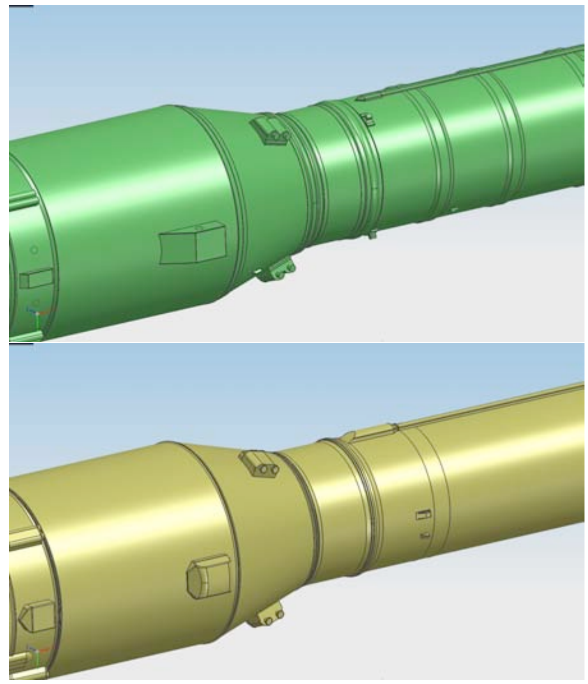

Figure 7. Interstage, frustum, and first stage protuberance comparison, (Ares I-X, top).

The FS aft skirt also has differences in protuberances (Figure 8) including a specific external camera fairing near the systems tunnel and just downstream of the aft-center to aft segment field joint. The camera housed within the fairing will be used for video recording of Ares I-X ascent and FS descent, which is also desirable to document in order to achieve the test flight objectives. The three stiffener rings, the kick ring, the rooster tail (just downstream of the systems tunnel on the aft skirt), and the hold-down post fairings (wedges) are all consistent between the two vehicles. The Ares I-X differs from the current Ares I in the aft skirt region with the inclusion of the live BTMs. The layout of the eight Booster Deceleration Motors (BDMs) for Ares I-X differs in two ways. First, they were limited to certain locations on the existing Shuttle solid rocket booster aft skirt to which they could be mounted. Second, Ares I recently increased the number of BDMs from eight to ten, as shown in Figure 8.

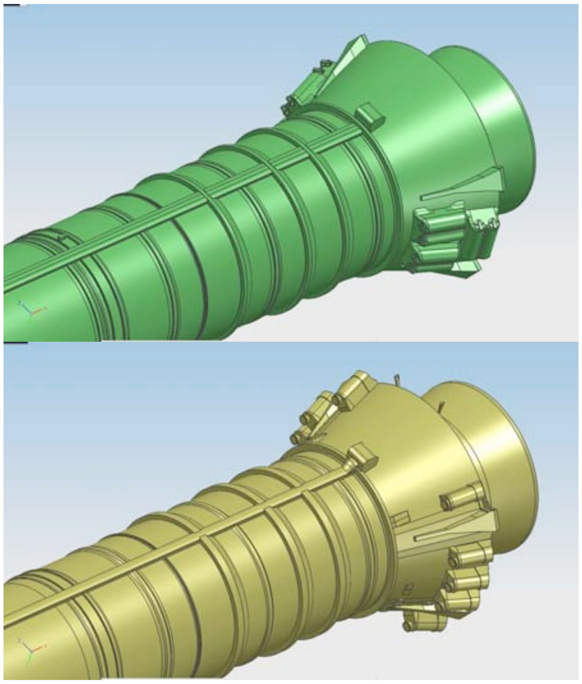

Figure 8. First Stage aft skirt protuberance comparison, (Ares I-X, top; Ares I, bottom).

Aerosciences

The differences in the Ares I-X and Ares I OMLs influence the aerodynamic, aeroacoustic, aeroelastic, and aerothermal effects on each vehicle. Wind tunnel test data and Computational Fluid Dynamics (CFD) solutions are providing the comparative assessment of the effects of the Orion OML change on aerodynamic performance differences between Ares I and Ares I-X.[5] Wind tunnel testing was performed on the basic configurations that represent Ares I-X and Ares I. Throughout the Mach number range tested (Mach 0.5 to 4.5), the Ares I benefits from a drag reduction of 20 to 30 percent.

Based on wind tunnel testing from subsonic (Mach=0.5) through transonic (Mach=1.2) conditions, the difference in pitching moment coefficient (C_M) as a function of angle of attack between the two configurations is fairly small. At increasing Mach numbers, however, the Ares I C_M values are larger in magnitude than those for Ares I-X, resulting in a configuration that is less longitudinally stable than Ares I-X. These differences are fairly significant, but since the acquisition of induced environments data is a secondary objective to the Ares I-X flight, the Ares Aerodynamics Panel has agreed to accept the differences in longitudinal aerodynamic performance, provided flight data is acquired on a subsequent Ares I flight test with the correct Orion shape to better anchor updated Ares I wind tunnel data and CFD predictions.

The other large, flow-induced difference that will result from the Orion OML change is in the aeroacoustic characteristics of this area. This fact partially contributed to the decision for a significant change to the Orion OML for the Ares I vehicle. The new configuration reduces the unsteady and locally separated flows and their associated acoustic signatures. Ares I-X flight data will be used to validate the analyses used to justify the Orion design change. Other acoustic areas that may be different include liftoff acoustics and overpressure, shock loads, and vibroacoustics. Interactions of unsteady flow with the vehicle structure (aeroelasticity) are also expected to be different for these two configurations mainly because of these changes to the Orion OML, and it is important to acquire data to validate ground-based predictions and better understand the effects of the full scale vehicle at flight conditions.

There are representative aerothermal comparisons between Ares I and Ares I-X. The ascent aerodynamic heating rates for both vehicles are similar and benign. Similar total heating rates near the aft skirt are expected for both vehicles throughout the ascent trajectory. Notable differences are that the Ares I-X plume radiation is slightly lower than Ares I during ascent and that, while the peak convective heating is similar, the total Ares I-X convective heating load is higher. The BDM plume impingement environments during separation are expected to be different due to both the variation in altitude when they fire and their placement on the aft skirt. Ares I-X heating on the first stage kick ring during separation is almost twice the value for Ares I, even though the nature of the heating environments is similar. Finally, because of the lower energy conditions experienced by Ares I-X at separation, the FS reentry thermal environments are considerably lower than what is expected for Ares I. Regardless, the local heating data obtained in this region and in regions affected by the RoCS plume for the Ares I-X flight will provide good validation data for the tools and methods that were used to generate predictions before flight.

Trajectory

The Ares I-X design reference trajectory was designed to conform to an earlier Ares I trajectory called Rev. 3 and represents a due east trajectory using mean annual winds and a 294 klb-thrust J-2X upper stage engine.[6] The Ares I-X input conditions include the current aerodynamic database and the Ares I-X mass properties. A comparison of dynamic pressure as a function of Mach number for the Ares I and Ares I-X trajectories is shown in Figure 9. The Ares I-X trajectory is optimized to match these parameters for as long as possible until Ares I-X first stage thrust begins to tail off. This match was achieved primarily by adding ballast and constraining the separation dynamic pressure to be no less than 100 psf. Overall, the dynamic pressure for Ares I-X varies by 7 percent or less compared to Ares I up to about Mach 4.0 and follows similar trends until motor thrust tail off. The Ares I-X maximum dynamic pressure condition is slightly lower and occurs at a lower Mach number than for Ares I. However, comparison with Rev. 5 of the Ares I trajectory (current at the time of this analysis) shows that the maximum dynamic pressure values are within about two percent of each other.

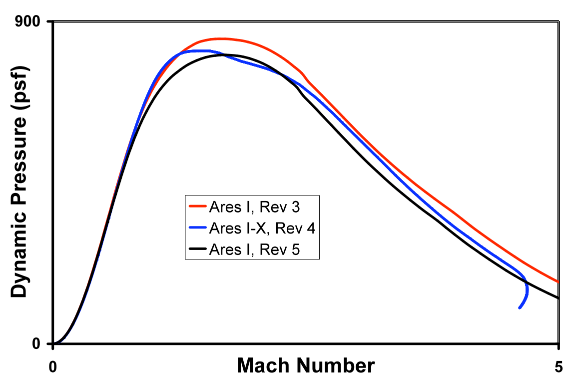

Figure 9. Ascent trajectory dynamic pressure vs. Mach number for Ares I-X and Ares I.

Using a four-segment motor that contains only about 80 percent of the total impulse of the Ares I five-segment motor, the Ares I separation conditions cannot be met during the Ares I-X flight because there is only about 80 percent of the FS chemical energy to provide thrust. This FS difference results in an Ares I-X separation condition at a lower Mach number and altitude. While it is possible to decrease the dynamic pressure at separation from the 100 psf constraint to be more like Ares I (10 to 20 psf), this reduction would cause the trajectory similitude during powered ascent to be significantly worse. Furthermore, being unable to match Mach number already precludes a good comparative separation condition. Analyses performed to date indicate that the Ares I-X separated first and upper stages are each neutrally stable. Because of the neutrally stable Ares I-X stages, the impacts of this dynamic pressure difference on separation are minor. However, if the aerodynamic predictions are in error or the individual FS or USS center of gravity locations change resulting in higher slopes of rotational moments, then successful separation for Ares I-X could be a greater risk. Finally, it is important for Ares I-X and Ares I to enter into separation with low body angular rates. Initial non-zero body rates greatly increase the impact of the aerodynamic forces and moments during separation and could preclude successful separation.

Structural Modes

Since essentially everything above the four-segment RSRM on Ares I-X is a mass, moment-of-inertia, and OML simulator, the Ares I-X structural bending modes need to be understood to provide an assessment of how similar the structural dynamics are with Ares I.[7] It is of concern that the differences are large enough that the use of the flight data for structural design and analysis tools verification will be suspect. Also, the low second bending mode may impact the approach used by Guidance, Navigation, and Control (GN&C) to stabilize the vehicle in flight. The Ares I-X structural design could have been modified to more accurately match Ares I bending modes; however, improvement is not planned due to the constraints of Ares I-X loads and the constraint of not moving the Ares I-X launch date.

Figure 10 shows a comparison of the first bending mode for the Ares I and Ares I-X configurations. Ares I has a relatively uniform mode shape, whereas the Ares I-X strain energy is concentrated in the forward RSRM segment due to the increased thickness of the frustum and forward skirt extension. Changing the fifth segment material to aluminum would allow the first and second bending mode frequencies to be within similitude requirements for Ares I, but the strength and/or stability margins for this segment would then be violated. The other thing to note in the figure is the absence of significant strain energy in the Ares I-X Upper Stage Simulator.

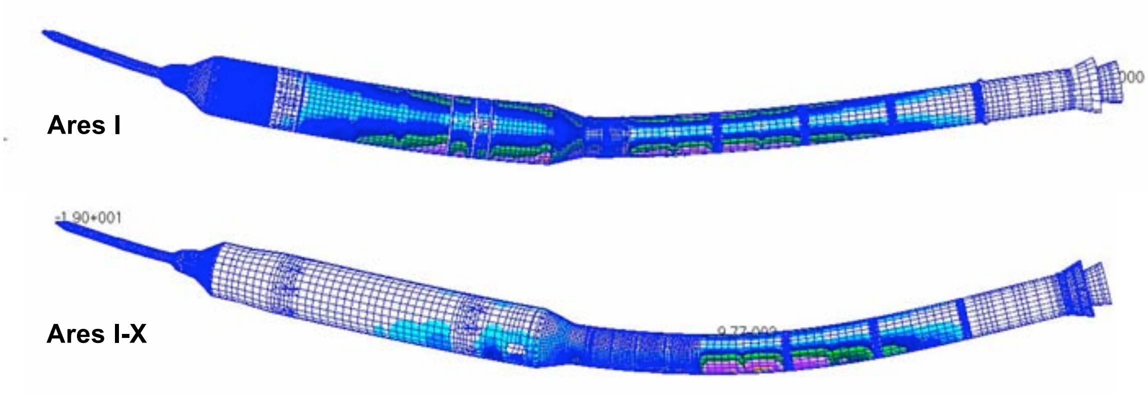

Figure 10. Comparison of first bending mode shapes.

Ascent Flight Control System Architecture

The number one primary Ares I-X objective is to demonstrate control of a vehicle dynamically similar to the Ares I using Ares I relevant flight control algorithms. Ares I and Ares I-X have benefited from an integrated GN&C team working on both vehicles. The vehicles use the same overall architecture and augmentation approaches, enabling common design and analysis techniques to be used for both vehicles. Despite the single-team approach to Ares I and Ares I-X GN&C, there are significant enough differences in the two vehicles that the Ares I-X flight test results will not directly validate Ares I control laws. Instead, they will be used to validate and calibrate the design and analysis tools used to develop the flight control architecture for Ares I.[8]

Similarities in the two vehicles include phase stabilization of the first structural bending mode and gain stabilization on the second and higher bending modes. As the Ares I-X flight progresses, the phase stabilization of the first bending mode might transition to gain stabilization as the first mode frequency increases. The goal is to maintain phase stabilization though Mach 4.0. The flight control architecture and parameter values also are designed to obtain desired gain and phase margins. The baseline vehicle gain and phase margin requirements are identical between Ares I and Ares I-X, though currently the Ares I has additional requirements in dispersed gain/phase requirements that Ares I-X does not have.

The baseline Ares I Flight Control System (FCS) includes the same anti-drift control law architecture that was developed for Ares I-X. In addition, as flight control design matures, a decision on load alleviation control options will be considered for Ares I that will not be a part of the Ares I-X flight test.

One of the fundamental differences that affect the FCS architecture is the placement of the major flight control sensors. For Ares I, the Inertial Measurement Unit (IMU) will be located in the instrument unit (at the top of the US), and two rate gyros will be located near the interstage and the FS aft skirt. For Ares I-X, the flight computer (which includes the IMU) will be located just above the top of the interstage while the rate gyros will be located near the top of the US and in the FS aft skirt. The result is that the dynamics that each IMU will experience are expected to be very different in the interstage area than in the instrument unit. Furthermore, Ares I-X will not use local sensors near nodes and anti-nodes for phase stabilization of the bending modes during flight, but these data may be acquired from development flight instrumentation (DFI) and used in post-flight analysis. Employing the rate gyro near the aft skirt will provide information to improve stability margin for many parts of ascent.

System Identification Maneuvers

During Ares I-X ascent, system identification maneuvers are being planned to extract as much flight data as possible to characterize the FCS architecture and the integrated roll torque caused by the combination of aerodynamic effects and the rolling moments induced by the first stage motor. The maneuvers will be executed via pre-programmed test inputs (PTIs) that will inject commands into the flight control system at pre-determined times in the flight.

Two separate types of maneuvers are expected to be employed to extract this information from the flight, namely, PTIs in the pitch and yaw axes and RoCS blackout periods. The PTIs will be incorporated during certain portions of the powered ascent to excite dynamics of interest. PTIs in the pitch and yaw axes will be implemented during the flight to determine control system margins, validate the structural flex model, and validate the aerodynamics model.

Another primary objective for Ares I-X is to characterize the magnitude of integrated vehicle roll torque throughout FS flight. This would be nearly impossible to determine unless the vehicle is able to fly for brief periods of time without the RoCS controlling the roll attitude and rate. One-second blackout periods of the RoCS are planned throughout the flight to quantify the combined roll torque due to the RSRM and vehicle aerodynamics.

90-Degree Roll

The Ares I-X orientation on the Mobile Launch Platform (MLP) differs from that planned for Ares I due to differences in their MLP mounting provisions. The attachment points for Ares I-X are the same holddown posts on the existing Shuttle MLP, resulting in an orientation with the z-axis of the structural-body-coordinate-system pointing to the South. For Ares I, the z-axis of the structural-body-coordinate-system points East (Orion capsule windows face East and the FS systems tunnel faces South) when mounted on the new Ares launch platform. For the exploration mission, the Ares I launch azimuth is East and, as it ascends from the MLP, the capsule windows and the systems tunnel remain facing East and South, respectively, for the planned head-down astronaut orientation. In order to match the roll orientation of Ares I in flight, Ares I-X must perform a 90-degree body-axis roll.

There are two reasons why this is important for similitude. The first is flight control similarity. Both vehicles use the same FS nozzle actuator arrangement in which the actuators produce deflections in rock and tilt axes rather than in pitch and yaw. A mixer function in the flight control system is used to transform body-axis pitch or yaw commands into rock and tilt commands. Without a roll maneuver, changes to some combination of guidance, flight control system, and/or mixer would be required which reduces the similarity to Ares I. The second reason it is important to perform the 90-degree body-axis roll is due to the orientation of the OML protuberances with respect to the atmospheric relative velocity. Without the roll maneuver, the angle between the protuberances and atmospheric velocity vector will be different and may affect roll torque similarity between the vehicles. Thus, to maintain as much similarity in the flight control laws and aerodynamic forces between Ares I and Ares I-X, a 90-degree body-axis roll is performed after clearing the launch tower.

First Stage—Upper Stage Staging Sequence

The second primary objective of the Ares I-X flight is to perform an in-flight separation/staging event between the first and upper stages. The Ares I staging sequence is depicted in Figure 11. The staging sequence for Ares I is initiated when RSRM thrust decreases below 40,000 lbf (thrust calculated from measured acceleration). Immediately prior to Upper Stage/interstage staging, eight BDMs mounted on the FS aft skirt are fired to decelerate the FS. At the same time, five ullage motors mounted on the US aft skirt are ignited to provide forward acceleration for propellant settling. Both the BDMs and the ullage motors are producing thrust at the moment of staging (physical separation is initiated by a linear shape charge (LSC) between the US aft skirt and the interstage) and for a short time thereafter. At a predetermined time after stage separation to ensure the spent FS has cleared the US, the two pairs of BTMs located on the frustum are ignited, imparting a pitch tumble on the spent stage. When the spent stage rotates approximately 180 degrees, a secondary separation event occurs. Another linear shaped charge on the FS separates the frustum/interstage from the FS. The FS continues to tumble to dissipate heat and further decelerate the FS, inducing proper conditions to initiate recovery. When the Altitude Switch Assembly senses that the vehicle is at the proper altitude, the nose cap is jettisoned and the pilot, then drogue, parachutes are deployed. Shortly thereafter, the forward skirt extension (which houses the main parachutes) separates from the rest of the first stage, and the main parachutes deploy. About 10 seconds before FS water impact, the RSRM nozzle extension is jettisoned.

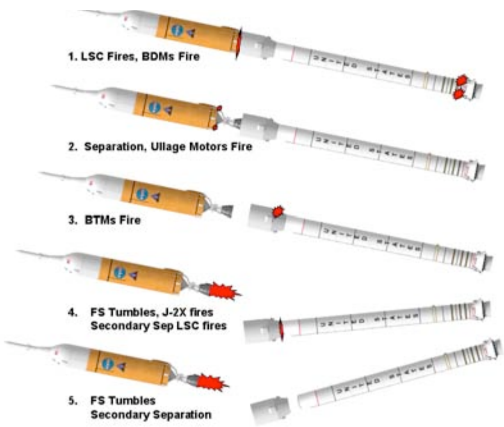

Figure 11. Ares I staging scheme.

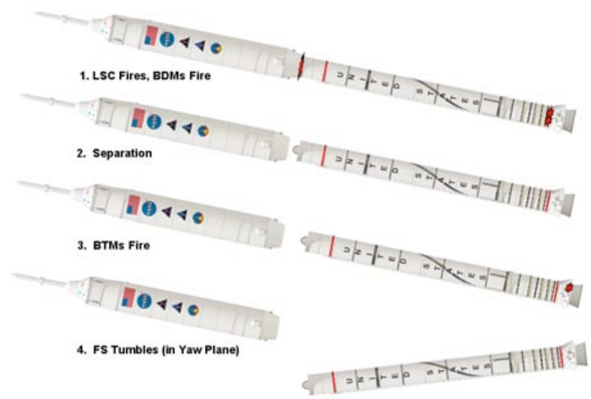

Figure 12. Ares I-X staging scheme.

Since the combined Ares I-X frustum and interstage combination are about 50,000 lb heavier than their Ares I counterparts, and since simulations showed that this extra inertia caused the tumble motors to rotate the FS less than 90 degrees before rotation stopped, the Ares I-X staging sequence was modified and is significantly different than the Ares I staging sequence (Figure 12). The new staging sequence for Ares I-X is still initiated when the RSRM thrust decreases below 40,000 lbf (thrust calculated from measured acceleration). At that point, a linear shape charge around the base of the frustum fires to physically separate the FS from the rest of the vehicle, and a total of eight BDMs (grouped in four pairs) located on the aft skirt fire to decelerate the FS. Approximately 3 seconds after this, the BTMs (located on the aft skirt) fire to initiate a rotation similar to that of Ares I. One notable exception is that, due to limitations in BTM placement on aft skirt and the 90-degree roll at liftoff, the "tumble" will take place mostly in the yaw plane instead of the pitch plane. Preliminary analysis showed that this change in tumble plane actually results in a more favorable situation to set the Ares I-X FS into a proper attitude for recovery; however, additional analyses are needed to understand the effect of the aerodynamic wake of the USS when the FS is in close proximity. From this point in the sequence forward, the recovery process is similar to Ares I.

Mass Properties

Presently, the Ares I-X vehicle is 10 percent lighter than Ares I at FS ignition, but Ares I-X has moments of inertia that are about 10 percent to 50 percent higher than Ares I.[9] Mass differences are understandable in that vehicle weight is one of the parameters varied to allow Ares I-X to fly a similar trajectory as Ares I. As the Ares I design continues to be refined, the trends for the moments of inertia are causing them to be further away from the Ares I-X values. Finally, with the ability to adjust ballast plates in the upper stage simulator, the axial centers of gravity at launch for both vehicles are within one percent of each other.

Relevant Element Comparisons

Even though the OML and recovery scheme (including parachute deployment) are generally the same for both Ares I-X and Ares I, several differences are noted below. The main propulsion source for Ares I-X comes from a Shuttle-heritage, four-segment RSRM. In order to maintain a flight date in April 2009, there was an insufficient amount of time to develop the Ares I five-segment version of the RSRM for the Ares I-X flight. As expected, with only about 80 percent of the total impulse available to Ares I, the Shuttle motor design used on Ares I-X will yield different propulsion characteristics. The Ares I-X inert fifth segment allowed the overall vehicle to maintain a FS OML that most closely represents Ares I. This segment is heavier than an empty segment because the FSAM, which includes a mounting surface and a large number of avionics boxes, has been located there. Furthermore, the Ares I-X frustum is made of steel and weighs about twice as much as the frustum being designed for Ares I. Ares I-X incorporates new as well as repackaged booster avionics that are different than both the current Shuttle application and Ares I. There is also a significant amount of DFI that has been added to Ares I-X. This added DFI provides data to support the development of the tools and models being used for design and analysis on Ares I. The impacts of the differences are that the Ares I-X FS has a mass, a center of gravity, and moments of inertia that do not match Ares I. Furthermore, without propellant in the fifth segment, this segment will not have the same structural stiffness due to the lack of pressurization by the combustion process.

The RoCS for Ares I-X primarily consists of hardware salvaged from the Peacekeeper fourth stage axial thruster system. The thrust capability from these engines is higher than what is currently being designed for Ares I. The propellants used by the Peacekeeper system (monomethylhydrazine/nitrogen tetroxide) are also different from the propellant envisioned for Ares I RoCS (hydrazine monopropellant).

Ares I-X is using Atlas V avionics hardware, including its Fault Tolerant Inertial Navigation Unit, instead of the flight computer and IMU planned for the Ares I. Because the Atlas avionics were not rated for the environment the FS is capable of producing, a significant amount of analysis is being performed to understand the shock and vibroacoustic induced environments to either design isolation systems for avionics boxes expected to exceed current qualification limits or to perform to qualification testing to the new required levels.

SUMMARY

The Ares I-X ascent development flight test will provide significant data and understanding to be used in the design and development of the Ares I. Although the vehicles are not identical, they are enough alike to meet the mission objectives and support Ares I development. The number one primary objective is to demonstrate control of a vehicle dynamically similar to the Ares I using Ares I relevant flight control algorithms. This objective will be met because the flight control system architecture, including the gain and phase stabilization, is similar for Ares I-X and Ares I, and the same GN&C team is working on both vehicles. Differences in structural dynamics and sensor placement related to flight control will be accounted for and incorporated during post-flight analysis of the data using the design and analysis tools and models that were used prior to flight.

The second primary objective is to perform an in-flight separation/staging event between the first and upper stage. Although the Ares I and Ares I-X staging scenarios are different, the data acquired during Ares I-X will help engineers evaluate the basic kinematics of staging for this class of vehicle, the timing of the staging sequence, the effectiveness of the BDMs, the FS thrust side load at staging, and pyroshock and debris transport properties.

The third primary objective is to demonstrate assembly and recovery of a new Ares I-like FS element at KSC. Although not discussed in this paper, Ares I-X provides the initial opportunity for processing, stacking, assembly, and recovery operations at KSC with a FS similar to Ares I.

The fourth primary objective is to demonstrate FS separation sequencing and quantify FS atmospheric entry dynamics and parachute performance. While there are some deficiencies in modeling all aspects of staging with different separation planes for Ares I-X and Ares I, this flight test demonstration will exercise a FS tumble, initiation of parachute deployment, deceleration using prototype Ares I main parachutes, and separation of the FS nozzle extension. Furthermore, flight data will be acquired to assess the models used to develop the FS atmospheric descent dynamics.

The fifth primary objective is to characterize the magnitude of integrated vehicle roll torque throughout FS Flight. Pure vehicle roll torque data are expected to be obtained by incorporating small periods of time throughout ascent when the roll control system will not be active.

Finally, while it was not originally conceived as a primary flight test objective, the potential for FS thrust oscillation (identified during Ares I design and analysis) will be addressed on Ares I-X by relocating and adding DFI to characterize the nature of the thrust oscillation for its four-segment RSRM.

In addition to the five primary objectives, there are six secondary objectives. They include (1) quantifying the effectiveness of the FS booster deceleration motors, (2) characterizing the induced environments and loads on the flight test vehicle during the ascent flight phase, (3) demonstrating a procedure to determine the vehicle's pre-launch geodetic orientation vector for initializing the flight control system, (4) characterizing induced loads on the launch vehicle on the launch pad, (5), assessing potential Ares I access locations in the Vehicle Assembly Building and on the pad, and (6) validating FS electrical umbilical performance.

Ares I-X has sufficient similitude with Ares I to meet all five primary objectives and all six secondary objectives. Ares I-X data will be used to validate tools and models being used in Ares I design and analysis and will be available in time to be incorporated into the Ares I design before its critical design review scheduled for 2011.

REFERENCES

1. System Requirements Document for the Ares I-X Flight Test Vehicle, AI1-SYS-SRD, Baseline v4.12, June 17, 2008.

2. Constellation Program Ares I-X Flight Test Plan, CxP 70127, Revision B, change 001, July 31, 2008.

3. Huebner, L. D.: Ares I-X Flight Test Vehicle Similitude Description to the Ares I Crew Launch Vehicle, APO-1017, April 23, 2008.

4. Ares I-X Flight Test Vehicle Outer Mold Line Definition, AI1-SYS-OML, Rev. 2.01, Nov. 27, 2007.

5. Ares I-X Flight Test Vehicle Aerodynamic Data Book, AI1-SYS-ARO, v2.00, April 3, 2008.

6. Ares I-X Flight Test Vehicle Trajectory Databook, AI1-SYS-TRAJ, v1.00, Feb. 5. 2008.

7. Ares I-X Flight Test Vehicle Structures Databook, AI1-SYS-SDB, rev. 3.00, March 18,. 2008.

8. Brandon, J.: Control Algorithm and Parameters for the Ares I-X Flight Test Vehicle, AI1-SYS-CAP-v1.01, July 24, 2007.

9. Ares I-X Mass Allocation Baseline, AI1-SYS-MAB, v1.00, Nov. 15, 2007.