Integrated System Test Approaches for the NASA Ares I Crew Launch Vehicle

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Abstract

The Ares I Crew Launch Vehicle (CLV) is being developed by the U.S. National Aeronautics and Space Administration (NASA) to provide crew access to the International Space Station (ISS) and, together with the Ares V Cargo Launch Vehicle (CaLV), serves as one component of a future launch capability for human exploration of the Moon. During the system requirements definition process and early design cycles, 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: 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 Main Propulsion Test Article (MPTA), acceptance tests of the integrated upper stage and upper stage engine assembly, a full-scale integrated vehicle dynamic test (IVDT), 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, and a high-altitude actuation of the launch abort system (LAS) following 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.

Nomenclature

AETF	Advanced Engine Test Facility
ARF	Aerodynamic Research Facility
CaLV	Cargo Launch Vehicle (Ares V)
COTS	Commercial Off-the-Shelf
CFD	Computational Fluid Dynamics
CDR	Critical Design Review
CEV	Crew Exploration Vehicle
CLV	Crew Launch Vehicle (Ares I)
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
IVDT	Integrated Vehicle Dynamic Test
KSC	Kennedy Space Center
LaRC	Langley Research Center
LAS	Launch Abort System
LEO	Low Earth Orbit
LH_2	Liquid Hydrogen
LO_2	Liquid Oxygen (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
SIL	Systems Integration Laboratory
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
USE	Upper Stage Engine
VSE	Vision for Space Exploration

Introduction

The U.S. National Aeronautics and Space Administration (NASA) is developing the Ares I Crew Launch Vehicle (CLV) to meet the

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Figure 1. Ares I and Ares V Launch Vehicles.

objectives of the Vision for Space Exploration (VSE) and open new frontiers for human exploration of the solar system.[1] The Ares I will provide the capability to deliver the Orion Crew Exploration Vehicle (CEV) to the International Space Station (ISS) following the 2010 retirement of the Space Shuttle. Together with the Ares V Cargo Launch Vehicle (CaLV), Ares I will also provide the launch capability for future lunar exploration missions. Initial operational capability (IOC) of the Ares I launch vehicle is scheduled no later than late 2014, with a goal of late 2013. Representations of the Ares I and Ares V vehicles are shown in figure 1.

Figure 2 shows the major components of the Ares I vehicle. The First Stage is five-segment solid propellant booster rocket, 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. The Upper Stage provides the propulsive thrust required for second stage flight and is powered by a single J-2X Upper Stage Engine (USE). 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 main propulsion system (MPS), thrust vector control (TVC), reaction control systems (RCS) for both the first and second stage flights, 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 USE avionics. A schematic of the Ares I upper stage major sub-systems is shown in figure 3. The CEV components, including the crew module, service module, and 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

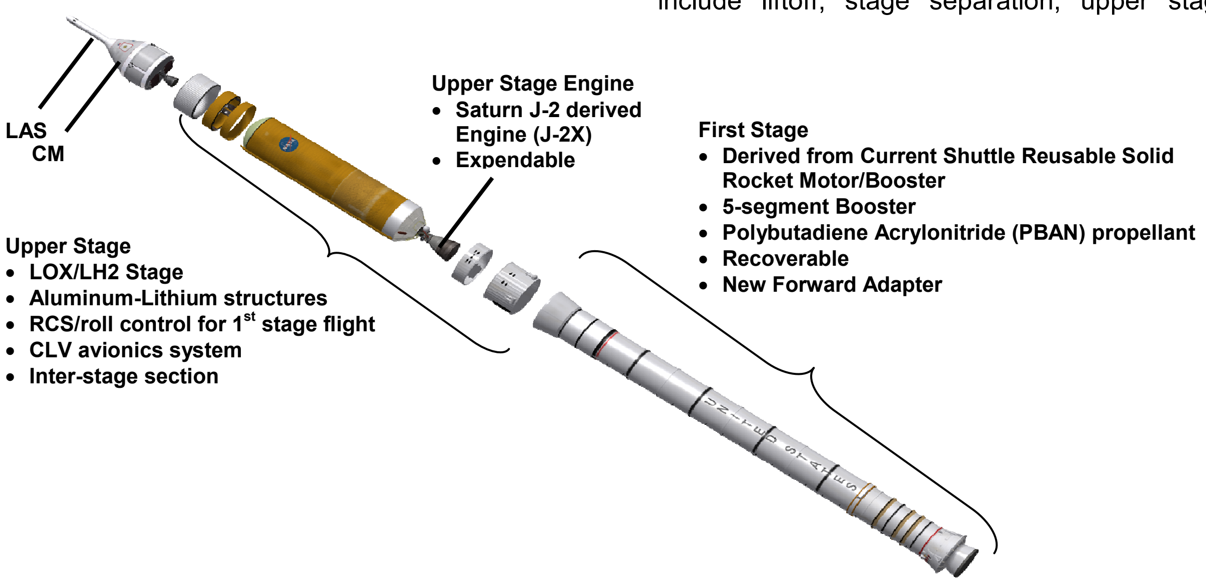

Figure 2. Schematic of the Ares I Launch Vehicle.

burn, LAS jettison, 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 recoverable.

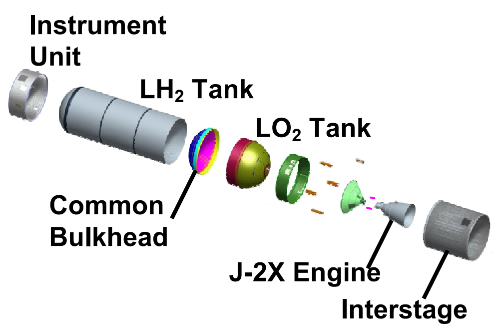

Figure 3. Ares I Upper Stage components, including J-2X Engine.

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 sub-system 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, to define or mature requirements, to design hardware or software, to define manufacturing processes, to define qualification or acceptance test procedures, or to investigate anomalies discovered during prior 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 during the development phase at the component, sub-system, and major assembly level. First Stage is conducting tests of the deceleration sub-system, which include drop tests and deployment of the parachute systems to enable recovery of the FSB. Multiple static

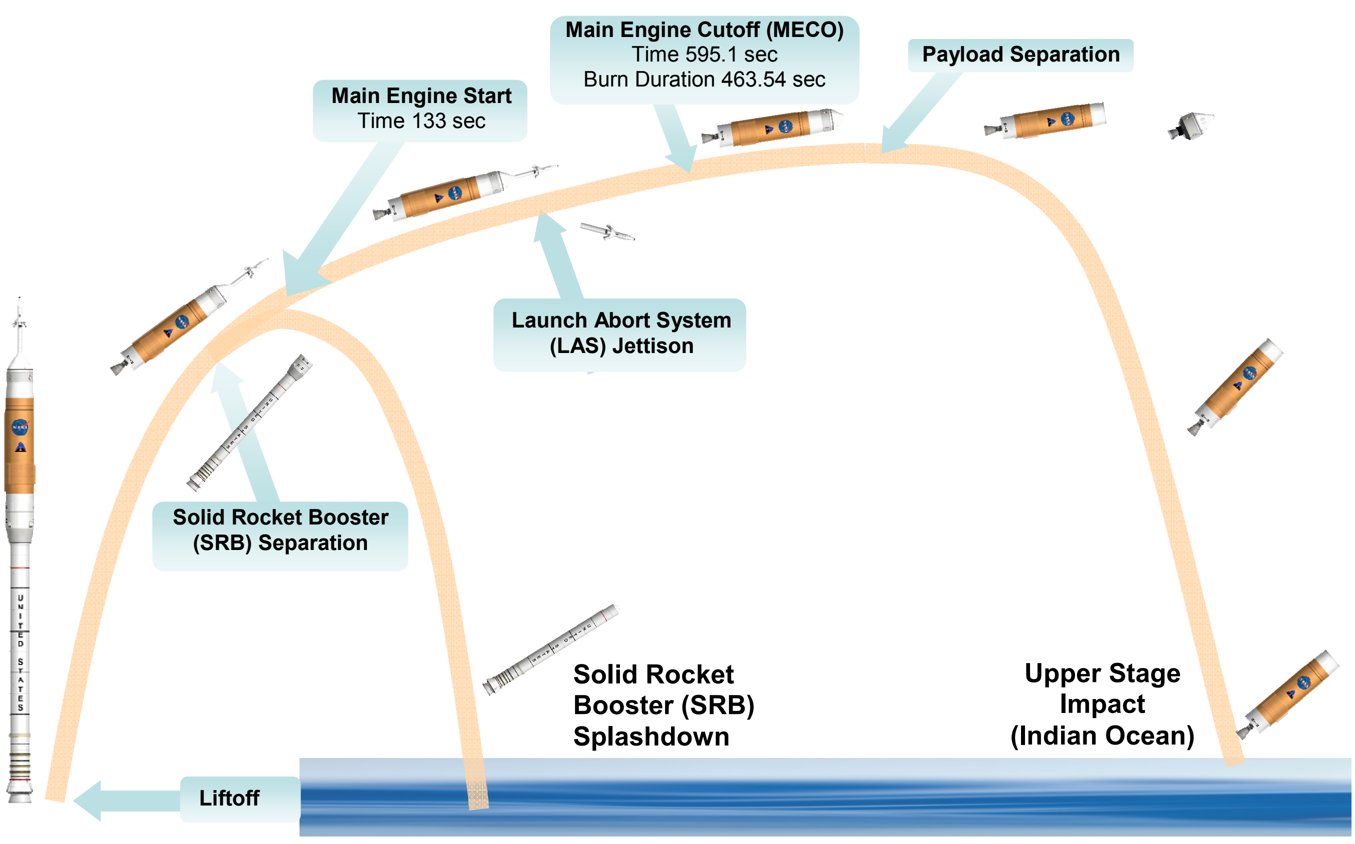

Figure 4. Ares I Design Reference Mission for ISS Access.

firings of development test motors will be performed, beginning in 2009. USE is conducting extensive development testing at both sea level and simulated altitude conditions to verify engine performance and certify operational capability prior to flight. NASA is building a new engine test facility, designated as the A-3 test stand, to provide a new capability for simulated altitude testing of the J-2X engine. Upper Stage is conducting structural strength tests of the integrated stage with the LH_2 and LO_2 tanks in the common bulkhead configuration. Major integrated system tests that will 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 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 sub-systems 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.

Integrated System Tests

Integrated Propulsion System Testing

The Main Propulsion Testing 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 the stand 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 5. 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 2011 and continue through the Ares I Design Certification Review (DCR).

Figure 5. Photograph of the Advanced Engine Test Facility (AEFT) at NASA Marshall Space Flight Center (MSFC).

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 6. The photograph shows the two test stand positions, designated B-1 and B-2, 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 6. Photograph of the B-2 Engine Test Stand at NASA Stennis Space Center (SSC).

Integrated Vehicle Dynamic Testing

An integrated vehicle dynamic test (IVDT) will be conducted on a full-scale test article simulating the Ares launch vehicle configuration. This test will provide data necessary to validate engineering models for the flight control system performance and the structural dynamics response of the vehicle during the ascent profile. The primary objectives of the IVDT are to:

- Obtain and verify the vehicle mode shapes, frequencies, 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 IVDT 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 lift-off configuration will be simulated through the use of an FSB test article with an inert propellant segment that duplicates the mass, mass distribution, interfaces, and other key parameters of an operational FSB. The first stage burnout configuration will be simulated with an empty booster segment, 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, but will not include all sub-systems from the operational flight design. The J-2X engine will be represented by a mass simulator test article. A trade study will be conducted to determine the need for a second stage test to obtain data for the portion of the ascent profile after first stage separation.

Test hardware for the IVDT will begin arriving at NASA MSFC's Dynamic Test Stand in 2010 and 2011, with testing conducted in 2011 and 2012 to support design certification of the Ares I vehicle. Stacking operations prior to the IVDT will 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 soft suspension system to simulate the flight profile boundary conditions. Random and sinusoidal excitation will be used to identify resonance response, damping values, and bending mode shapes.

The Dynamic Test Stand was utilized 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 7. A key element of the IVDT 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.

Integrated Vehicle Performance Testing

Aerodynamic testing is being conducted to characterize aerodynamic performance during

Figure 7. 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.

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 was completed during the first design cycle 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. These early aerodynamic tests provided aerodynamic force, moment, and surface pressure data used to evaluate design cycle configuration trades and provide preliminary databases for structural loads and GN&C assessments. The results were also used to calibrate computational fluid dynamics (CFD) codes for higher-fidelity analyses. Figure 8 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. The test program prior to the Ares I preliminary design review (PDR) will include an evaluation of Reynolds number scale effects, proximity aerodynamic interference effects during stage separation, and higher-fidelity configuration assessments.

Aeroelasticity testing is being conducted to obtain data used to investigate aeroelastic effects and instabilities on vehicle structural loads and performance. Testing consists of rigid aerodynamic models to investigate 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 forward frustum of the first stage may cause regions of flow separation that will have

1.0-percent scale model

0.5-percent scale model

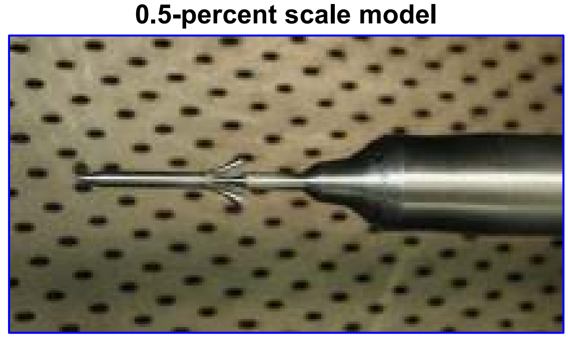

Figure 8. Photographs of 1.0-percent scale and 0.5-percent scale models tested in NASA Wind Tunnel Facilities.

an effect on aerodynamic loading in the transonic and low supersonic speed regime, where the vehicle experiences maximum dynamic pressure. Testing to investigate loads due to unsteady aerodynamic phenomena will also be performed. Finally, wind tunnel testing to model the launch vehicle configuration on the launch platform at the NASA Kennedy Space Center (KSC) will be performed to validate that the vehicle is capable of withstanding expected aerodynamic loading due to ground winds at the launch site. An initial feasibility test was performed in the NASA LaRC Transonic Dynamics Tunnel (TDT) in early 2007 to evaluate test technique approaches for ground winds loading.

Avionics and Software Testing

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 CEV interfaces, in the development SIL. The SIL provide an environment for real-time hardware-in-the-loop (HWIL) testing for formal verification of requirements, pre-launch support, day-of-launch support, and anomaly investigation.

Flight Testing

Development, validation, and operational flight tests will be performed prior to the first human launch of Ares I. Figure 9 shows the flight manifest leading to 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.

The Ares I-X development flight test will use a modified 4-segment SRB with an additional empty segment. The Upper Stage, J-2X, and CEV components will be non-functional mass simulator units. This approach is designed to achieve similitude with the Ares I operational vehicle with respect to aerodynamic characteristics, structural dynamics response, and control system design during first stage ascent and separation. The avionics system is a

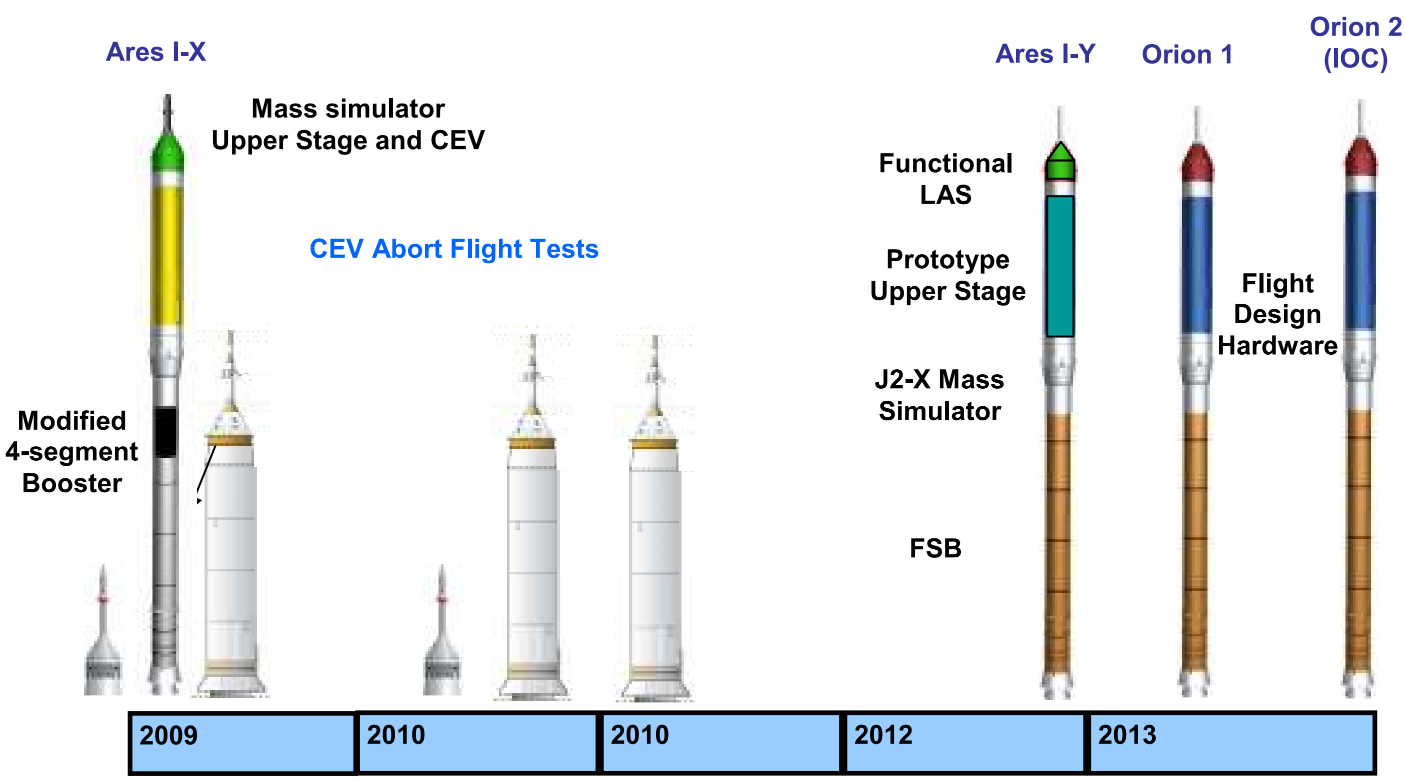

Figure 9. Ares Launch Vehicle and Crew Exploration Vehicle (CEV) Flight Test Elements.

commercial off-the-shelf (COTS) system designed to accommodate Ares 1-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 10.

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

- Demonstrate control of a dynamically similar, integrated CLV/CEV, using CLV ascent control algorithms.
- Perform an in-flight separation/staging event between a CLV-similar First Stage and a representative Upper Stage.
- Demonstrate assembly and recovery of a new CLV-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 un-crewed validation flight test conducted in September 2012. The Ares I-Y FTV will consist of an 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 will also 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. Additionally, the Ares I-Y will demonstrate the first assembly, processing, and launch from modified launch facilities at NASA 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 possibly cryogenic fuel fill and drain operations.

Orion 1 will be an un-crewed operational flight test conducted in March 2013. The Orion 1 vehicle will consist of flight-design hardware for

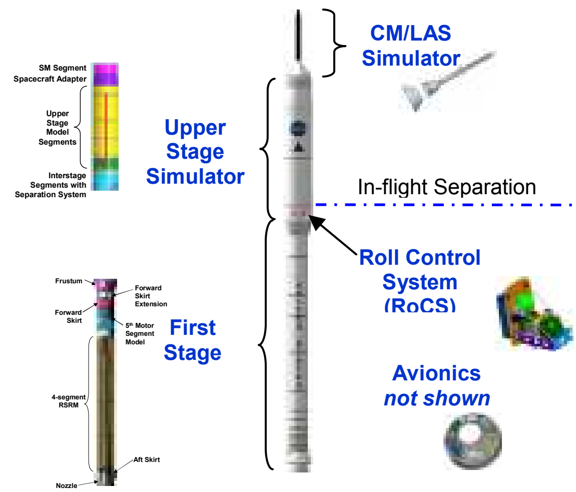

Figure 10. Components of the Ares I-X flight test vehicle (FTV).

the FSB, Upper Stage, J-2X, and CEV. 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. The flight will also insert the CEV into orbit, with re-entry, decent, and landing of the crew module. The first crewed launch of the Ares I vehicle is designated as Orion 2.

Concluding Remarks

NASA is developing the Ares I Crew Launch Vehicle (CLV) to meet the objectives of the Vision for Space Exploration (VSE). The Ares I will deliver the Crew Exploration Vehicle (CEV) to the International Space Station (ISS) and, together with the Ares V Cargo Launch Vehicle (CaLV), will provide the launch capability for future human exploration of the Moon. Test and verification strategies have been developed to meet vehicle design requirements.

The Main Propulsion Test Article (MPTA), consisting of an Ares I upper stage and upper stage development engine assembly, will undergo an extensive test program prior to design certification of the Ares I vehicle. Flight upper stage and upper stage engine assemblies will be hot-fire acceptance tested for the first three flights starting with the first un-crewed flight test involving an operational J-2X upper stage engine. A full-scale integrated vehicle dynamic test (IVDT) will be conducted in the NASA Marshall Space Flight Center (MSFC) Dynamic Test Stand, previously used for similar testing of the Saturn V and Space Shuttle. The

IVDT will provide data to calibrate critical engineering models used to characterize the structural dynamic response of the vehicle and for design of guidance, navigation, and control (GN&C) models. Aerodynamic testing is being conducted in various facilities spanning the ascent flight profile, including ground winds loading with vehicle and modified launch pad models.

A series of flight tests will be conducted prior to the first crewed launch. The Ares I-X development flight test will be conducted in 2009 with a modified 4-segment booster and non-functional simulators for the upper stage and CEV. The Ares I-X flight will demonstrate control of a dynamically-similar vehicle during the first stage of flight; demonstrate separation, re-entry, and recovery of the first stage booster; and will provide data to calibrate key engineering models. The Ares I-Y flight test will be conducted in 2012 with a five-segment FSB, flight-design upper stage, and a mass simulator to represent the J-2X upper stage engine. The Ares I-Y flight follow the Ares I first stage ascent flight profile, including separation and re-entry of the first stage booster. This flight will also demonstrate a high-altitude abort scenario through actuation of the launch abort system (LAS) following stage separation. An un-crewed operational flight test, designated as Orion-1, will be conducted prior to the first crewed launch. The Orion-1 flight will be the first test will production flight hardware for the launch vehicle and CEV and will follow the nominal flight profile for delivery of the CEV to low Earth orbit (LEO) as well as re-entry, landing, and recovery of the crew module.

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