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Synergistic Development, Test, and Qualification Approaches for the Ares I and V Launch Vehicles

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Abstract

The U.S. National Aeronautics and Space Administration (NASA) initiated plans to develop the Ares I and Ares V launch vehicles in 2005 to meet the mission objectives for future human exploration of space. Ares I is designed to provide the capability to deliver the Orion crew exploration vehicle (CEV) to low-Earth orbit (LEO), either for docking to the International Space Station (ISS) or docking with an Earth departure stage (EDS) and lunar lander for transit to the Moon. Ares V provides the heavy-lift capability to deliver the EDS and lunar lander to orbit. An integrated test plan was developed for Ares I that includes un-crewed flight validation testing and ground testing to qualify structural components and propulsion systems prior to operational deployment. The overall test program also includes a single development test flight conducted prior to the Ares I critical design review (CDR). Since the Ares V concept was formulated to maximize hardware commonality between the Ares V and Ares I launch vehicles, initial test planning for Ares V has considered the extensibility of test approaches and facilities from Ares I. The Ares V test plan was part of a successful mission concept review (MCR) in 2008.

Nomenclature

BDM	booster deceleration motor
CDR	critical design review
CEV	crew exploration vehicle
CFM	cryogenic fluid management
CM	crew module
EDS	Earth departure stage
FSB	five segment booster
FTV	flight test vehicle
GN&C	guidance, navigation, and control
HAA	high altitude abort
LAS	launch abort system
LEO	low-earth orbit
LH_2	liquid hydrogen
LO_2	liquid oxygen
LSC	linear shape charge
IOC	initial operational capability
ISS	international space station
ISTA	integrated stage test article
IVGVT	integrated vehicle ground vibration test
MCR	mission concept review
MECO	main engine cut-off
MLP	mobile launch platform
MPS	main propulsion system
MPTA	main propulsion test article
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Admin.
OET	orbital environments test
PDR	preliminary design review
RCS	reaction control system
SA	spacecraft adapter
SLWT	Super Lightweight (External) Tank
SM	service module
SRB	solid rocket booster
SSC	Stennis Space Center
TLI	trans-lunar injection
TVC	thrust vector control
USM	ullage settling motor

Introduction

The U.S. National Aeronautics and Space Administration (NASA) initiated the development of new launch vehicles in 2005 to provide the capability for future human and cargo transport to the International Space

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Station (ISS) and future human exploration of the solar system. Ares I was initiated to provide crew transport capability to low-earth orbit (LEO), while Ares V was selected to provide the heavy-lift cargo transport capability necessary for lunar exploration and beyond. The two vehicle concepts were selected on the basis of development cost, safety, performance, and operational life cycle costs. In order to minimize costs, commonality between hardware elements was also a selection factor.[1] This transportation system is also extensible to potential future exploration of near-Earth objects and Mars. The Ares V could also provide for enhanced science mission capability.[2,3]

The Constellation Program was initiated to develop the systems for both initial (ISS transportation) and lunar capability, including Ares I, Ares V, the Orion crew exploration vehicle (CEV), the lunar lander, and future lunar surface systems. ISS capability development began in 2005. The design, development, test, and evaluation (DDT&E) plan for Ares I includes an integrated test plan with ground testing leading to vehicle qualification, and flight validation testing leading to initial operational capability (IOC). Additionally, a development flight test, known as Ares I-X, was formulated to provide flight data in the early development stages. Concept development was also initiated for the lunar capability phase. Ares V conducted a mission concept review (MCR) in 2008 which included a point of departure (POD) configuration and DDT&E plan that builds on Ares I approaches. The synergistic test approaches for Ares I and V are the result of element commonality.

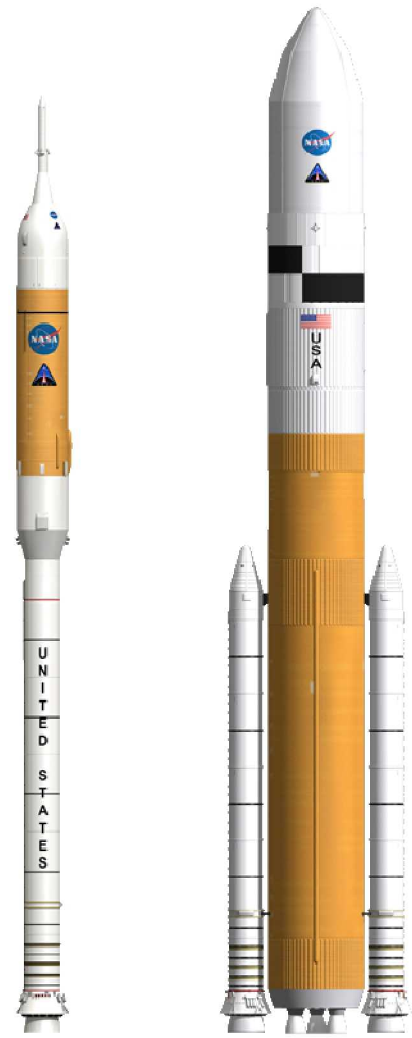

Figure 1. Ares I and V launch vehicle concepts.

Configuration Description

The Ares I (Figure 1) is designed to deliver the Orion CEV to LEO, either for docking to the ISS or docking with the Earth departure stage (EDS) for lunar transit. The Ares V (also shown in figure 1) is designed to deploy the EDS and the lunar lander into LEO for docking with Orion. Following a maximum 4-day loiter period in LEO, the EDS/lunar lander/Orion system is to perform a trans-lunar injection (TLI) burn for transit to the Moon.

Figure 2 shows the major components of the Ares I vehicle. The first stage is a five-segment solid rocket motor, derived from the Space Shuttle Solid Rocket Booster (SRB), also known as the five-segment booster (FSB). The upper stage, powered by a single J-2X upper stage engine, is to provide the thrust required for second stage flight. The J-2X is a derivative of the Saturn V J-2 upper stage engine. The Ares I upper stage design consists of a liquid hydrogen (LH_2) and liquid oxygen (LO_2) common-bulkhead cryogenic fuel tank, 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 the instrument unit with avionics hardware. The Ares I upper stage is to provide all guidance, navigation, and control (GN&C) for the first and second stages of flight in conjunction with FSB and J-2X avionics. 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.

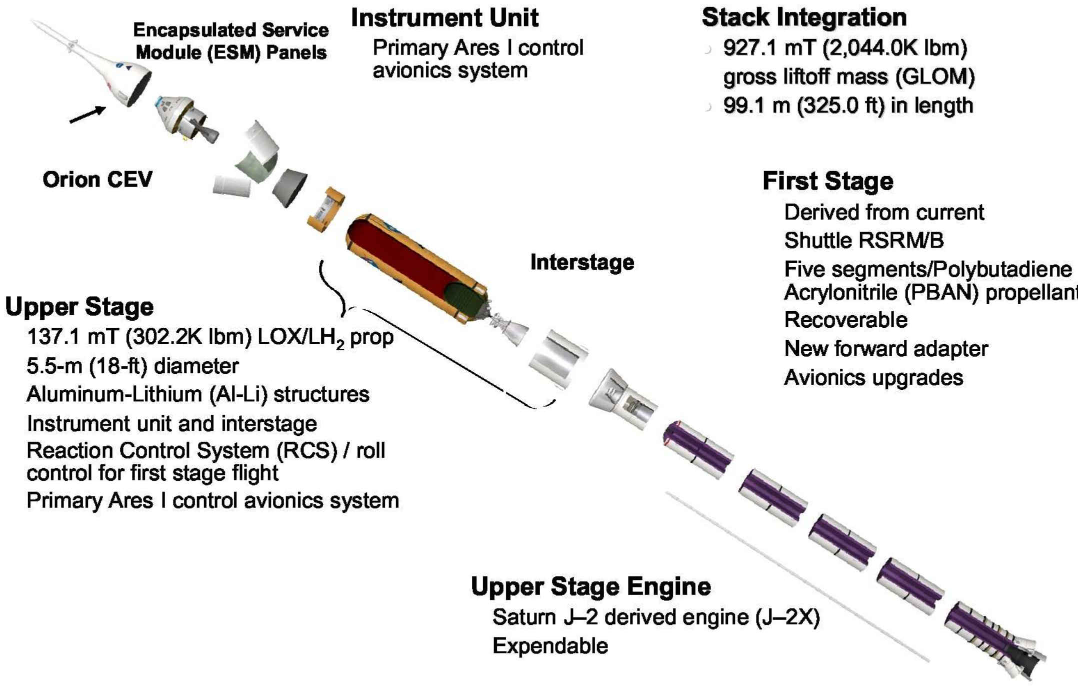

Figure 2. Major components of the Ares I crew launch vehicle concept.

Figure 3 shows the major components of the Ares V POD configuration. This configuration consists of a core stage, powered by six RS-68B LH_2/LO_2 engines, two solid rocket boosters, an EDS, powered by a single J-2X engine, and two solid rocket boosters. The J-2X engine which powers the EDS is identical to the Ares I upper stage engine. The FSB is also similar to the Ares I first stage booster, but options exist for upgrades, including propellant grain formulation, composite casing, longer nozzle extension, electro-mechanical TVC actuators, and a longer booster for additional performance. The Ares V also has a payload shroud which houses the LSAM. Figure 4 describes the common vehicle elements for Ares I and V, including heritage systems from the Saturn V and the Space Shuttle. The design concept for Ares V presents some test and verification challenges. There is a requirement for the EDS to remain in LEO for a maximum 4-day loiter period and perform the TLI burn. Cryogenic fluid management (CFM) to ensure settling of fluid in the propellant tanks, thermal management, delivery of propellants to the J-2X engine, and re-start of the engine must be considered. Larger-diameter metallic and composite structures create challenges for structural qualification testing, dynamic testing, logistics, and manufacturing. Developing and validating similar flight performance models will be necessary as part of the Ares V qualification plan (aerodynamics, vibro-acoustic, structural dynamics, loads, thermal, control system development), but the size and complexity will be increased compared to Ares I.

Development Flight Testing

During the Constellation program's formulation phase, options for development flight testing were examined. The systems engineering life cycle generally includes development, detailed design, production, and deployment phases. The development phase generally concludes with the critical design review (CDR). Although it is a significant undertaking, flight testing during the development phase may be performed if system requirements cannot be fully validated or uncertainties cannot be fully quantified through ground testing and analysis. The risk to early development testing is that the flight test vehicle configuration must be determined well before the design of the operational configuration reaches full maturity.

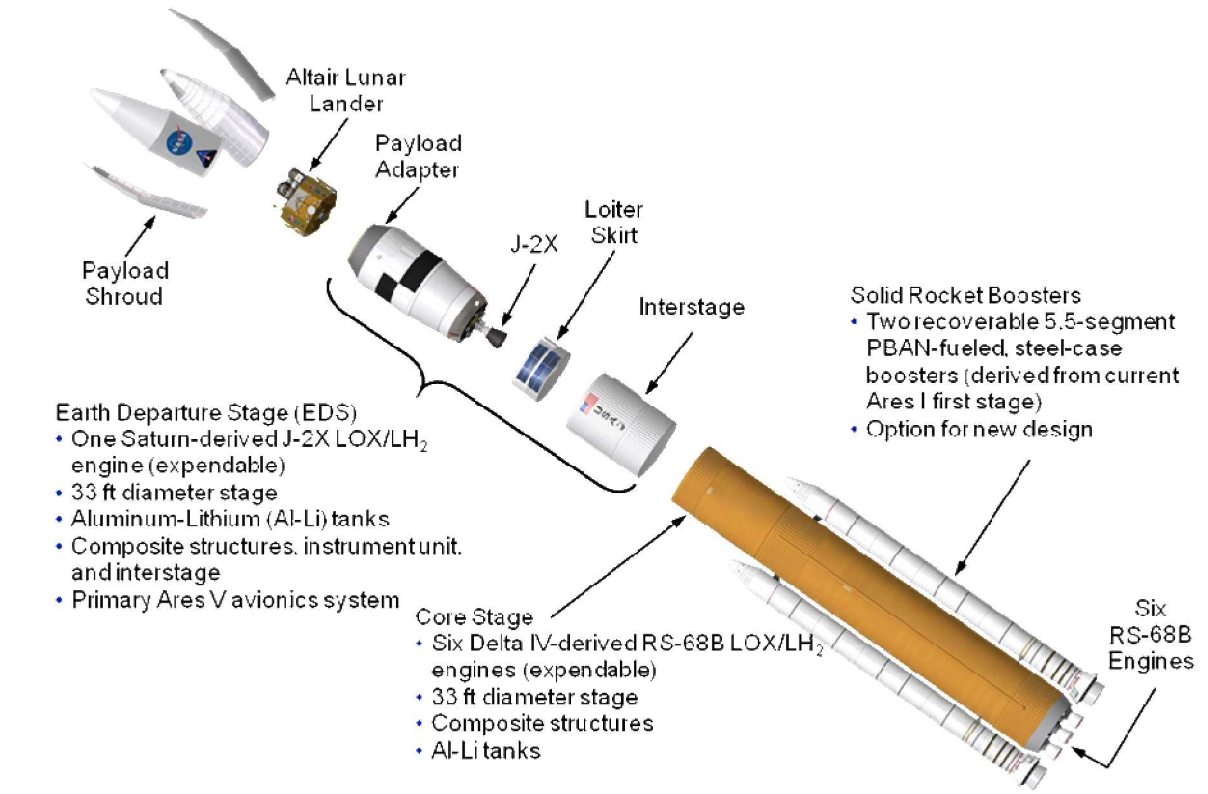

Figure 3. Major components of the Ares V heavy-lift launch vehicle concept.

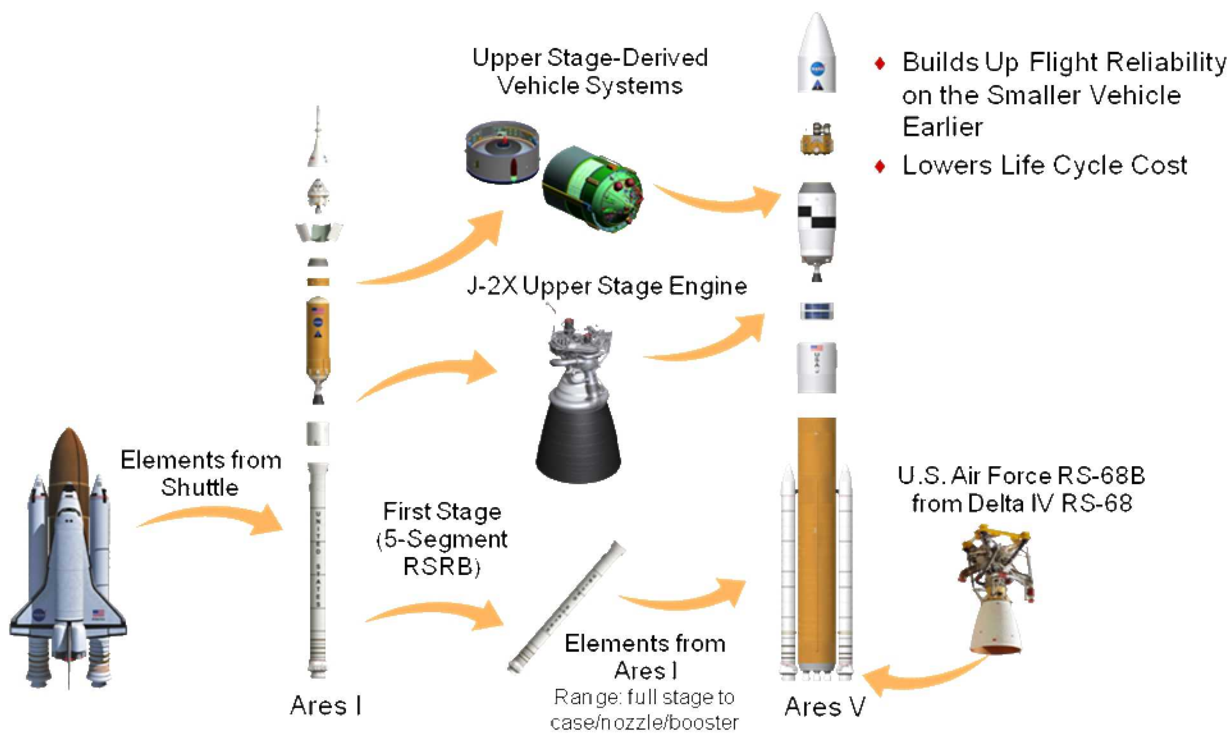

Figure 4. Common vehicle elements of Ares I, Ares V, and heritage systems.

A study team examined options for early development flight testing by considering the following.[4]

- *Key Ares I technical risks:* During the formulation phase, the key technical risks that could be mitigated through flight testing were identified as first stage ascent performance (including flight control system methodology), development of a new deceleration system for first stage, launch abort system functionality, and stage separation.

- *Availability of flight assets:* The ability to test early was a function of the flight test vehicle (FTV) configuration, ability to deliver flight assets, and the risk that the development FTV would depart from the operational configuration.

- *Lessons learned:* Experiences from Saturn, Shuttle, and other launch vehicle development programs that demonstrated the benefits of early flight testing.

Since a five-segment booster and prototype upper stage could not be made available as flight assets prior to the Ares CDR, the key to formulation was analysis that examined the use of an existing Space Shuttle four-segment SRB with a fifth-segment simulator and a mass-simulator upper stage. The analysis showed that the dynamic response of the Ares I vehicle could be approximated with a four-segment booster, an added inert fifth segment, and a mass simulator upper stage, crew module, and LAS. The result was the formulation of the Ares I-X flight test, which is currently scheduled to fly no earlier than October 31, 2009. There are five primary test objectives associated with Ares I-X as indicated in figure 5.

The Ares I-X flight test objectives have evolved as the Ares I and the Ares I-X configurations have matured though their respective design and development phases. As an example, demonstrating the Ares I stage separation was initially a primary objective for Ares I-X. However, the evolution of the Ares I-X upper stage simulator design and the post-separation characteristics of the first stage booster necessitated a change in the separation plane location. Also, the dynamic response of the Ares I-X vehicle does not duplicate the Ares I response, but both configurations are still characterized by low bending mode frequencies and use a similar control system algorithmic approach.[5]

The Ares I-X flight will provide valuable data

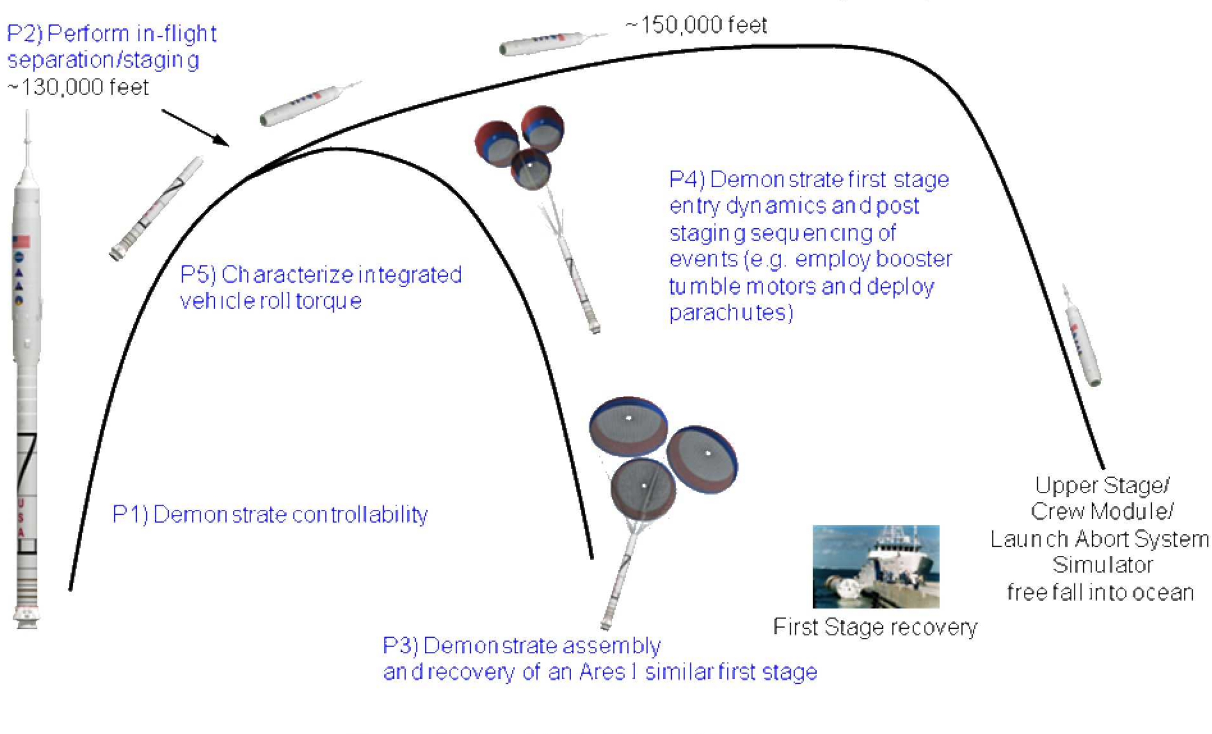

Figure 5. Ares I-X flight test objectives.

to validate key engineering tools, methods, and processes for Ares I development. A detailed flight test analysis plan was developed for use in engineering model validation prior to Ares I CDR.

Validation Flight Testing

Flight validation testing is essential to the deployment of new operational launch systems. Flight testing is not used as part of the formal process of verifying system requirements, which is typically done through analysis, ground test, or inspection. Rather, flight testing is used to demonstrate the functionality of the integrated system in the correct environment. This includes demonstrating complex system interactions that cannot be tested on the ground. Lessons learned from early Shuttle flights demonstrated the significance of engineering model validation and the impacts to flight vehicle design.[4]

The general approach for Ares flight validation testing is to conduct one or two un-crewed test flights with production (or production equivalent) hardware. Options exist for a possible sub-orbital test flight and/or a launch site operations pathfinder using a mixture of flight production systems, prototypes, and/or simulators. IOC is achieved with the first crewed flight and docking with the ISS.

The flight test objectives for the validation phase of the program generally fall into three categories.

- Ground assembly and vehicle integration, including mechanical, electrical, and fluid connections, loading of cryogenic propellants, and launch pad operations.

- Ares first and second stage flight performance, including operation of the five-segment booster, integrated first stage performance, stage separation, and powered second stage flight to main engine cutoff (MECO). (Descent and recovery of the first stage booster are also potential test objectives.)

- Orion CEV orbital insertion, orbital operations (including proximity operations and docking with the ISS), re-entry, descent, landing, and recovery.

The first un-crewed validation flight test was designated as Ares I-Y. The Ares I-Y FTV was formulated as a flight-production FSB, prototype upper stage, J-2X mass simulator, and prototype Orion. Ares I-Y was formulated as a demonstration of first stage flight, stage separation, descent and recovery of the FSB. Demonstration of an Orion LAS high altitude abort (HAA) was studied as a flight test objective, but was deleted following maturation of Orion LAS verification and test plans.

The requirements for the Ares I-Y upper stage configuration were matured through initial trade studies. An appropriate simulation of the structural load path and dynamic response requires flight-like propellant tanks and primary structures. Loading of cryogenic propellants in the upper stage fuel tanks is also required to provide the appropriate mass, mass distribution, and propellant slosh characteristics during the first stage ascent, even without second stage engine operation. Other risks mitigated through using cryogenic propellants include demonstration of ground operations at KSC for fill and drain, characterization of propellant slosh during ascent, demonstration of propellant tank ullage pre-pressurization, and characterization of the ullage due to the separation shock (risk of ullage collapse during the separation event and the need for rapid pressurization).

Additional studies performed to mature the Ares I-Y FTV included:

- Ability of the Ares I-Y FTV to demonstrate the J-2X engine “start box” conditions. The potential to achieve this test objective is limited with a J-2X mass simulator, but could be enhanced by using a development test engine, or an upgraded simulator that included fuel circulation lines.

- Ability of the Ares I-Y FTV to demonstrate the first stage-upper stage separation systems and sequence. During the Ares I design phase, trade studies were performed to define the Ares I separation sequence and a test and verification plan for separation systems was developed.[6] The baseline sequence is to have a separation plane at the upper stage-interstage interface, activated by a linear shape charge (LSC). (More recently, the LSC design was modified to use a frangible joint, which provides instantaneous separation of components while minimizing explosive debris.) The upper stage ullage settling motors (USM) are also activated during the sequence to accelerate the stage away from the first stage and booster deceleration motors (BDM) are fired to orient the first stage for re-entry. Flight validation is a central element of the separation systems test and verification plan. A sub-orbital Ares I-Y could achieve a partial validation of the separation sequence without firing of the USMs and the J-2X engine.

- Ability of the Ares I-Y FTV to incorporate thrust oscillation damping and characterize the vibration response. Thrust oscillation of the solid rocket motors was identified a technical risk as the Ares I design matured. The analysis indicated a risk that the oscillations would be at the resonant frequency of the integrated launch vehicle stack, resulting in an unacceptably high vibration response at the crew module location. Flight validation is a critical component of the verification plan.

- Requirements for Ares I-Y flight software development, testing, and delivery. Due to some differences between the Ares I-Y and the operational Ares I configuration, the Ares I-Y FTV requires a unique flight software version.

A second un-crewed validation flight test is designated Orion 1. The Orion 1 FTV configuration is to include a flight-production FSB, flight-production upper stage, and a J-2X development engine delivered for flight following its development test series. Orion 1 is also to include recovery of the FSB, delivery of the Orion crew module to LEO, proximity operations with the ISS, and re-entry, landing, and recovery of the crew module. Opportunities to re-configure the Ares I-Y and Orion 1 configurations based on this evolution of test requirements will be studied further prior to the Constellation preliminary design review (PDR), scheduled for early 2010.

Ares V Flight Validation

The initial test plan for Ares V contains a single validation test flight prior to a combined Ares I/V operational flight. The first Ares V flight is designated Ares V-Y. While still in the early formulation stage, consideration of key Ares V-Y test objectives were part of the 2008 MCR. These include:

- Operation of the core stage system with RS-68B engines through the first stage profile, including burn, separation, and potential recovery of the first stage solid rocket boosters.

- Full duration burn of the EDS to orbital insertion of the payload, including shroud deployment.

- Aspects of CFM during LEO loiter and re-ignition of the J-2X engine for the TLI burn. The first flight may or may not include a full duration burn.

Propulsion and Stage Systems Testing

The Ares I integrated test plan, test data analysis, and engineering model correlation was structured to be complete prior to the Design Certification Review (DCR). The DCR includes full verification of all system requirements prior to operational flights. However, key system and sub-system tests must be complete or partially complete prior to the un-crewed validation flight tests (Ares I-Y and Orion 1).

The upper stage engine plans to conduct 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 at Stennis Space Center (SSC), to provide a new capability for simulated altitude testing of the J-2X engine.[7] Engine certification testing is to be complete prior to the current Orion 1 flight date. Four development motor static firings and three qualification static firings of the FSB are to be performed. All of the FSB qualification testing are to be complete prior to Ares I-Y.

The upper stage integrated stage test article (ISTA) is a key integrated systems test. The ISTA consists of a prototype upper stage test article and a development J-2X engine, which is to be delivered for stage testing after completion of a series of engine development tests. Key objectives of the ISTA are to verify the upper stage system performance during propellant fill and drain, engine start, main stage operation, and shutdown. Stage operation includes tank pressurization, engine conditioning, engine gimbaling, integration of sub-systems, and functionality of the MPS. Thermal qualification testing of the instrument unit and interstage subsystems is also planned for the ISTA test series. (The addition of thermal qualification test objectives led to the ISTA designation as compared to an earlier designation as the main propulsion test article (MPTA).) The ISTA test series is to be partially completed prior to the current Ares I-Y and Orion 1 flight dates. ISTA cold-flow testing (fill and drain operations with cryogenic propellants) provides risk mitigation for launch site operations prior to Ares I-Y and ISTA hot-fire testing provides risk reduction prior to acceptance testing and flight of the Orion 1 flight stage.

Starting with Orion 1, all of the integrated flight stages are to be acceptance tested with their flight engines at the SSC B-2 test stand prior to arrival at the launch site. The approach to acceptance testing was addressed through a trade study completed in the formulation stage of the Ares Project.[8] Several options were examined, including no acceptance testing, testing every flight stage with a slave engine until experience dictated otherwise, cold-flow testing only at the pad (wet flight readiness test), and hot-fire testing of every flight stage with its flight engine until experience dictates otherwise. The latter approach was selected as the baseline with the intent that acceptance testing will be examined after 3-5 flights.

Similar approaches to development and acceptance testing have been incorporated in the initial Ares V test plan reviewed at the MCR. During Ares I development, the J-2X engine is to be qualified for atmospheric operation. Options for orbital environments testing (OET) have been studied to validate the ability of the EDS to deliver cryogenic propellants at conditions required for re-start of the engine. The POD test plan includes a sub-scale EDS test article and a J-2X development engine in a simulated thermal-vacuum environment. OET and re-start validation is to be accomplished through short duration hot-fire testing to demonstrate re-start capability.

The integration of the core stage with 6 RS-68B engines was considered in the POD test plan. The plan includes an integrated stage test article, similar to the Ares I upper stage ISTA. The integrated core stage testing programs are to be conducted at the SSC B-2 test facility. The B-2 test stand was first used in the Saturn S-IC test program and was subsequently used to test the Space Shuttle MPTA. The B-2 test stand is also to be used for Ares I upper stage acceptance testing and some facility modifications will be required to support Ares V core stage testing.

Structural Qualification and Modal Testing

The Ares I upper stage is planning structural qualification testing. A structural test article that includes the common-bulkhead propellant tanks, domes, and aft thrust structure is to be tested with cryogenic propellants. Sufficient completion of the upper stage structural qualification testing is necessary prior to the Ares I-Y flight.

Trade studies have examined potential approaches for cryo-structural qualification testing for both the core and Earth departure stages for Ares V. A full-scale test of the core stage LH_2 tank loaded with cryogenic propellants would require a substantial facility investment. Therefore, an analysis of sub-scale testing (full-scale diameter, single barrel section) has been performed. The Space Shuttle super-light-weight external tank (SLWT) was qualified in this manner with a test article known as the Aluminum Lithium Test Article (ALTA).[9] The ALTA was a single barrel section with forward LH_2 dome and aft LO_2 dome. An initial buckling assessment of the Ares V core stage LH_2 tank was performed and the analysis showed that a sub-scale test article could capture the stability failure behavior of a full scale tank. However, additional analysis will continue as the Ares V design matures.

A full-scale integrated vehicle ground vibration test (IVGVT) is also planned for Ares I, to be conducted at the Marshall Space Flight Center (MSFC) dynamic test stand, which is shown in figure 6. These tests are to provide data necessary to validate engineering models for the flight control system performance and the vehicle's structural dynamics response during ascent.[10] The primary objectives of the IVGVT are to:

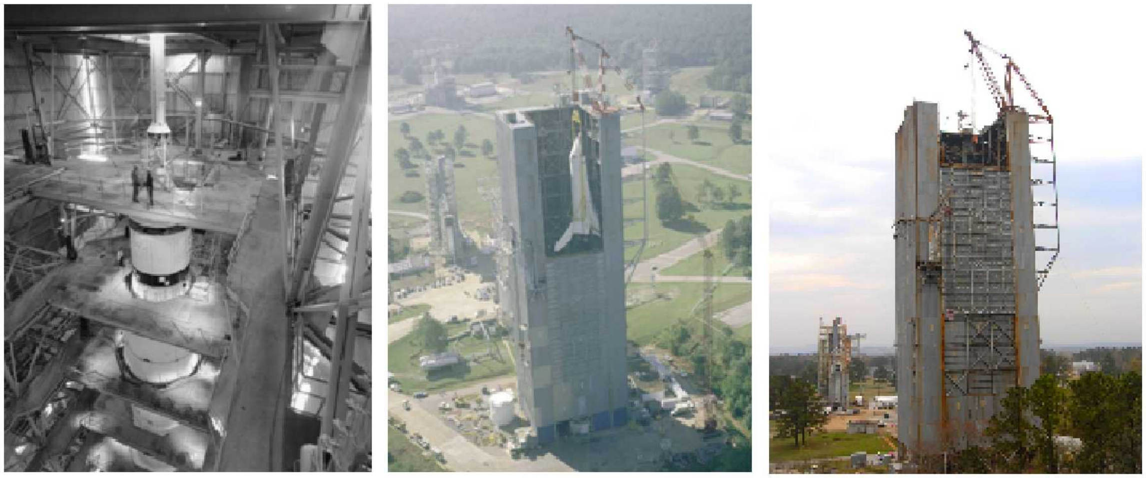

Figure 6. Photographs of the MSFC Dynamic Test Stand with the Saturn V, Space Shuttle, and in preparation for Ares I testing.

- 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 to be 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.

In addition to the baseline tests of the liftoff and first stage burnout configurations, a complete second stage test series was added early in the test planning. The "short stack" test consists of the Orion and upper stage configurations and is to characterize the modal response of the flight vehicle following stage separation. Four tests are planned for this configuration, covering major mass shifts from the full upper stage at USE ignition to the point on the trajectory of upper stage main engine cutoff. The IVGVT test series is to be complete prior to Ares I-Y, but full correlation of the test data with engineering finite element models may not occur until the Ares I DCR.

Extensive analysis has been conducted to define the test article requirements for IVGVT. The liftoff configuration requires an 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 requires empty booster segments, which would be refurbished and used as flight hardware for later Ares I flights. The upper stage test article requires a close approximation of the Ares I upper stage primary structure, including propellant tanks, but not all subsystems from the operational flight design. The J-2X engine requires a mass simulator test article. The Orion test article requires high-fidelity dynamic mass simulators, sufficient to model the primary structure and approximate the overall vehicle dynamic response.

Ares I-X also conducted modal testing of the Ares I-X FTV. The Ares I-X modal test plan consisted of two partial stack tests and a full-stack test conducted on the mobile launch platform (MLP). The first partial stack consisted of the Orion simulator hardware (crew module, service module, spacecraft adapter, and launch abort system). This partial stack captured the CM/SM interface. The second partial stack consisted of the interstage, frustum, forward skirt, and the SRB's fifth segment simulator. The two partial-stack configurations did not represent flight configurations, but provided a partial correlation of engineering models through testing that included critical interfaces along the load path. This approach allowed for verification of the complete vehicle modal response (natural frequencies, mode shapes, and damping characteristics) through a "build up" of finite element models used to analyze each structural component. The full-stack test on the MLP provided a final validation of the full vehicle response.

The use of the MSFC dynamic test stand for potential dynamic testing of Ares V has been examined. Full-scale modal testing of the Ares V POD configuration would require modifications to the facility to account for door clearance and height of the Ares V vehicle. Lessons learned from Ares I-X and Ares I modal testing will assist in a better understanding of engineering model predictive capabilities and requirements to validate these models through modal testing of the Ares V vehicle.

Concluding Remarks

Design and development of the Ares I launch vehicle was initiated in 2005. Flight validation testing for the Ares I is currently planned as a set of two flight tests, known as Ares I-Y and Orion 1, with extensive ground testing being conducted prior to flight and full design certification. Key system-level ground tests include development and certification testing of the liquid-fueled J-2X engine and static firings of the five-segment solid rocket motor. The upper stage, which houses the liquid propellant tanks, avionics, and other subsystem required for second stage flight of Ares I, is to undergo structural qualification testing, integrated stage testing with the J-2X engine, and acceptance testing of flight stages and engines starting with Orion 1. An integrated ground vibration test is to be conducted for Ares I in order to experimentally determine natural bending mode frequencies, mode shapes, and damping characteristics for control systems development prior to flight.

A development flight test, known as Ares I-X, was formulated early in the Ares I design and development process. While there are some differences between the Ares I-X flight test vehicle and the Ares I operational configuration, this development flight test will provide data to inform engineering model development used in the Ares I design process. The Ares I-X is also conducted modal testing on the integrated vehicle stack as well as two partial stack configurations to validate the finite element models used to predict the dynamic response of the vehicle.

Ares V concept development was initiated in 2005. An initial test plan was reviewed at the 2008 mission concept review and includes structural qualification testing, integrated stage propulsion systems testing, integrated vehicle modal testing, and flight validation testing. The Ares V test plan will continue to mature prior to future system development.

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