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Engineering America's Future in Space: Systems Engineering Innovations for Sustainable Exploration

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Abstract

The National Aeronautics and Space Administration (NASA) delivers space transportation solutions for America's complex missions, ranging from scientific payloads that expand knowledge, such as the Hubble Space Telescope, to astronauts and lunar rovers destined for voyages to the Moon. Currently, the venerable Space Shuttle, which has been in service since 1981, provides U.S. capability for both crew and cargo to low-Earth orbit to construct the International Space Station, before the Shuttle is retired in 2010, as outlined in the 2006 NASA Strategic Plan.[1] In the next decade, NASA will replace this system with a duo of launch vehicles: the Ares I Crew Launch Vehicle/Orion Crew Exploration Vehicle and the Ares V Cargo Launch Vehicle/Altair Lunar Lander (figs. 1 and 2). The goals for this new system include increased safety and reliability, coupled with lower operations costs that promote sustainable space exploration over a multi-decade schedule.

Fig. 1. The Ares I/Orion will provide crew transportation in the 2014–15 timeframe; test flights begin in 2009.

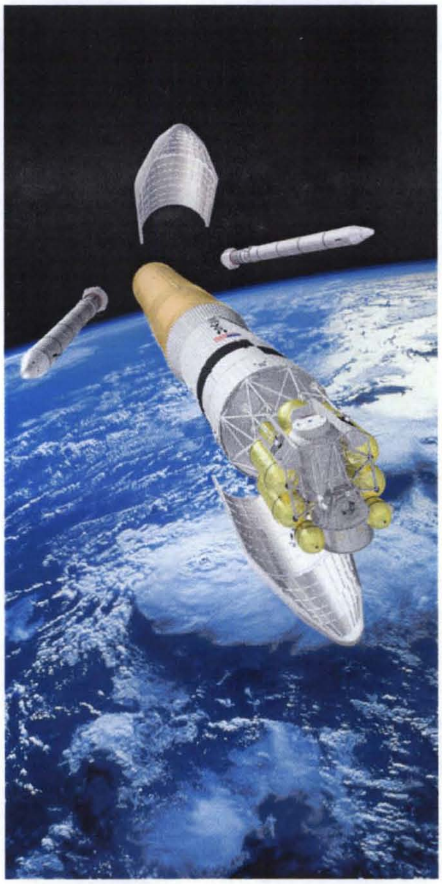

Fig. 2. The heavy-lift Ares V will transport the Altair to low-Earth orbit; its Earth departure stage will place payloads and the mated Orion crew capsule into lunar orbit in the 2020 timeframe (NASA concept).

It has been 30 years since the United States last designed and built a human-rated launch vehicle. NASA has marshaled unique resources from the Government and private sectors to perform the technically and programmatically complex work of delivering a next-generation space exploration architecture. NASA's experience has taught the value of adhering to sound systems engineering principles, while applying aerospace best practices and lessons learned. To fly humans safely aboard a launch vehicle requires a variety of methodologies to reduce the technical, schedule, and cost risks inherent in the complex business of space transportation.

NASA's Marshall Space Flight Center manages the Shuttle's propulsion elements, as well as science operations on the Station. Its engineers also are performing design, development, test, and evaluation of the Ares rockets, along with a host of other assignments in the fields of science and exploration.[2] The Marshall Center's Engineering Directorate provides the skilled workforce and unique capabilities needed to build modern systems upon the 50-year foundation laid by the Mercury, Gemini, Apollo, and Shuttle programs. The Engineering Directorate's Spacecraft and Vehicle Systems Department is a microcosm of the breadth of work being performed, including sustaining engineering for current missions, as well as design and development for future science and exploration missions. Taking a disciplined approach to marrying requirements with a sound technical architecture, Space and Vehicle Systems personnel apply industry best practices such as Lean Six Sigma, as well as sound systems engineering and integration practices, as codified in NASA's Systems Engineering Processes and Requirements document, which provides clear standards and milestone guideposts for measuring progress.[3]

This paper will provide details of the in-house systems engineering and vehicle integration work now being performed for the Ares I and planned for the Ares V. It will give an overview of the Ares I system-level test activities, such as the ground vibration testing that will be conducted in the Marshall Center's Dynamic Test Stand (see fig. 3) to verify the integrated vehicle stack's structural integrity against predictions made by modern modeling and simulation analysis. It also will give information about the work in progress for the Ares I-X developmental test flight planned in 2009 to provide key data before the Ares I Critical Design Review. Activities such as these will help prove and refine mission concepts of operation, while supporting the spectrum of design and development tasks being performed by Marshall's Engineering Directorate, ranging from launch vehicles and lunar rovers to scientific spacecraft and associated experiments. Ultimately, the work performed will lead to the fielding of a robust space transportation solution that will carry international explorers and essential payloads for sustainable scientific discovery beyond planet Earth.

Fig. 3. The Space Shuttle was structurally tested in the Marshall Center's Dynamic Test Stand, which will be used for the Ares I integrated stack testing.

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Engineering America's Future in Space: Systems Engineering Innovations for Sustainable Exploration

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Abstract

The National Aeronautics and Space Administration (NASA) delivers space transportation solutions for America's complex missions, ranging from scientific payloads that expand knowledge, such as the Hubble Space Telescope, to astronauts and lunar rovers destined for future voyages to the Moon. Currently, the venerable Space Shuttle, which has been in service since 1981, provides U.S. capability for both crew and cargo to low-Earth orbit to construct the International Space Station, before the Shuttle is retired in 2010, as outlined in the 2006 NASA Strategic Plan. In the next decade, NASA will replace this one-of-a-kind system with an evolutionary architecture: the Ares I crew launch vehicle/Orion crew exploration vehicle and the Ares V cargo launch vehicle/Altair lunar lander. The goals for this new transportation system include increased safety and reliability, coupled with lower operations costs that promote stable space exploration over a multi-decade schedule. It has been 30 years since the United States last designed and built a human-rated launch vehicle. NASA has marshaled unique resources from the Government and private sectors to perform the technically and programmatically complex work of delivering a next-generation space exploration architecture. NASA's 50 years of experience has taught the value of adhering to sound systems engineering principles, while applying industry best practices and lessons learned. To fly humans safely aboard a launch vehicle requires a variety of methodologies to reduce the technical, schedule, and cost risks inherent in the complex business of space exploration. This paper gives details of the in-house systems engineering and vehicle integration work now being performed for the Ares I and planned for the Ares V at NASA's Marshall Space Flight Center. It gives an overview of the Ares I system-level test activities, such as the ground vibration testing that will be conducted in the Marshall Center's Dynamic Test Stand to verify the integrated vehicle stack's structural integrity against predictions made using modern modeling and simulation tools. It also gives top-level information about the work in progress for the Ares I-X developmental test flight planned in 2009 to provide key data before the Ares I Critical Design Review. Activities such as these will help prove and refine mission concepts of operation, while supporting the spectrum of design and development tasks being performed by Marshall's Engineering Directorate for the Exploration Systems Mission Directorate and the Constellation Program, ranging from launch vehicles and lunar rovers, to scientific spacecraft and experiments. Ultimately, technical work integrated using systems engineering practices and principles will lead to the fielding of a robust space transportation solution that will carry international explorers and essential payloads for futuristic scientific discovery beyond planet Earth.

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I. The New Age of Space Exploration Begins

The U.S. Space Exploration Policy and the National Aeronautics and Space Administration's (NASA) 2006 Strategic Plan lay out a multi-decade roadmap (fig. 1) for renewing America's ability to send astronauts to the Moon and establishing an outpost as a major step toward one day placing the first human footprints on Mars, where the Phoenix lander has sent back data that support the presence of water on the red planet, opening a new set of opportunities for future Martian crews.[1,2,3] With a commitment to delivering this new national asset, which is being designed for safety, reliability, and cost-effective operations for sustainable missions over many years to come, NASA has recently completed an internal Lunar Capabilities Concept study, as well as another in conjunction with the European Space Agency that builds on the agreements outlined in the Global Exploration Strategy — a 14 country strategic plan for uniting resources to realize mutually beneficial objectives in the space arena.[4,5,6] These policies and studies are indicative of the expansive planning and measurable progress being made toward strategic space goals.

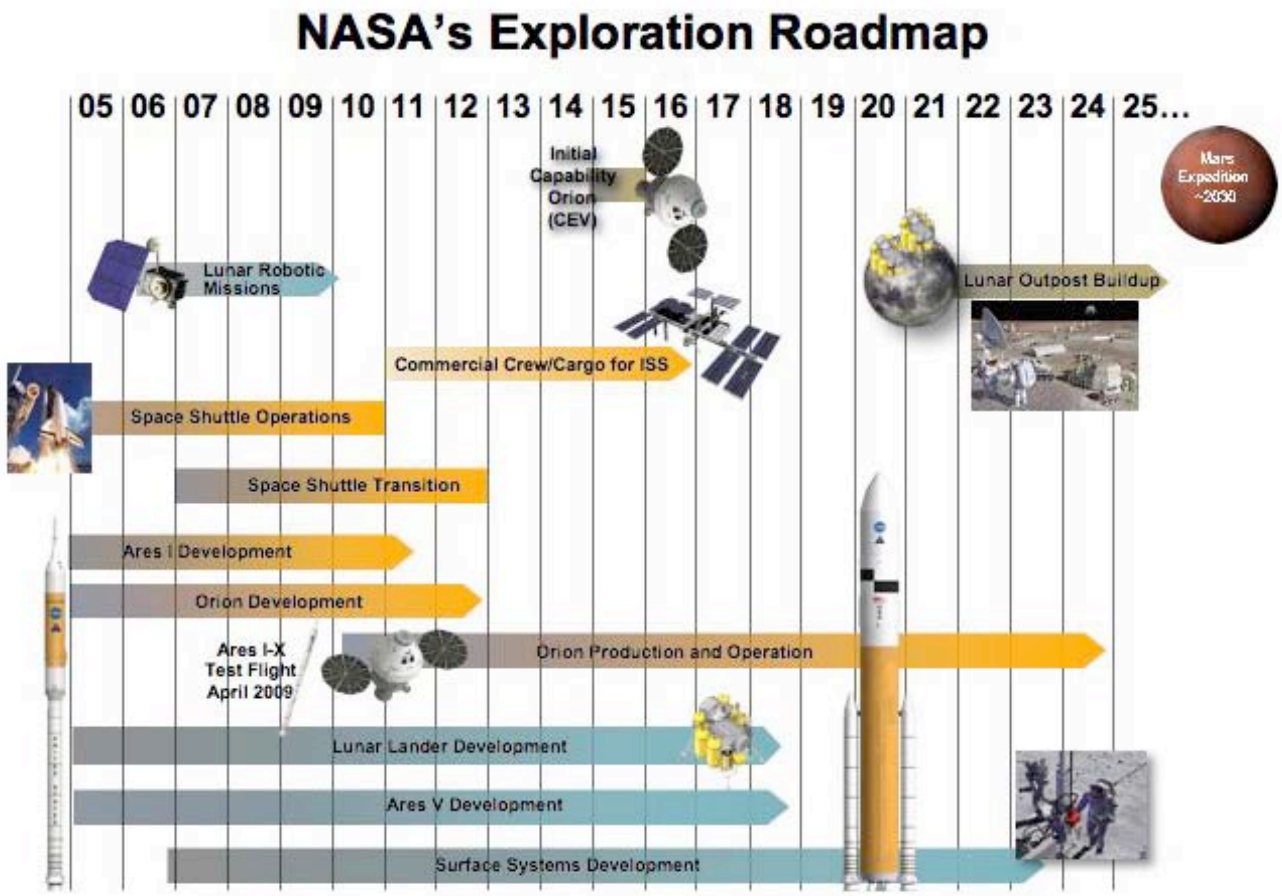

Fig. 1. The exploration timeline spans several decades.

As shown in the timeline, a combination of systems will give people the means to further explore their cosmic neighborhood, gaining scientific understanding and spurring leading-edge technologies that will benefit life on Earth. The Space Shuttle, which has served with distinction for almost 30 years, is due for retirement in 2010, after it completes its missions of building the International Space Station and servicing the Hubble Space Telescope. In parallel, the Ares I/Orion system (fig. 2) will be flight tested in 2009, using a mix of real and simulated hardware traveling a suborbital trajectory. The system will be tested with a crew on board in 2013, and ready for up to 6 astronauts and small cargo rotations to the Space Station in 2015, or up to 4 astronauts for later lunar missions in the 2020 timeframe. The Ares V is expected to be tested in 2018 and the capability to send astronauts to the Moon in 2020 (fig. 3).

Fig. 2. NASA concept of the Ares I/Orion launching.

The Marshall Space Flight Center hosts the Ares Projects Office and is engaged in lunar work, as well. Marshall's Engineering Directorate provides a majority of the workforce and many of the facilities for integrating the Ares I vehicle stack and designing the clean-sheet upper stage using in-house capabilities. Engineering personnel also are involved in Ares I first stage and upper stage engine oversight functions, and are performing advanced concept studies for the Ares V. With responsibility for meeting schedule and budget while delivering safe, reliable, and affordable space transportation solutions, Marshall's Engineering employees build on lessons learned while applying appropriate industry best practices and standards, including Lean/Six Sigma processes.

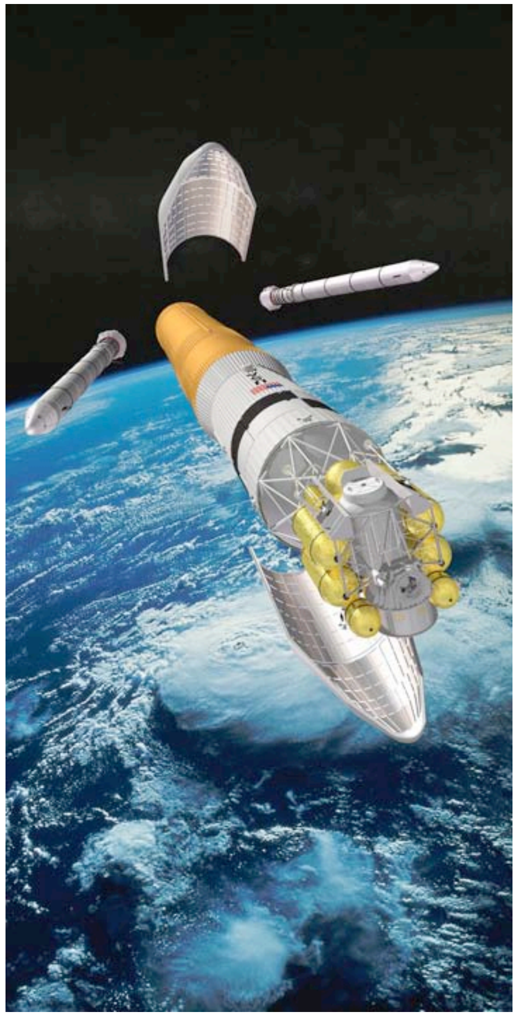

Fig. 3. NASA concept of the Ares V and Altair in Earth orbit.

Throughout the process of fielding a new capability, a network of systems engineers is integrating the numerous facets that must come together to meet the requirements levied on the systems now in the design phase. The success of complex space systems being fielded for tomorrow's demanding missions — both autonomous/robotic and human-rated — depends greatly on the systems engineering process being exercised in concert with all levels of design and management. This disciplined approach is chronicled in "The Secret of Apollo," which credits systems management and engineering with the ultimate success of America's first Moon excursions.[7] NASA's Systems Engineering Handbook and other overarching documents codify guidance from the NASA Chief Engineer. The Engineering Directorate's systems engineering approach is to implement policies, manage mission requirements, and ensure verification and validation of integrated space systems in a timely, cost-effective manner. This philosophy will be explored in the text below.

II. America's Next Moon Rockets: Ares I and Ares V

This section provides a brief background of the work now in progress by a nationwide Government and industry team. In mid 2005, NASA released the results of the Exploration Systems Architecture Study (ESAS), which recommended separating crew from cargo to improve safety and pointed to Shuttle-derived vehicles as the most affordable in terms of non-recurring and recurring costs.[8] The ESAS panel consisted of aerospace experts who measured both reusable and expendable launch vehicle options against figures of merit such as safety, reliability, and cost in relation to design reference missions to the International Space Station and the Moon.

Subsequently, NASA's Exploration Systems Mission Directorate and its Constellation Program chartered the Ares Projects Office at the Marshall Center to design, develop, test, and evaluate (DDT&E) the Ares I transportation system, as well as the Ares V heavy-lift cargo system.[9] NASA's approach is to use an open architecture that allows commercial and international partners to participate to the fullest extent possible.[10] Leveraging 50 years of lessons learned, NASA is building on proven hardware experience (fig. 4). Following is a top-level description of the Ares I, Ares V, and a notional lunar mission scenario.[10,11]

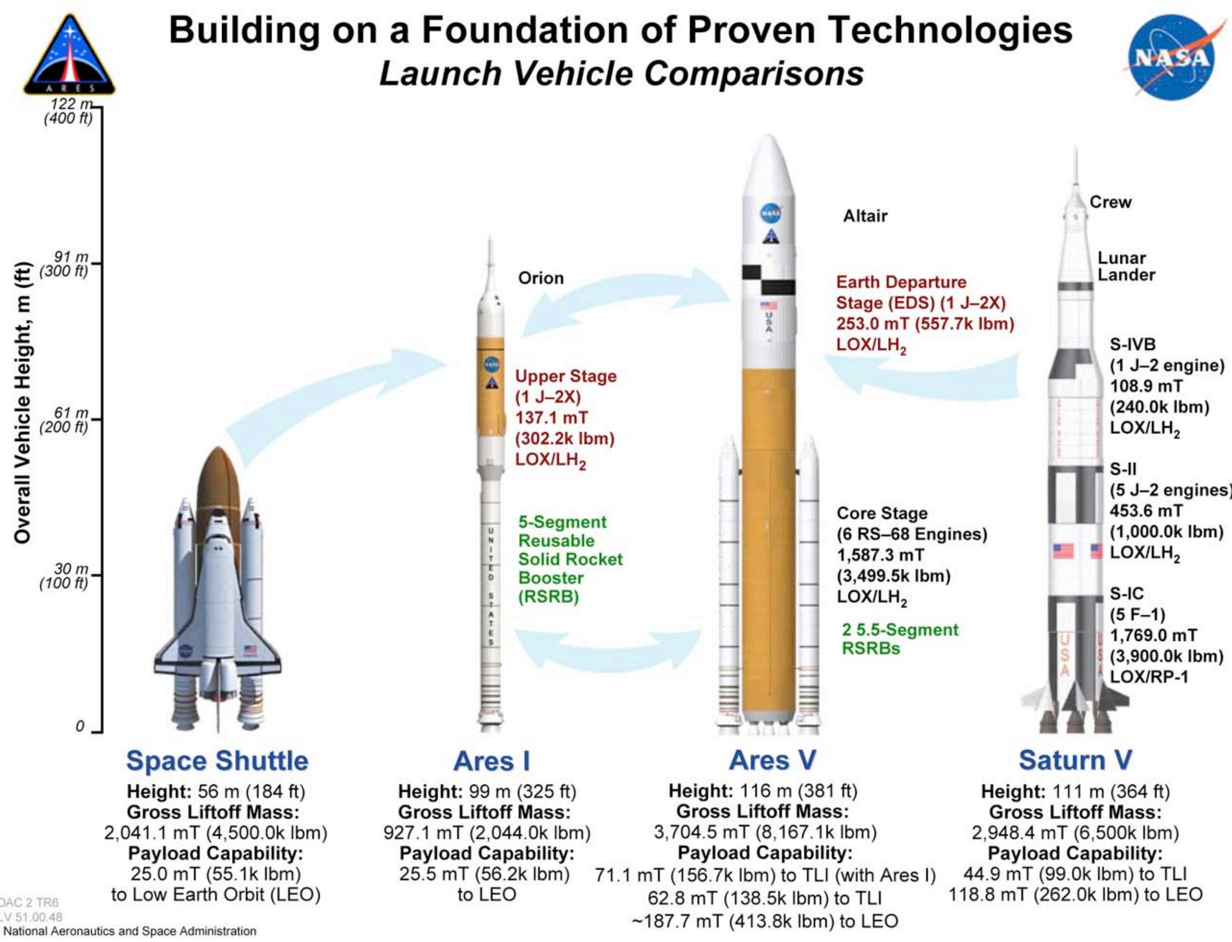

Fig. 4. The Ares I and Ares V are evolutionary systems.

A. Ares I Crew Launch Vehicle

The human-rated Ares I is an in-line, two-stage rocket that will deliver the Orion crew exploration vehicle, its crew module/service module, and a launch abort system to Earth orbit. The Ares I will replace the Shuttle for human transport to Earth orbit and, combined with the Ares V, will be capable of journeys to the Moon (fig. 5). Separating crew from cargo, in combination with the Ares I rocket's configuration and Orion's launch abort system, which can move astronauts away quickly in case of a launch emergency, will contribute to crew safety.

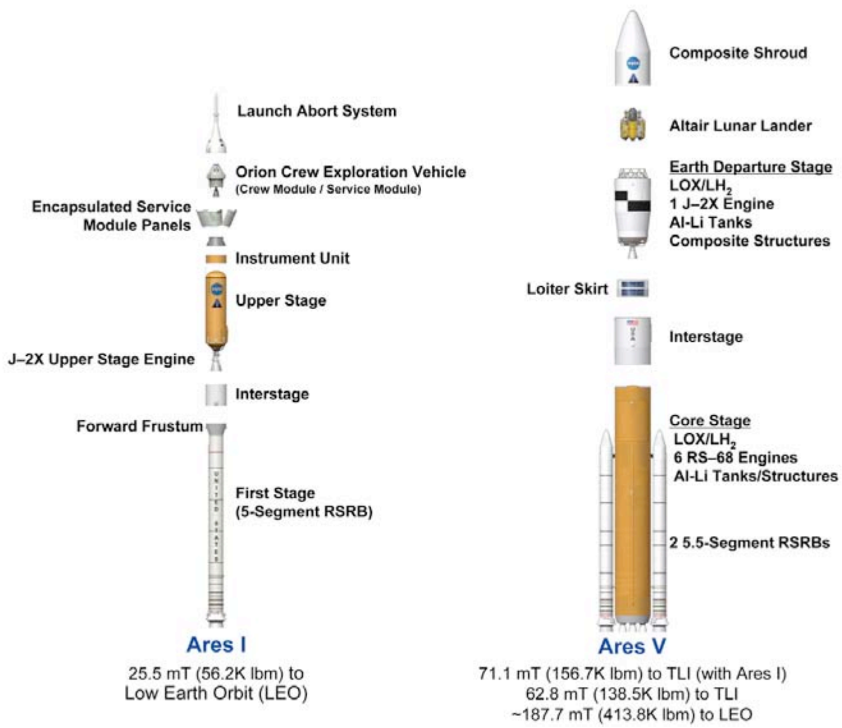

Fig. 5. Ares I and Ares V expanded views.

The Ares I will be 325 feet tall, weigh 2 million pounds at launch, and be capable of lifting 56,500 pounds into low-Earth orbit. The Ares I first stage is a 5-segment reusable solid rocket motor/booster based on the 4-segment version currently used on the Space Shuttle. The first stage burns a specially formulated and shaped solid propellant called polybutadiene acrylonitrile (PBAN). The upper stage is a clean-sheet designed structure that delivers liquid oxygen (LOX)/liquid hydrogen (LH2) to the J-2X upper stage engine. The J-2X is an evolved variation of two historic predecessors: the powerful J-2 upper-stage engine that propelled the Apollo-era Saturn 1B and Saturn V rockets to the Moon, and the J-2S, a simplified version of the J-2 developed and tested in the early 1970s. The J-2X engine also will propel the Ares V upper stage, known as the Earth departure stage (EDS). A newly designed forward adapter will mate the vehicle's first stage to the second, and will be equipped with booster separation motors to disconnect the stages during ascent.

As mentioned earlier, the upper stage is being designed in-house at Marshall and will be produced by the Boeing Company at NASA's Michoud Assembly Facility. The total vehicle stack is being integrated in-house at Marshall through the Ares Vehicle Integration Office, which is staffed with systems engineers who reside primarily in the Engineering Directorate's Spacecraft and Vehicle Systems Department, along with the Ares Chief Engineer, who integrates a network of element-level engineers. The first stage and upper stage engine are being designed by industry, with Government oversight. The first stage contractor is ATK and the upper stage engine contractor is Pratt & Whitney Rocketdyne.

In addition to its primary mission – carrying crews of up to six astronauts to Earth orbit – the launch vehicle's 56,200-pound (25.5-metric-ton) payload capacity may be used for delivering small cargo to space, bringing resources and supplies to the Space Station or dropping payloads off in orbit for retrieval and transport to exploration teams on the Moon.

For lunar missions, the Ares I will transport Orion and a crew of up to four astronauts to Earth orbit, where it will rendezvous and dock with the Ares V's Earth departure stage (EDS), which will transport the Altair (fig. 6). After mating, the J-2X engine will perform the trans-lunar injection burn. Once in lunar orbit, the crew will transfer to the Altair for descent to the Moon's surface. After the crew's mission is complete on the lunar surface, the Altair's ascent stage will return the crew to the Orion, which is waiting in lunar orbit for return to Earth.

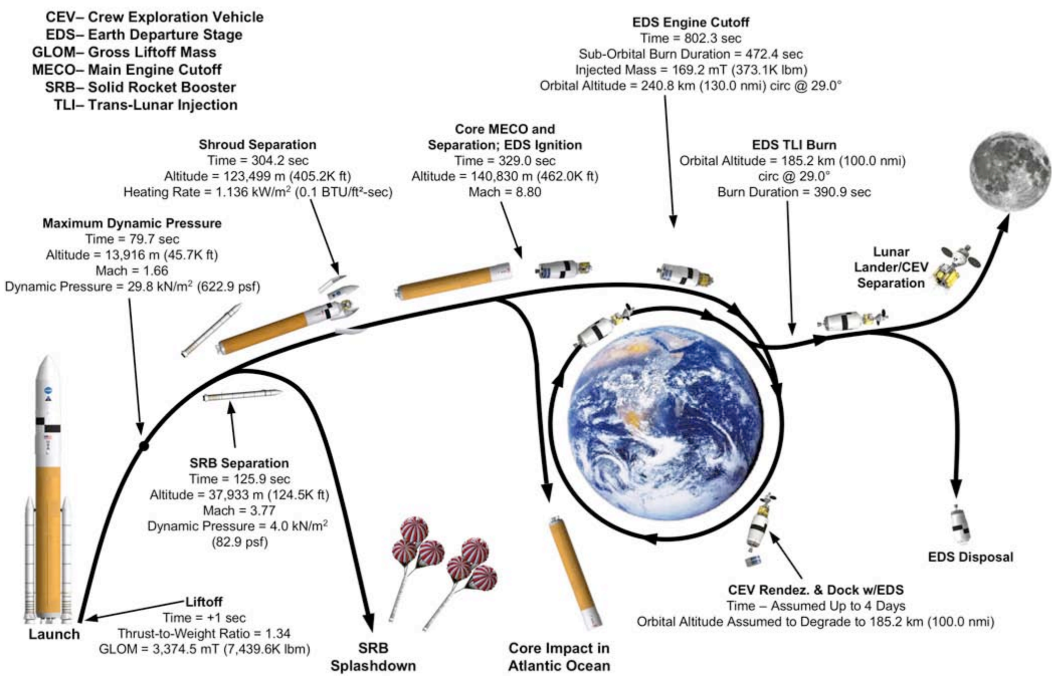

Fig. 6. Notional lunar mission scenario.

B. Ares V Cargo Launch Vehicle

The Engineering Directorate's Advanced Concepts Office has performed pre-phase A advanced studies of the Ares V and produced a concept that can perform stakeholder requirements for lunar missions. This information was used in the Agency's recent baselining of the Ares V and Altair lander as part of a comprehensive Lunar Concept Capabilities study.

The heavy-lift Ares V is a two-stage launch vehicle. It can carry nearly 414,000 pounds (188 metric tons) to low-Earth orbit. When working together with the Ares I to launch payloads into Earth orbit, the Ares V can send nearly 157,000 pounds (72 metric tons) to the Moon. For insertion into Earth orbit, the Ares V first stage relies on two five-and-a-half-segment reusable solid rocket boosters. These are derived from the Shuttle solid rocket boosters and are similar to the Ares I first stage. The twin reusable solid rocket boosters of the cargo lifter's first stage flank a single liquid-fueled central booster element, known as the core stage. Derived from the Saturn V, the core stage tank delivers LOX and LH2 to a cluster of six RS-68 engines, which are upgraded versions of those currently used in the Delta IV, developed in the 1990s by the U.S. Air Force for its Evolved Expendable Launch Vehicle program and commercial applications. Together, these propulsion elements comprise the Ares V's first stage.

Atop the central booster element is an interstage cylinder that includes booster separation motors. It connects the core stage to the Ares V EDS, powered by the J-2X engine. Anchored atop the EDS is a composite shroud containing Altair, with its descent stage that will carry explorers to the Moon's surface and an ascent stage that will return them to lunar orbit to rendezvous with the Orion for return to Earth.

Again, ATK Launch Systems is the prime contractor for the reusable solid rocket boosters, while Pratt & Whitney Rocketdyne is the prime contractor for both the J-2X upper stage engine and the RS-68 core stage engines**.**

III. Systems Engineering: Adding Value Throughout the Program's Lifecycle

From the macrocosm imaged by the strongest space telescopes, to the microcosm revealed by the most powerful electron microscopes, systematic patterns can be observed even at the subatomic level. Taking a cue from this natural synergy and symmetry, the systems engineering approach recognizes the uniqueness of each part, but continually address it as a subset of a larger interconnected system for end-to-end interoperability. Seamless integration with robotic and human explorers presents a range of challenges to designers, manufacturers, and operators. Systems engineering ensures that the boundaries between interfaces are clearly understood and addressed, while balancing a continually evolving concept that is geared toward providing value to stakeholders in a cyclical process.

As has been shown, the Ares I Project is a nationwide effort with multiple partners at multiple locations contributing unique expertise and facilities to delivering a new national strategic capability for human space flight (fig. 7). In keeping with the depth and breadth of the work in progress, systems engineering provides a foundation for optimizing resource investments based on sound judgment informed by technology development trade studies, risk analyses, and cost-to-benefit investigation using tools and best practices drawn from public and private industry. It capitalizes on commonality and modularity, as well as streamlined operations, to maximize affordability while reducing development, production, and lifecycle costs.

Fig. 7. Systems engineering integrates a nationwide team.

This section gives an overview of the in-house systems engineering and vehicle integration work being performed for the Ares I and planned for the Ares V. It includes a survey of guiding documents as prescribed by the NASA Chief Engineer, to unite various discipline engineers and systems engineers behind a common set of standards and a disciplined, documented process for engineering the entire system — from conception to retirement.

A. In-House Systems Engineering and Integration

The Ares Vehicle Integration Office is responsible for integrating the stack using in-house capabilities — both personnel and facilities. Included in the team are matrixed personnel from Marshall's Engineering Directorate, including discipline engineers, systems engineers, and chief engineers, who embody the technical excellence and technical authority approach to reducing the risk of space flight. The functions and responsibilities of systems engineering relative to project management are collaborative (fig. 8).

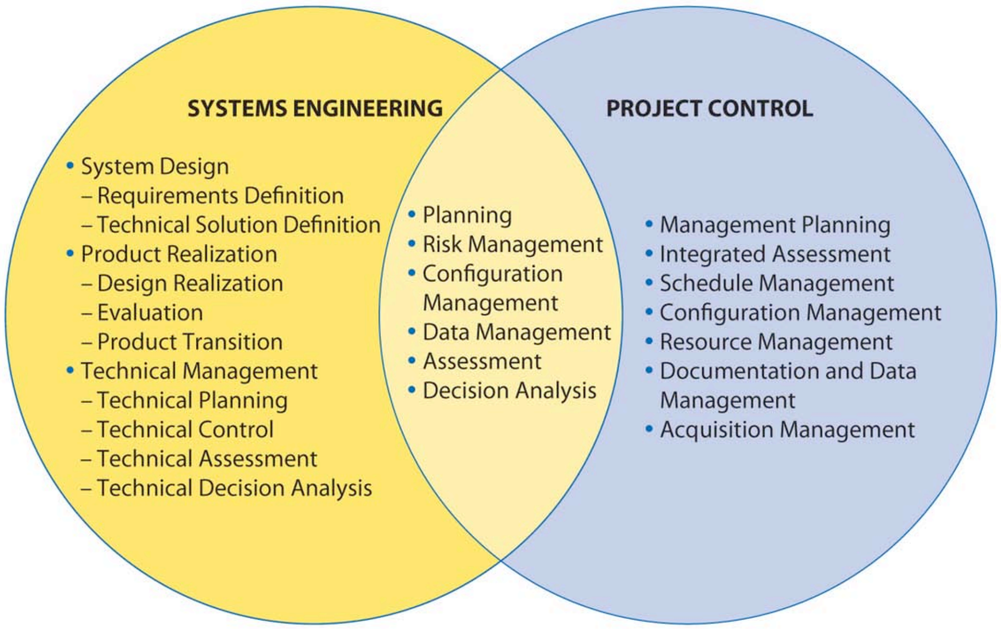

Fig. 8. Systems engineering and project management roles and responsibilities.

Through this organization, systems engineering and integration brings together technical work performed geographically dispersed partners. Participating agency facilities include Johnson Space Center, which is responsible for the Orion spacecraft and flight operations projects; Stennis Space Center, which is primarily responsible for J-2X and stage testing; Glenn Research Center, which is responsible for developing the ascent development flight test upper stage mass simulator and upper stage power, thrust vector control and sensor development; Langley Research Center, which is responsible for aerodynamic characterization, ascent development flight test vehicle integration and Orion mass simulator development, and support to flight mechanics and structure development; Ames Research Center, which is responsible for integrated health monitoring, blast modeling and reliability analysis support; Michoud Assembly Facility in New Orleans, which will manufacture and assemble the Ares I upper stage; and Kennedy Space Center, which performs launch operations and associated ground activities. These Government assets are combined with industry partners' capabilities to deliver the new exploration infrastructure.

Ares vehicle integration is on par with the various hardware elements (first stage, upper stage, and upper stage engine). Vehicle integration includes functions such as requirements validation and verification; integrated design and analysis; configuration and data management; integrated operations and logistics; operability design and analysis; interface definition and control; and systems analysis of loads; thermal; guidance, navigation, and control; separation; and liftoff events.

Much of the in-house systems engineering work is being performed by the Spacecraft and Vehicle Systems Department, which is responsible for the Ares Systems Engineering Management Plan (SEMP) referenced below. Its Spacecraft and Vehicle System Engineering and Integration Division is responsible for the integrated vehicle design, design process, and subsequent functionality. Some of the functions it performs include:

- Technical characterization of the complete vehicle by using lessons learned, applying engineering standards, and performing empirical and analytical analysis to verify the system.
- Vehicle technical design from concept through post-flight performance assessments.
- Integrating elements, element interconnections, ground stacking and launch facilities, and operation process design drivers.
- All major integrated vehicle development milestones (discussed below).
- Vehicle systems engineering support to ground operations, launch support reviews, hardware acceptance reviews, etc.

To achieve these objectives, the Spacecraft and Vehicle System Engineering and Integration Division is responsible for vehicle systems design integration; vehicle system analysis and attributes; systems engineering planning and control; and vehicle hardware development and evaluation. It touches every component, part, subsystem, and system in the entire vehicle, while iterating information throughout the range of disciplines through formal design analysis cycles that are managed by a disciplined configuration control process (fig. 9).

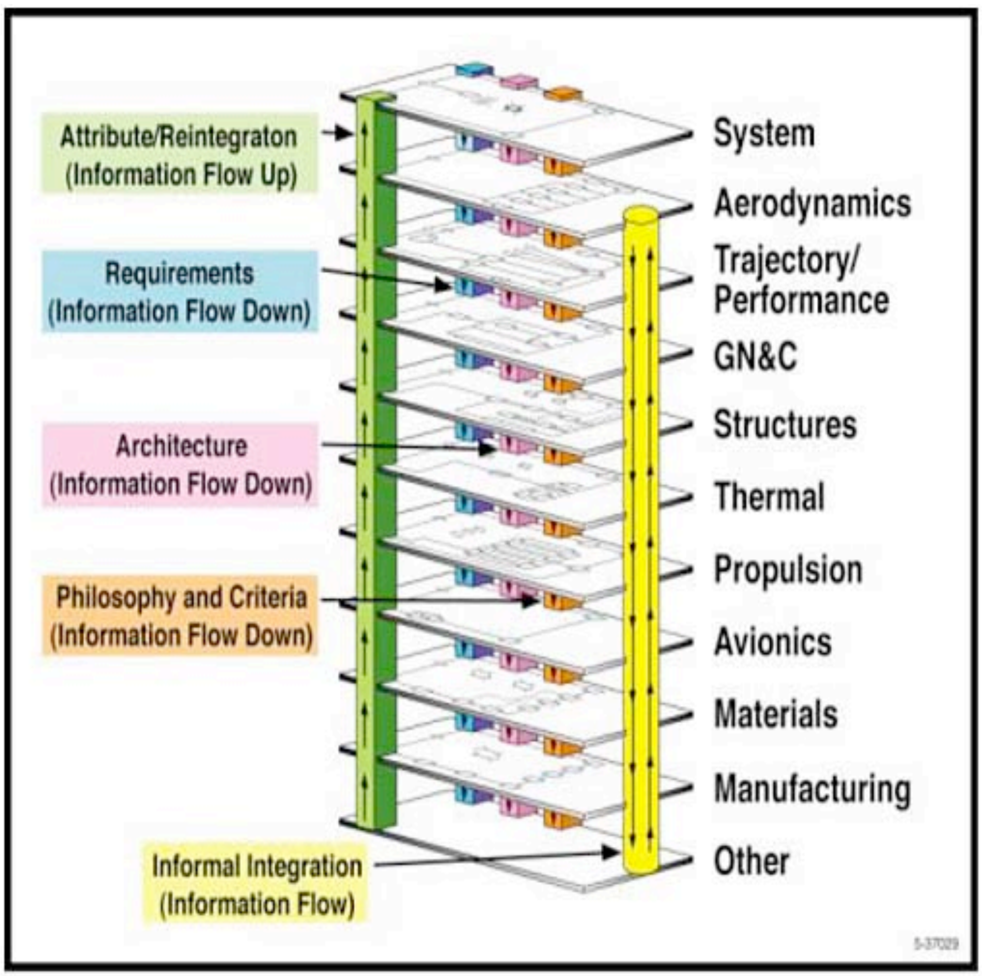

Fig. 9. Systems engineering is an iterative process that bridges functional areas, both horizontally and vertically.

Mission success demands a disciplined, innovative approach. An excellent example of systems engineering innovation is the Engineering Information Center (EIC), where personnel who are assigned to various disciplines regularly provide the status on a range of set parameters, both technical and programmatic. The EIC is a tangible physical environment that is structured for dialogue and bottom-line understanding of the complexities of information that usually is relegated to Powerpoint charts and may, therefore, be lost in translation. Participation in the EIC process sets the stage for expectations for technical excellence and disciplined innovation. The EIC provides a focal point for communicating a range of metrics, from resource allocations to product deliverables. This environment serves as an entrance point from the engineers conducting the design and integration work performed for the Ares Projects, as it mirrors similar management risk-reduction tools maintained for in-house vehicle integration and the in-house upper stage.

B. Systems Engineering Guiding Principles

Three guiding documents are primarily used by systems engineers codifying the principles and processes for this development program: NASA Systems Engineering Processes and Requirements, NASA Procedural Regulation (NPR) 7123.1A; NASA Systems Engineering Handbook, Special Publication (SP) 6105; and the Ares Projects Office Systems Engineering Management Plan, Constellation Program (CxP) 72018.[12,13,14] These comprehensive engineering doctrines describe both the overarching philosophy and top-level implementation of systems engineering policies and processes, which are described in detail in the Ares Systems Engineering Management Plan (SEMP).

As articulated in the NASA Systems Engineering Handbook, systems engineering involves the rigorous implementation of processes necessary to separate elements into manageable work elements and then analyze them so they can be effectively integrated into a complex final product that meets stated requirements. These processes include interface optimization, risk management, and configuration control. With these and other responsibilities in mind, systems engineering creates an environment for mission success by balancing requirements on paper and numbers in spreadsheets, bringing concepts from virtual reality to hardware delivery.

To facilitate clear communications, the Systems Engineering Management Plan serves as the guidebook for its broad range of activities. In the overall business of fielding new systems, the SEMP is an important instrument to inform the design and development team of the appropriate standards against which processes and progress will be measured. Specific information contained in the SEMP provides a guidepost for designers, builders, and operators by documenting standards and processes and defining how they should be applied. Although under configuration control, it is a living document, and audits are regularly performed to ensure processes are sound and that they are being followed correctly. Interface Control Documents, the Work Breakdown Structure, and other controlled documents provide a foundation for success. These and other applicable standards provide rules of engagement in an effort to establish effective communication, ensuring that expectations are explicitly clear between and among team members and partners.

C. Systems Engineering Milestones

Delivering value to customers and stakeholders alike requires rigorous application of engineering practices and standards to facilitate accountable, disciplined progress. Systems engineering pursues understanding of reasonable design alternatives to support decision-making and implementation. Milestone reviews provide decision gates aligned with acquisition strategies. In this way, the business of developing the new architecture rests squarely on a foundation of fiscal responsibility and effective strategic planning girded by the systems engineering factor in the equation of schedule, cost, and technical performance.

Systems engineering milestones that have been completed by the Ares I Project to date include the system requirements review, the system definition review (fig. 10). The SRR demonstrated that the Constellation requirements have been properly analyzed, functionally decomposed, allocated, and validated. The SDR assured that the Ares I System Requirements Document was clear, achievable, responsive, and appropriate to fulfill mission needs. The PDR will demonstrate that the hardware design is capable of meeting those vetted requirements, as well as satisfy issues of cost, operability, and availability of the system. The next major milestone — the Preliminary Design Review (PDR) — is being conducted in July and August, with the board in September 2008. The objective of the Ares I PDR is to provide a solid set of design-to specifications, preliminary designs, and verification plans to take the design forward into the final design phase of the project.

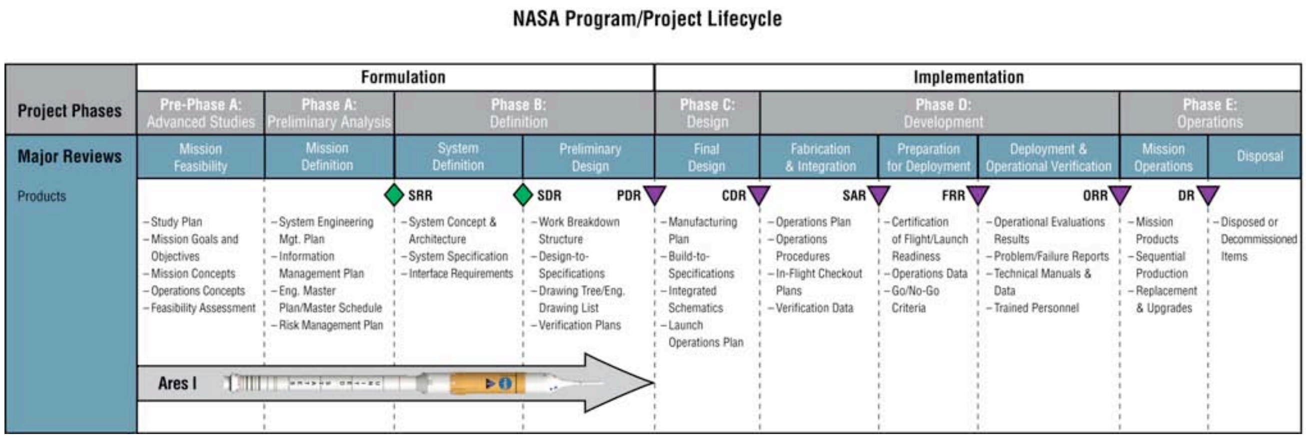

Fig. 10. Ares I systems engineering milestones.

The systems engineering process ensures that mission requirements are properly addressed and design specifications are met through integrated testing and verification. For example, in addressing requirements in relation to improving capabilities, existing technologies are appropriate for some applications, whereas technology maturation is needed in other critical areas. This gap analysis is provided to technologists as potential opportunities. Design trade studies identify architecture and technology alternatives that may reduce risk and increase chance of mission success. From requirements definition, to concept definition and demonstration, to fielding, systems engineering is an analytical, advisory, and planning function performed in concert with requirements management and verification, including testing using a combination of ground-based methods, such as modeling and simulation, and demonstrators to "test as we fly." The objective is to ensure that individual systems are designed, built, and operated so that they integrate to accomplish stated mission requirements for stakeholders — including operators and astronauts — within budget and on schedule.

IV. Testing Verifies Engineering Design Analysis

Hardware and software development is a precarious business, especially when factoring humans and the space environment into the equation. Systems engineering is about exploring options that lead to systemic improvements in everything from designing, manufacturing, and testing systems to operating, evolving, and retiring them, with an eye toward minimizing lifecycle costs. It is about ensuring safety, which comes from adhering to proven standards. Systems engineering serves a give-and-take role that manages the needs of designer, builder, and operator within a framework that continually pulses the interests of stakeholders and user communities and then integrates that feedback into more effective products. In keeping with the guidance for system validation and verification, engineering analyses are informed by a portfolio of integrated vehicle testing.

One of the engineering innovations in progress for the Ares I is early verification and validation testing. While verification testing relates to requirements, validation testing relates to the concept of operations document, which has been prepared by the Engineering Directorate's Mission Operations Laboratory. For example, Ares discipline engineers have conducted over 6,000 hours of wind tunnel testing, using models of increasing fidelity and scale, to attain the best possible aerodynamic data for use in the vehicle design (fig. 11). With facilities at Marshall, Langley Research Center, Ames Research Center, and Boeing, the team has captured high-fidelity aerodynamic, acoustic, and thermal data across the full operational Mach range of the Ares I. Data derived from these wind tunnel tests informed the redesign of the Ares I Launch Abort System, to lessen the aerodynamic forces experienced by the vehicle during ascent.

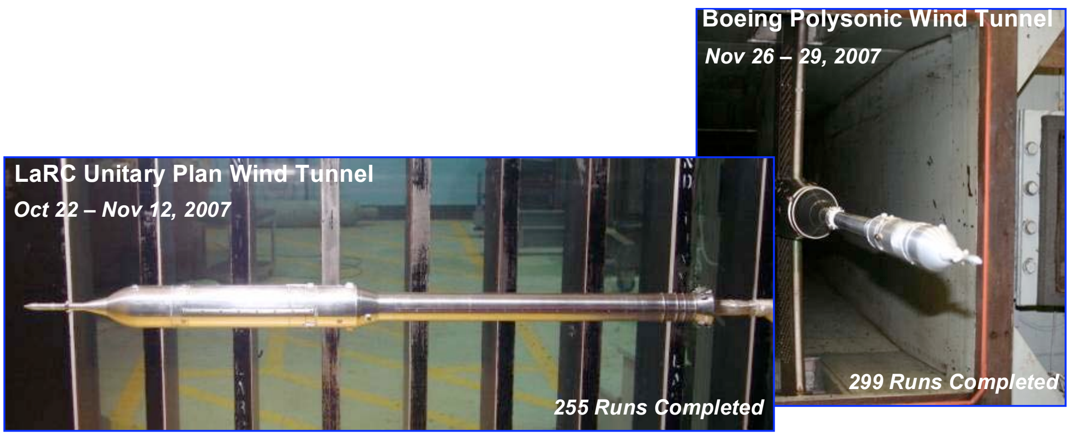

Fig. 11. Sample Ares I wind tunnel testing configurations.

Another example of early testing is the first J-2X engine test series, which was completed in 2008, using hardware infrastructure assets at the Stennis Space Center, as an important step in the development of that engine, which is expected to generate 294,000 pounds of thrust with a specific impulse of 448 seconds. Data obtained from these tests will be used to refine the design of the J-2X pumps and other engine components to provide the performance required. The Upper Stage Engine Element Office began early testing with heritage J-2 engine hardware at Marshall, focusing on injector and valve hardware (fig. 12). During these hot-fire tests, engineers fired the injector horizontally at steady-state conditions for 10 to 20 seconds at 20,000 pounds of thrust. Such investigations have contributed to design options and potential performance maximization.

Fig 12. J-2X subscale main injector hot-fire testing at Marshall.

This section gives an overview of Ares I system-level test activities, The testing series planned for each element and the integrated vehicle come from the Saturn Project's playbook of building block, incremental testing, followed by full-up automated vehicle testing on the ground and in space prior to human test flights. Discussed below are the ground vibration testing that will be conducted in the Marshall Center's Dynamic Test Stand 4550 to verify the integrated vehicle stack's structural integrity against predictions made by modern modeling and simulation analysis and the main propulsion test article test to be conducted in Marshall's Static Test Stand 4670. It also give a brief description of the first flight test of the system, known as the Ares I-X mission, which is scheduled for 2009 to inform the Ares I Critical Design Review milestone in 2010.

A. Integrated Vehicle Ground Vibration Testing (IVGVT)

Ground vibration testing measures the fundamental dynamic characteristics of launch vehicles during various phases of flight. During the series of tests, properties such as natural frequencies, mode shapes, and transfer functions are measured directly. These data are then used to calibrate loads and control systems analysis models to verify launch vehicle analyses. For the Ares I, the Ares Projects' Flight and Integrated Test Office will be conducting the Integrated Vehicle Ground Vibration Test series from 2011 to 2012 using Test Stand (TS) 4550, which supported similar tests for the Saturn V and Space Shuttle vehicle stacks (fig. 13). In the Dynamic Test Stand, the integrated vehicle will be supported on a soft suspension system to simulate free-free boundary conditions. This is an example of how the Agency is leveraging one-of-a-kind facilities for new missions.

This series will measure the fundamental dynamic characteristics of Ares I during various phases of operation and flight. The final measured results of the IVGVT are clearly dependent on the vehicle hardware used during the test. A fundamental philosophy of structural dynamic testing is to have as few differences between the test article and the flight article as possible. To accurately represent the properties of the flight vehicle, the Ares I IVGVT will be conducted on a test article built to flight-like specifications.

Ares I hardware delivery begins with the 5-segment first stage in 2010. The upper stage test article and the J-2X engine are expected in 2011. The models correlated from IVGVT test data will support the Ares I Design Certification Review (DCR) in mid-2013. The DCR supports the first crewed test of the Ares I/Orion vehicle, planned for late 2013.

Fig. 13. Test Stand 4550 with the Space Shuttle Enterprise test article (1978).

B. Main Propulsion Test Article (MPTA) Testing

As mentioned earlier, the Ares I upper stage is a clean-sheet approach that is being designed and developed in-house. The Upper Stage Element concept is a self-supporting cylindrical structure, approximately 115-feet long and 216-inches in diameter. A clean-sheet upper stage design inherently carries more risk than a modified design, while offering many advantages: increased reliability; built-in evolvability to allow for commonality/growth without major redesign; incorporation of state-of-the-art materials and hardware; and incorporation of design, fabrication, and test techniques and processes to facilitate a potentially better, more reliable, and more operable system.

Upper Stage Element development activities incorporate extensive component, subsystem, and overall stage-level testing to support hardware verification and stringent human-rating requirements. The Upper Stage Element will fabricate and assemble three major test articles at Marshall: a structural test article to qualify the assembled core stage structure under simulated flight load conditions; a Main Propulsion Test Article to provide a hot-firing test bed for the development and verification of the integrated propulsion system and its related subsystems (fig. 14); and a Ground Vibration Test structure to support the overall crew transportation system and the Upper Stage/Orion configuration dynamic characterization tests discussed above. The test program will verify that the design and performance of components, subsystems, and system meet requirements, demonstrate the acceptability and readiness of deliverable hardware for intended uses, and validate critical analyses and analytical models.

Ares test objectives are to hot-fire the MPTA to verify design performance, as well as to validate the performance algorithms, system, and subsystem models. The test article — outfitted with operational flight instrumentation and ground test instrumentation — will be a combination of flight, flight-equivalent, and engineering model hardware and software. The fully integrated stage will be tested in pre-launch and static firing/mission simulation scenarios. Every interaction, such as gimballing the engine and pressurizing the LOX/LH_2 tanks, as well as starting and stopping the Upper Stage Engine, will be performed.

Fig. 14. The Main Propulsion Test Article will be tested in Marshall's Test Stand 4670.

C. Ares I-X Development Flight Test

As part of its flight testing strategy, Ares will conduct its initial suborbital test flight in 2009, known as the Ares I-X mission (fig. 15), which will inform the Critical Design Review in 2010. Flying the Ares I-X provides an early opportunity to perform proof-of-concept testing of the first stage's reusable solid rocket motor hardware, as well as to gather data about the dynamics of the integrated launch vehicle stack, including flight controllability. In addition, as the Kennedy Space Center transitions from the Shuttle to the Ares/Orion system, the Ares I-X mission provides an excellent point from which to perfect ground operations scenarios, including modifications to Launch Complex 39B.

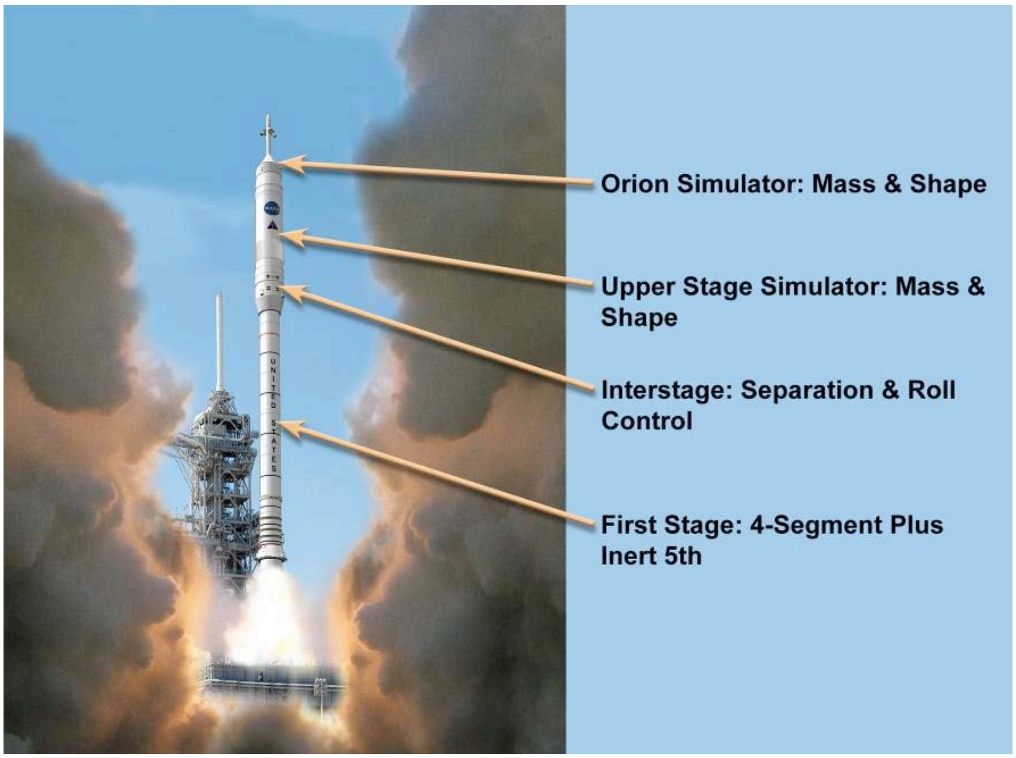

Fig. 15. The Ares I-X test vehicle includes active and passive systems.

Specifically, this fight test will demonstrate the ascent flight control system performance with dynamically similar hardware, determine roll control methods during flight, better characterize the stage separation environment experienced during future operational flights, test the parachute and recovery systems, validate ground operations, and gather critical data about the flight dynamics of the integrated launch vehicle stack. The Ares I-X test vehicle will incorporate a mix of flight and mockup hardware, reflecting a configuration similar in mass and weight to the operational vehicle. The vehicle's flight profile will closely approximate the flight conditions the Ares I will experience and will aid the timing of first stage burnout, first stage separation, and upper stage ignition.

An important part of the Ares I-X test flight is the avionics system, which is a pathfinder for blending avionics systems from Evolved Expendable Launch Vehicles and heritage Space Shuttle systems. The Ares team employs a Systems Integration Laboratory that tests the avionics on the ground and reflects the industry best practice of "test as you fly." The avionics also will employ the aircraft-qualified development flight instrumentation used for the Boeing 777 series and the U.S. Air Force Joint Strike Fighter to collect, transmit, and store the data vital for a successful test flight. Basing vehicle design refinements on flight and ground test information puts NASA one step closer to the full-up "test as you fly" scenarios and a fully operational fleet of launch vehicles.

V. Conclusion: Systems Engineering Creates a Climate for Mission Success

Strategically speaking, only three countries have the ability to put humans into space: the United States, Russia, and China. As America's space program turns plans into action with a return to the Moon by 2020, NASA is focusing its resources to deliver space architecture solutions that are safe, reliable, and affordable. Powering the future of space-based scientific exploration will be the Ares I, which will transport the Orion to orbit where it will rendezvous with the Altair, which will be delivered by the Ares V for lunar exploration. This capability will rekindle investigation of Earth's natural satellite — the Moon — in the not too distant future (fig. 16). While maximizing its industrial base and specialized skill set, the systems engineering function is a major risk-reduction strategy to ensure that complex systems designed to safely transport crews to and from space meet their stated requirements with sustainable infrastructure investments.

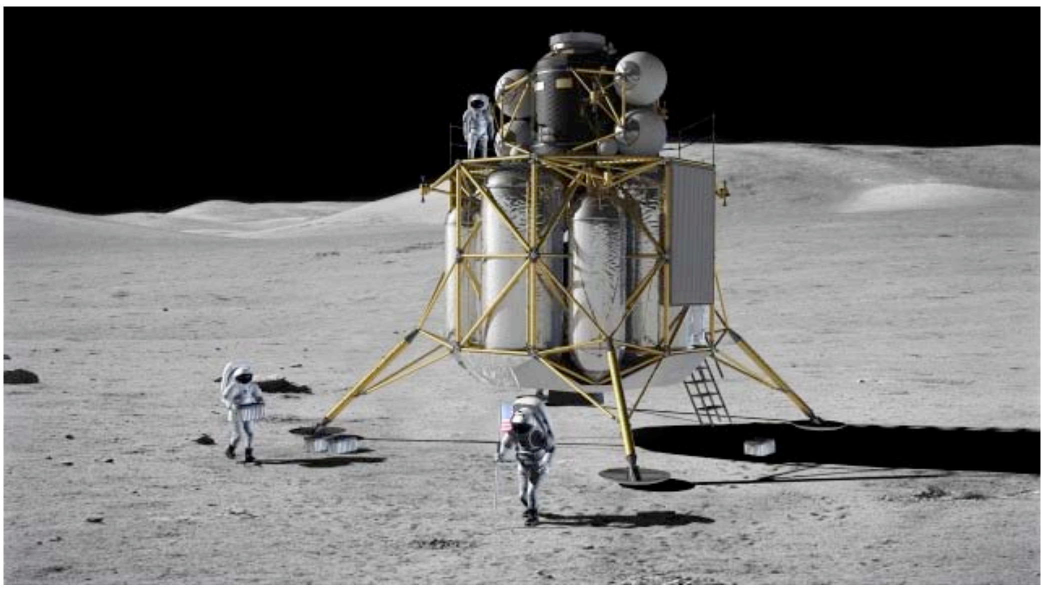

Fig. 16. NASA concept of Altair and lunar mission.

Systems engineering and integration builds and bridges communication channels between project management and technical implementation teams, and within the various technical working groups where launch vehicle design, analysis, and testing are performed. It provides a framework for risk reduction and mission success built on the foundation of principles and practices that position hardware and software in a collaborative environment where government and contractor interests are united behind a common agenda.

Seeking the answers to age-old questions is the cause for exploration. Over the decades ahead, relevant, compelling missions will spark the imagination and help sustain the Nation's technological superiority and security. With a sound approach and overarching commitment to systems engineering and integration, NASA and its domestic and international partners are sewing the seeds of engineering and managerial innovation that will bring the realm of space into sharp view for generations to come.

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