Integrated Testing Approaches for the NASA Ares I Crew Launch Vehicle

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Abstract

The Ares I crew launch vehicle is being developed by the U.S. National Aeronautics and Space Administration (NASA) to provide crew and cargo access to the International Space Station (ISS) and, together with the Ares V cargo launch vehicle, serves as a critical component of NASA's future human exploration of the Moon. During the preliminary design phase, NASA defined and began implementing plans for integrated ground and flight testing necessary to achieve the first human launch of Ares I. The individual Ares I flight hardware elements—including the first stage five segment booster (FSB), upper stage, and J-2X upper stage engine—will undergo extensive development, qualification, and certification testing prior to flight. Key integrated system tests include the upper stage Main Propulsion Test Article (MPTA), acceptance tests of the integrated upper stage and upper stage engine assembly, a full-scale integrated vehicle ground vibration test (IVGVT), aerodynamic testing to characterize vehicle performance, and integrated testing of the avionics and software components. The Ares I-X development flight test will provide flight data to validate engineering models for aerodynamic performance, stage separation, structural dynamic performance, and control system functionality. The Ares I-Y flight test will validate ascent performance of the first stage, stage separation functionality, validate the ability of the upper stage to manage cryogenic propellants to achieve upper stage engine start conditions, and a high-altitude demonstration of the launch abort system (LAS) following stage separation. The Orion 1 flight test will be conducted as a full, un-crewed, operational flight test through the entire ascent flight profile prior to the first crewed launch.

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Nomenclature

AETF	Advanced Engine Test Facility
ARF	Aerodynamic Research Facility
COTS	Commercial Off-the-Shelf
CFD	Computational Fluid Dynamics
CDR	Critical Design Review
CM	Crew Module
DCR	Design Certification Review
DFI	Development Flight Instrumentation
FSB	Five-Segment Booster
FTV	Flight Test Vehicle
GLOW	Gross Lift-Off Weight
GN&C	Guidance, Navigation, and Control
HWIL	Hardware In-the-Loop
IOC	Initial Operational Capability
ISS	International Space Station
IVGVT	Integrated Vehicle Ground Vibration Test
JDTV	Jumbo Drop Test Vehicle
KSC	Kennedy Space Center
LaRC	Langley Research Center
LAS	Launch Abort System
LEO	Low Earth Orbit
LH_2	Liquid Hydrogen
LO_2	Liquid Oxygen (also: LOX)
MAF	Michoud Assembly Facility
MECO	Main Engine Cut-Off
MPS	Main Propulsion System
MPTA	Main Propulsion Test Article
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Admin.
PDR	Preliminary Design Review
RCS	Reaction Control System
SA	Spacecraft Adapter
SIL	Systems Integration Laboratory
SM	Service Module
SRB	Solid Rocket Booster
SSC	Stennis Space Center
SSME	Space Shuttle Main Engine
TDT	Transonic Dynamics Tunnel
TVC	Thrust Vector Control
UPWT	Unitary Plan Wind Tunnel

Introduction

The U.S. National Aeronautics and Space Administration (NASA) is developing the Ares I crew launch vehicle to meet the objectives of the U.S. Space Exploration Policy and open new frontiers for human exploration of the solar system.[1] The Ares I will deliver the Orion crew exploration vehicle to the International Space Station (ISS) following the 2010 retirement of the Space Shuttle. Together with the Ares V cargo launch vehicle, Ares I (Figure 1) also will provide the launch capability for future lunar exploration missions. Initial operational capability (IOC) of the Ares I launch vehicle is scheduled no later than 2015.

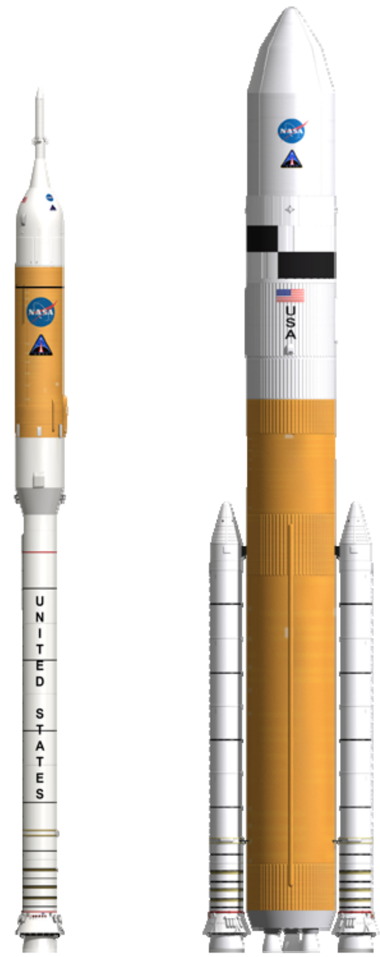

Figure 1. Ares I (left) and Ares V (right) will provide the launch capabilities for America's space exploration effort.

Figure 2 shows the major components of the Ares I vehicle. The first stage is five-segment solid rocket motor, derived from the Space Shuttle Solid Rocket Booster (SRB). The Five-Segment Booster (FSB) will be recovered and refurbished after each Ares I launch for re-use on subsequent flights.

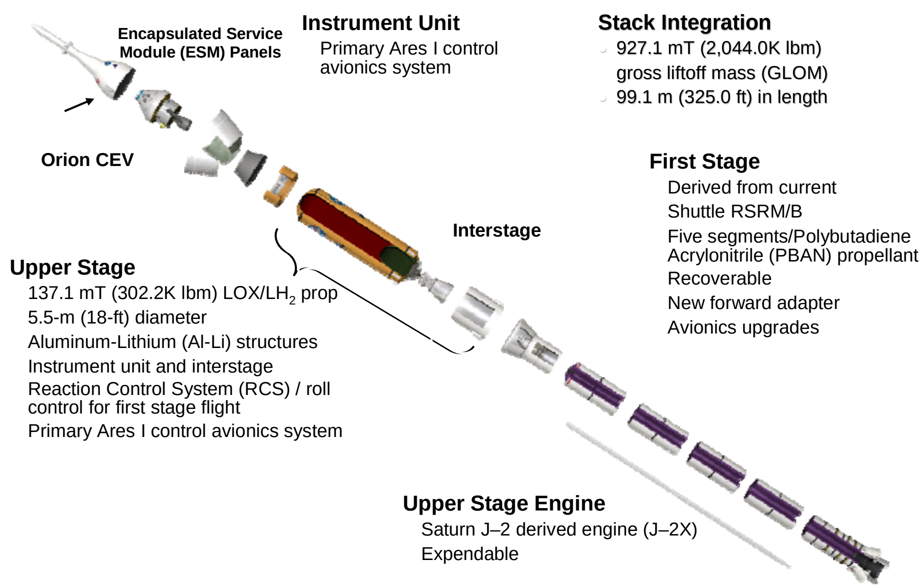

Figure 2. Schematic of the Ares I launch vehicle

The upper stage provides the thrust required for second stage flight and is powered by a single J-2X upper stage engine. The J-2X is a derivative of the Saturn V J-2 upper stage engine. The Ares I upper stage consists of liquid hydrogen and liquid oxygen cryogenic tanks, using a common-bulkhead design approach, along with the main propulsion system (MPS), thrust vector control (TVC), reaction control systems (RCS) for both the first and second stages of flight, and avionics hardware. The Ares I upper stage provides all guidance, navigation, and control (GN&C) for the first and second stages of flight in conjunction with FSB and J-2X avionics. A schematic of the Ares I upper stage major subsystems is shown in Figure 3. The Orion components, including the crew module (CM), service module (SM), spacecraft adapter (SA), and launch abort system (LAS) complete the integrated launch vehicle stack. Key events for the Ares I mission to the ISS are shown in Figure 4 and include liftoff, stage separation, upper stage burn, LAS jettison, Orion payload separation, first stage re-entry and recovery, and descent and impact of the upper stage. The upper stage and upper stage engine are not recovered.

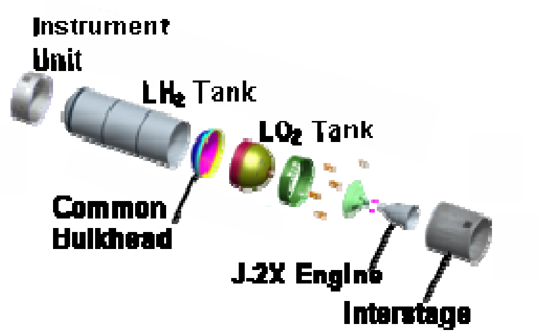

Figure 3. Ares I Upper Stage components, including J-2X engine.

Test and Verification Framework

The NASA systems engineering process defines test and verification methodologies as part of a typical project life cycle.[2] Verification of system and subsystem requirements is accomplished in stages: development, qualification, acceptance, and preparation for deployment.

The development stage is the period in which a new system is formulated up to the qualification of flight hardware and manufacturing stage. Verification activities during the development stage provide confidence that the system can accomplish mission goals and objectives. Testing provides data needed to reduce risk, define or mature requirements, design hardware or software, define manufacturing processes, define qualification or acceptance test procedures, or investigate anomalies discovered during testing. Verification testing during this stage typically supports the critical design review (CDR). Each of the three hardware elements (first stage, upper stage engine, and upper stage) will conduct extensive ground test programs at the component, subsystem, and major assembly level during the development phase.

The First Stage Element Office is conducting tests of the deceleration subsystem, which include drop tests and deployment of the parachute systems to enable recovery of the FSB. Multiple static firings of development test motors will be performed, beginning in 2010. During preliminary design, a successful flight test was conducted for the first stage deceleration drogue parachute system. A 68-foot diameter parachute was tested using a Jumbo Drop Test Vehicle (JDTV) deployed from a U.S. Air Force C-17 aircraft. Deployment and inflation of the drogue chute was successfully accomplished in flight.

The upper stage engine team is conducting extensive development testing at both sea level and simulated altitude conditions to verify engine performance and certify operational capability prior to flight. Early testing of turbomachinery subsystems prior to the engine critical design review (CDR) was conducted using modified heritage J-2 engine hardware. NASA is building a new engine test facility, designated as the A-3 test stand at Stennis Space Center (SSC), to provide a new capability for simulated altitude testing of the J-2X engine.

The upper stage team is conducting structural strength tests of the integrated stage with the liquid hydrogen (LH_2) and (LO_2) tanks in the common bulkhead configuration. Major integrated system tests to be performed during design, development, and qualification phases are described in a subsequent section of this paper.

Flight testing may be performed during the development stage if system requirements cannot be validated, or if risks and uncertainties cannot be fully quantified through analysis and ground testing. The benefits of flight testing may be driven by the limitations of test facilities to simulate flight environments; limitations of scale models to adequately simulate flight-like responses; limitations in engineering models to approximate flight conditions; and/or an inability of engineering models to simulate the complex physical interactions necessary to fully evaluate key aspects of the system design. The Ares I-X flight test will be conducted as a development test, simulating key aspects of the Ares I vehicle design and providing flight data to calibrate engineering models used in the design process. Subsequent flight testing will use prototype flight hardware to validate the performance of the launch vehicle system and functionality of key subsystems prior to operational capability. The objectives of the Ares I-X and the subsequent validation flight tests are described in a later section of this paper.

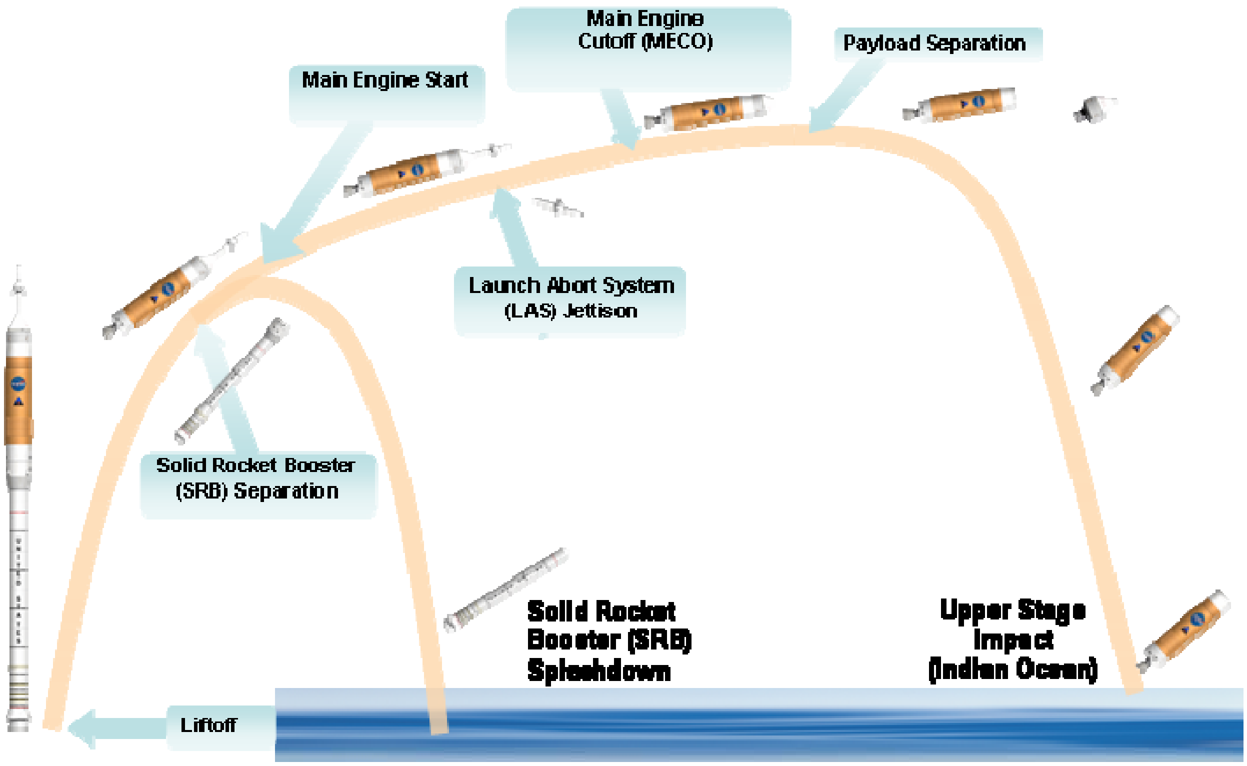

Figure 4. Ares I Design Reference Mission for ISS Access

Integrated System Tests

Integrated Propulsion System Testing

The Ares Projects have developed an Integrated Test Plan (ITP) as part of the formulation activities. The ITP will be used to link the Design Verification Objectives (DVOs) of the vehicle system requirements to the various element and vehicle ground and flight testing activities. Figure 5 provides an illustration of the process that the Ares Projects have developed to provide this integration framework.

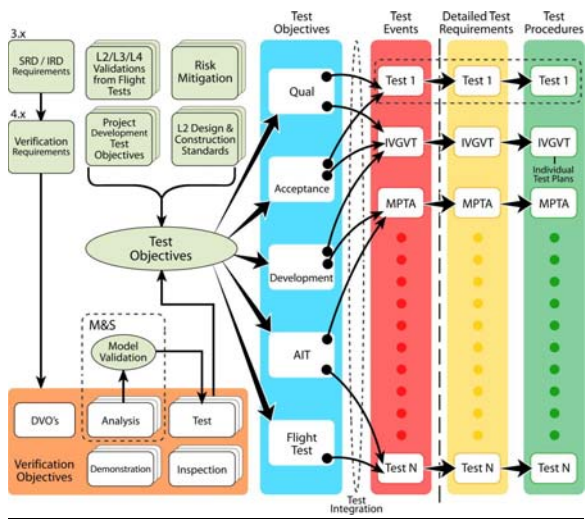

Figure 5. Ares Process for Decomposition of Test Objectives into an Integrated Test Plan

The Main Propulsion Test Article (MPTA) is the first integrated system test with the upper stage and J-2X engine assembly. This test program is designed to verify the functionality and performance of the integrated stage. The MPTA test will be conducted in the Advanced Engine Test Facility (AETF) at NASA's Marshall Space Flight Center (MSFC). The AETF is a two-position tri-propellant stand capable of evaluating and characterizing engine and vehicle stage systems in a vertical configuration. It was originally designed for the Saturn S-IC engine stage cluster and was modified in 1978-79 to perform structural tests for the Space Shuttle External Tank. In 1988, modifications were completed to allow single-engine testing with advanced components on the Space Shuttle Main Engine (SSME).[3] A photograph of the AETF is shown in Figure 6.

Figure 6. Photograph of the Advanced Engine Test Facility (AETF) at NASA Marshall Space Flight Center (MSFC).

The Ares I MPTA test program will address issues associated with transient and main stage performance, propellant management, pressurization system performance, and cryogenic operation of MPS components. Additionally, avionics and TVC components will be tested. MPTA testing is scheduled to commence in 2012 and continue through the Ares I Design Certification Review (DCR).

Upper Stage flight hardware will be manufactured and then mated with the J-2X Engine at NASA's Michoud Assembly Facility (MAF). The integrated upper stage assembly will then be tested in a "Green Run" acceptance test NASA's Stennis Space Center (SSC) prior to flight, beginning with the first un-crewed operational flight test, designated as Orion 1. Green Run testing will be performed for the first three flight upper stage and upper stage engine assemblies. A photograph of the B-complex test facility at SSC is shown in Figure 7. The photograph shows the two test stand positions, designated B-1 and B-2, which are serviced by a common central core. The B-2 test position was first used in the Saturn S-IC test program. Subsequently, it was used to test the Space Shuttle MPTA, which consisted of an external tank, Shuttle orbiter aft-bulkhead/propulsion compartment simulator, and three SSMEs.[4]

Figure 7. Photograph of the B-2 Engine Test Stand at NASA Stennis Space Center (SSC).

Integrated Vehicle Ground Vibration Testing (IVGVT)

IVGVT will be conducted on a full-scale Ares launch vehicle test article. These tests will provide data necessary to validate engineering models for the flight control system performance and the vehicle's structural dynamics response during ascent. The primary objectives of the IVGVT are to:

- Obtain and verify the vehicle mode shapes, frequencies, and generalized mass and damping characteristics, which are used in the stability equations. These form the basis of the final verification loads used in GN&C system analyses.
- Obtain amplitude and phase response data at flight control sensor locations.

- Obtain the experimental non-linear characteristics of the vehicle by exciting the test article at different force levels.

Test configurations for the IVGVT will include a simulation of the liftoff configuration at the total predicted gross lift-off weight (GLOW) and at the first stage burnout condition. The liftoff configuration will be simulated by using a FSB test article with inert propellant segments that duplicates the mass, mass distribution, interfaces, and other key parameters of an operational FSB. The first stage burnout configuration will be simulated with empty booster segments, which will be refurbished and used as flight hardware for later Ares I flights. The upper stage test article will closely approximate the structural configuration of an Ares I flight upper stage, including propellant tanks and high-fidelity primary structure, but will not include all subsystems from the operational flight design. The J-2X engine will be represented by a mass simulator test article. The second stage configuration (upper stage, Orion crew module, service module, and launch abort system) will be tested separately to characterize the modal response during the second stage of flight. The Orion test article will consist of a mass simulator for the LAS, CM, SM, and SA, which will be based on the design dropped at PDR. There will be four tests conducted on the flight configuration of the upper stage after first stage separation. These tests will cover major mass shifts from the full upper stage at USE ignition to the point on the trajectory of upper stage main engine cutoff..

Test hardware for the IVGVT will begin arriving at MSFC's Dynamic Test Stand in 2010 and 2011, with testing conducted in 2012 and 2013 to support design certification of the Ares I vehicle. Stacking operations prior to the IVGVT also provide an opportunity to test procedures related to hardware handling, stacking, and interface checks. The full launch vehicle test article will be supported on a hydraulic suspension system to simulate the flight free-free boundary conditions. Random and sinusoidal excitation will be used to identify resonance response, damping values, and bending mode shapes.

The Dynamic Test Stand was used for ground vibration testing of the Saturn V launch vehicle and the Space Shuttle.[5] Photographs of the test stand with these vehicles and in its current configuration are shown in Figure 8. A key element of the IVGVT includes the necessary facility modification and refurbishment for test readiness. This includes the hydrodynamic support system that was used for Shuttle and Saturn V tests, suspension and access platforms to accommodate the Ares I configuration, and lifting capabilities to enable stacking, assembly, and test operations.

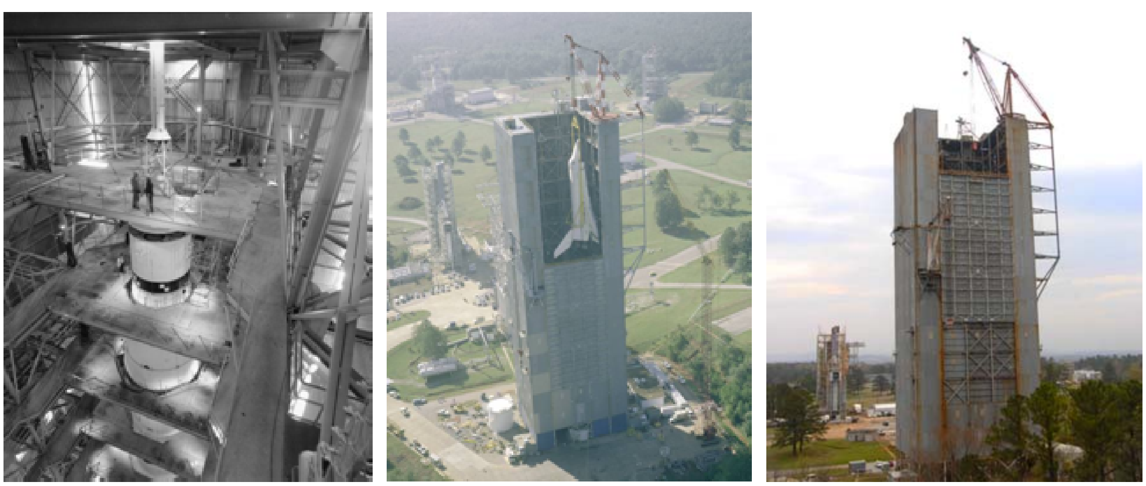

Figure 8. Photographs of the MSFC Dynamic Test Stand representing (from left to right) Saturn V testing, Space Shuttle dynamic testing, and prior to refurbishment for Ares I testing.

<u>Integrated Vehicle Performance Testing</u>

Aerodynamic testing is being conducted to characterize aerodynamic performance during ascent, stage separation, and FSB re-entry.[6] These tests also provide data to validate engineering tools used to predict aerodynamic loads for structural analyses. Testing is being conducted in multiple facilities to simulate subsonic, transonic, and supersonic flight conditions and to address ground-to-flight scaling parameters. Wind tunnel testing has been performed during the preliminary design phase at four different facilities, spanning a Mach number range from 0.5 to 4.96 using 0.5-percent and 1.0-percent scale models. The completed PDR test matrix represents approximately 50 percent of the total aerodynamic characterization effort.

These pre-PDR tests provided aerodynamic force, moment, and surface pressure data, which were used to evaluate design cycle configuration trades and provide preliminary databases for structural loads and GN&C assessments. The results also were used to calibrate computational fluid dynamics (CFD) codes for higher-fidelity analyses. Figure 9 shows a photograph of a 1.0-percent scale Ares I model being tested in the Unitary Plan Wind Tunnel (UPWT) at NASA's Langley Research Center (LaRC) and a 0.5-percent model tested in the Aerodynamic Research Facility (ARF) at NASA MSFC.

Figure 9. Photographs of 1.0-percent scale and 0.5-percent scale models tested in NAS wind tunnel facilities.

The test program prior to the Ares I critical design review (CDR) will include an evaluation of Reynolds number scale effects, proximity aerodynamic interference effects during stage separation, characterization of plume interactions from reaction control systems, and higher-fidelity configuration assessments.

Aeroelasticity testing is being conducted to obtain data for investigating aeroelastic effects and instabilities on vehicle structural loads and performance. Testing consists of rigid aerodynamic models for investigating the effects on static loads of a deformed vehicle. Many features of the Ares I launch vehicle, including the LAS, crew module capsule flares, and the aft-facing frustum atop the first stage may cause regions of flow separation that affect aerodynamic loading in the transonic and low supersonic speed regime, where the vehicle experiences maximum dynamic pressure. A rigid buffet test was conducted using a 3.5-percent scale Ares I-X configuration in the NASA LaRC Transonic Dynamics Tunnel (TDT). Finally, wind tunnel testing will be performed to model the launch vehicle configuration on the launch platform at the NASA Kennedy Space Center (KSC) to validate that the vehicle can withstand expected aerodynamic loading due to ground winds at the launch site. An initial feasibility test was performed in the TDT with a 4.5-percent scale model for this test.

<u>Avionics and Software Testing</u>

The functionality of avionics and software components will be verified in a Systems Integration Laboratory (SIL) prior to flight. Upper stage, upper stage engine, and first stage will test and qualify avionics hardware at the component level in individual laboratories. These components will be integrated, along with simulators for ground systems and Orion interfaces, in the development SIL. The SIL provides an environment for real-time hardware-in-the-loop (HWIL) testing, for performing formal verification of requirements, pre-launch support, day-of-launch support, and for anomaly investigation.

Flight Testing

Development, validation, and operational flight tests will be performed prior to the first human launch of Ares I. Figure 10 shows the flight manifest leading to Initial Operational Capability (IOC – first human launch) of the Ares I launch vehicle. The key flight test events are the Ares I-X development flight test, the Ares I-Y validation flight test, the Orion 1 operational flight test, and Orion 2, which is the designation for IOC.

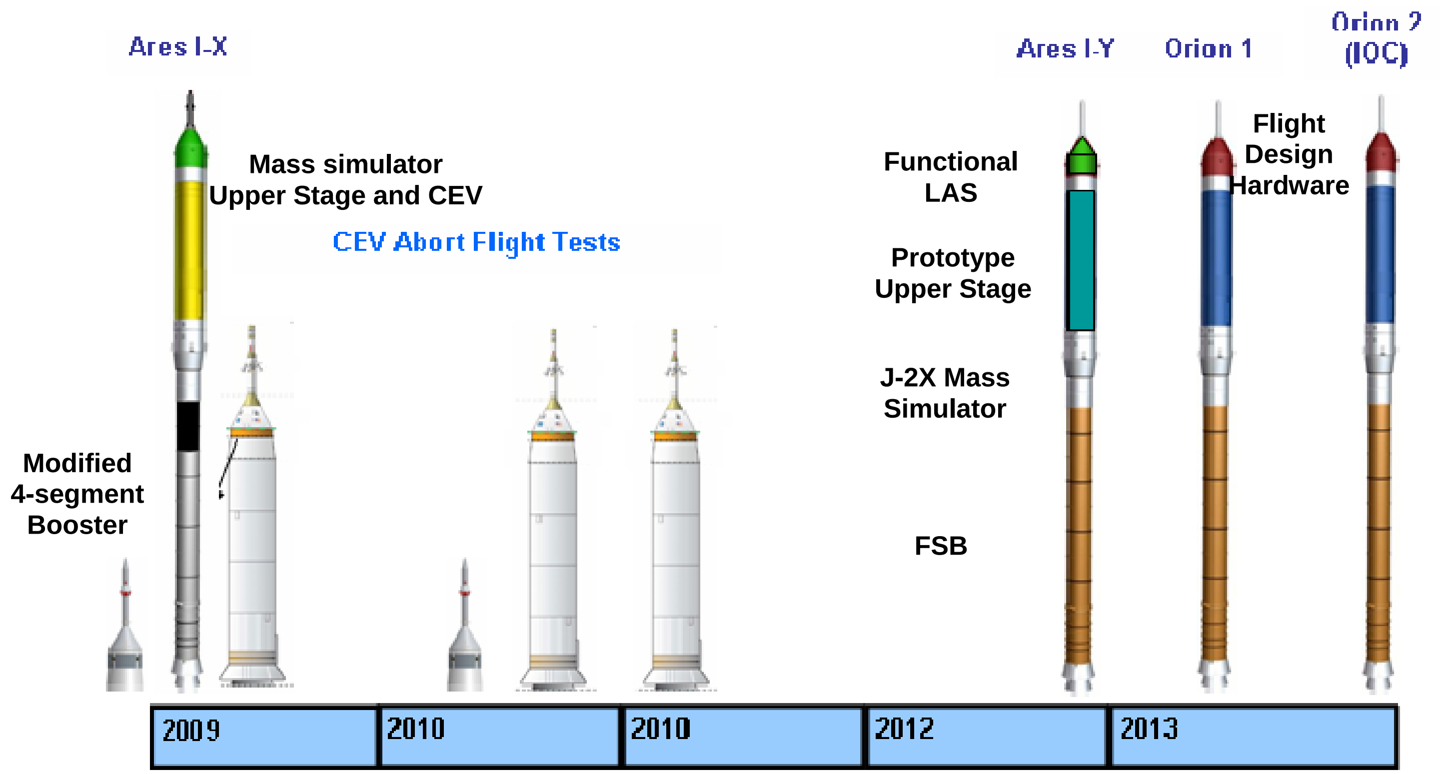

Figure 10. Ares Launch Vehicle and Orion Crew Exploration Vehicle flight test elements.

The Ares I-X development flight test will use a modified 4-segment SRB with an additional empty spacer segment. The upper stage, J-2X, and Orion components will be non-functional mass simulator units matching the outer mold line. This approach is designed to achieve similitude with the Ares I operational vehicle in aerodynamic characteristics, structural dynamics response, and control system design during first stage ascent and separation. The avionics system is an off-the-shelf system designed to accommodate Ares I-similar control system algorithms. A schematic of the Ares I-X flight test vehicle (FTV) with functional and non-functional components is shown in Figure 11.

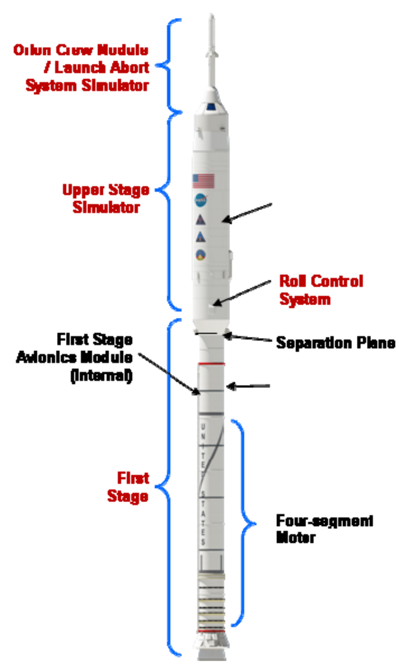

Figure 11. Components of the Ares I-X flight test vehicle (FTV).

The primary objectives of the Ares I-X flight, scheduled for 2009, are to:

- Demonstrate control of a dynamically similar, integrated Ares I/Orion, using Ares I ascent control algorithms.
- Perform an in-flight separation/staging event between an Ares I-like first stage and a representative upper stage.
- Demonstrate assembly and recovery of a new Ares I-like first stage element at Kennedy Space Center (KSC).
- Demonstrate first stage separation sequencing, and quantify first stage atmospheric entry dynamics, and parachute performance.
- Characterize magnitude of integrated vehicle roll torque throughout First Stage flight.

Ares I-Y will be an uncrewed validation flight test conducted in September 2013. The Ares I-Y FTV will consist of a FSB; a prototype upper stage with cryogenic tanks, MPS, and TVC components; and a mass simulator for the J-2X engine. The test will validate the vehicle performance through first stage ascent and separation. The test also will include simulated detection of engine-out conditions following separation and a high-altitude test of the LAS, separating the crew module from the launch vehicle and demonstrating safe re-entry, descent, and landing. Ares I-Y also will test cryogenic propellant management and the ability of the main propulsion system (MPS) to meet the J-2X starting conditions. Ares I-Y will demonstrate the first assembly, processing, and launch from modified launch facilities at KSC. NASA is modifying existing Space Shuttle launch pad facilities to accommodate the Ares I. Ares I-Y will provide an opportunity for the first validation of stacking, interface testing, and cryogenic fuel fill and drain operations.

Orion 1 will be an un-crewed operational flight test conducted in March 2014. The Orion 1 vehicle will consist of flight-design hardware for the FSB, Upper Stage, J-2X, and Orion. The Orion 1 flight will be the first flight test of the J-2X engine and upper stage throughout the nominal second stage ascent flight profile. This flight also will insert Orion into orbit, and will include re-entry, decent, and landing of the crew module. The first crewed launch of the Ares I vehicle is designated for the Orion 2 mission.

Concluding Remarks

NASA is developing the Ares I crew launch vehicle to meet the objectives of the U.S. Space Exploration Policy. The Ares I will deliver the Orion crew exploration vehicle to the ISS and, together with the Ares V cargo launch vehicle, provide the launch capability for future human exploration of the Moon. Integrated test and verification strategies have been developed and will be critical to building functional and safe launch vehicles that will meet the nation's exploration goals.

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