

# Designing the Ares I Crew Launch Vehicle Upper Stage Element and Integrating the Stack at NASA's Marshall Space Flight Center

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## Abstract

Fielding an integrated launch vehicle system entails many challenges, not the least of which is the fact that it has been over 30 years since the United States has developed a human-rated vehicle — the venerable Space Shuttle. Over time, whole generations of rocket scientists have passed through the aerospace community without the opportunity to perform such exacting, demanding, and rewarding work. However, with almost 50 years of experience leading the design, development, and end-to-end systems engineering and integration of complex launch vehicles, the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center offers the in-house talent — both junior- and senior-level personnel — to shape a new national asset to meet the requirements for safe, reliable, and affordable space exploration solutions. The technical personnel are housed primarily in Marshall's Engineering Directorate and are matrixed into the programs and projects that reside at the rocket center. Fortunately, many Apollo-era and Shuttle engineers, as well as those who gained valuable hands-on experience in the 1990s by conducting technology demonstrator projects such as the Delta-Clipper Experimental Advanced, X-33, X-34, and X-37, as well as the short-lived Orbital Space Plane, work closely with industry partners to advance the nation's strategic capability for human access to space. The Ares Projects Office, resident at Marshall, is managing the design and development of America's new space fleet, including the Ares I, which will loft the Orion crew capsule for its first test flight in the 2013 timeframe, as well as the heavy-lift Ares V, which will round out the capability to leave low-Earth orbit once again, when it delivers the Altair lunar lander to orbit late next decade. This paper provides information about the approach to integrating the Ares I stack and designing the upper stage in house, using unique facilities and an expert workforce to revitalize the nation's space exploration resources.

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## **I. Background: The New Age of Exploration**

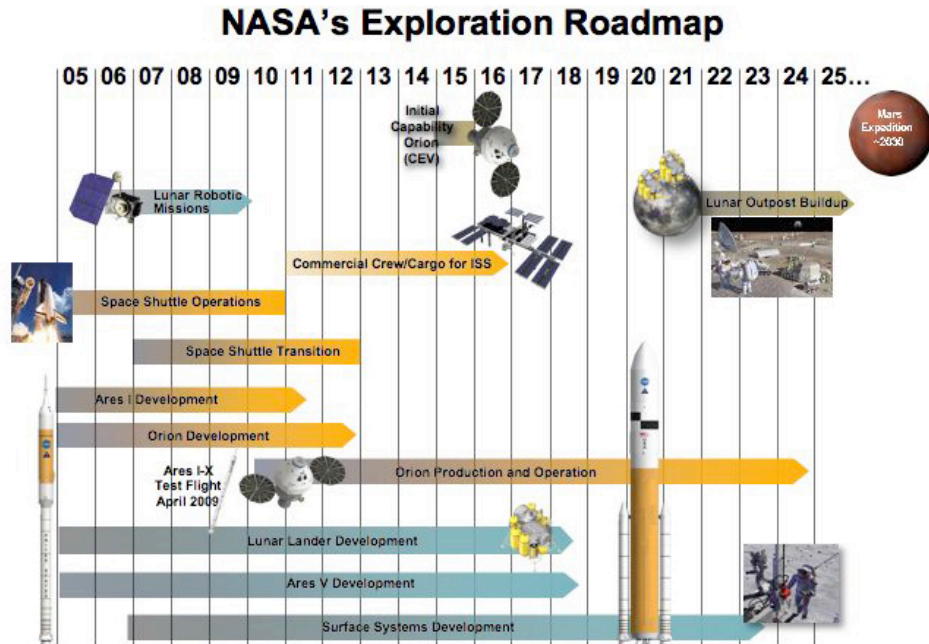
Although there are many international astronauts, currently, only three spacefaring nations have the distinction of human spaceflight capabilities, including the United States, Russia, and, more recently, China. The U.S. National Space Policy of 2006 directs that NASA provide the means to travel to space, and the NASA Appropriations Act of 2005 provided the initial funding to begin in earnest to replace the Shuttle after the International Space Station construction is complete in 2010.<sup>1</sup> These and other strategic goals and objectives are documented in NASA's 2006 Strategic Plan.<sup>2</sup>

In 2005, a team of aerospace experts was commissioned by the NASA Administrator to conduct the Exploration Systems Architecture Study, which recommended a two-vehicle approach to America's next space transportation system for missions to the International Space Station in the next decade and to explore the Moon and establish an outpost around the 2020 timeframe.<sup>3</sup> Based on this extensive study, NASA selected the Ares I crew launch vehicle and the Ares V cargo launch vehicle, which increases efficiency and safety by separating the crew from cargo (fig. 1).



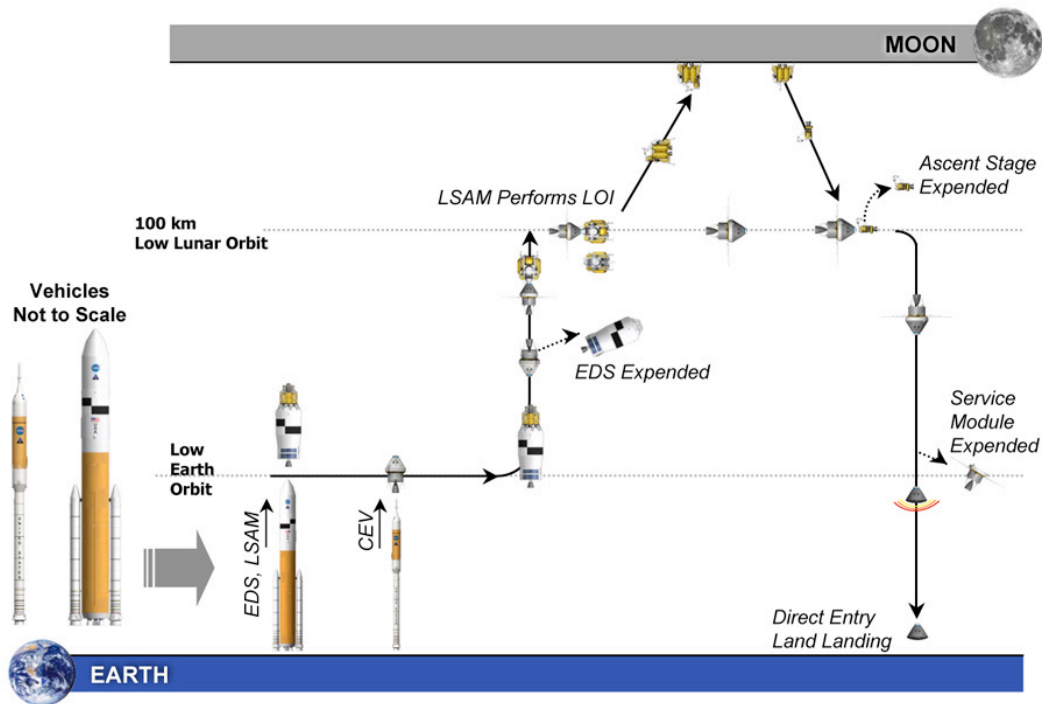
***Fig. 1. NASA concept of America's new launch vehicles—Ares I (right) and Ares V.***

NASA's long-term exploration strategy includes a new space fleet that will come on line in a phased approach after the Shuttle, which has served with distinction for almost 30 years, is retired at the end of this decade (fig. 2). The various vehicles in this fleet will be phased in over time beginning in 2015, with delivery of up to 6 crewmembers to the International Space Station, and culminating in the start of renewed lunar exploration beginning in 2020.



*Fig 2. NASA's exploration strategy is a multi-decade endeavor.*

For lunar missions, the Ares I will transport Orion and a crew of up to 4 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. 3). After mating, the EDS 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 orbit, for return to Earth.

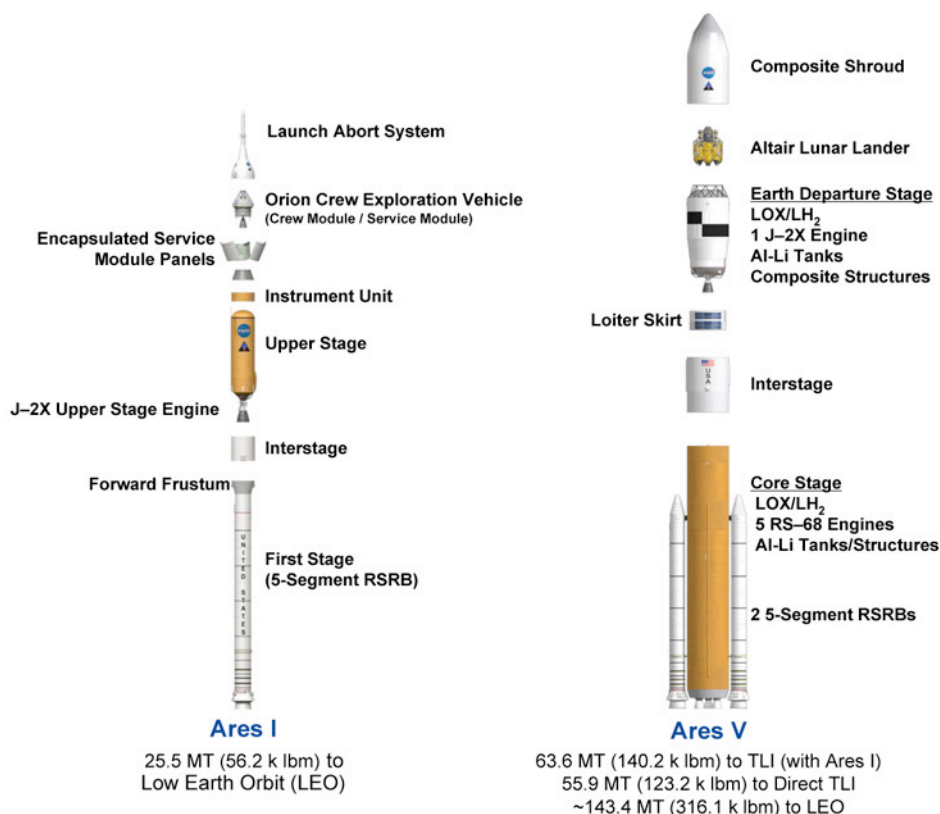


*Fig. 3. Notional lunar mission scenario.*

Following is an overview of NASA's approach to integrating the Ares I vehicle stack using capabilities and assets that are resident in Marshall's Engineering Directorate and within the Ares Projects Office, working in partnership with other NASA Centers and the U.S. aerospace industry. It also provides top-level details on the approach and progress of the in-house design of the Ares Upper Stage Element.

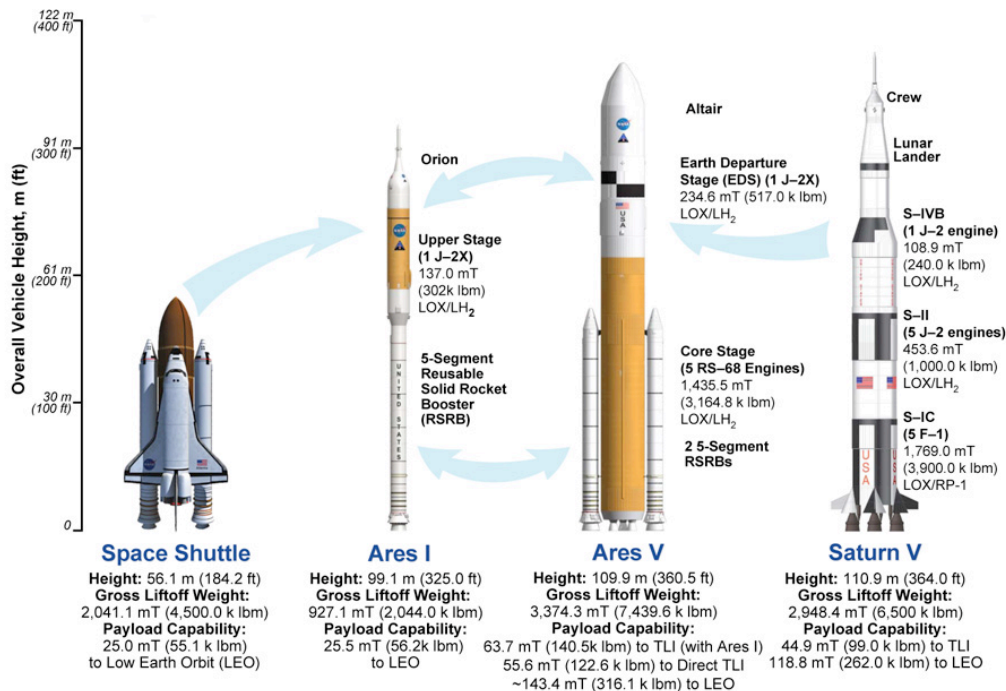
## II. Ares I Vehicle Stack Integration

The Ares I is an in-line rocket configuration, with a 5-segment reusable solid rocket motor first stage and an upper stage powered by a J-2X engine, capable of putting approximately 25.5 metric tons (MT) (56,200 pounds) into orbit (fig. 4). The Ares I and Ares V will have common propulsion and structural elements; therefore, lessons derived from the Ares I design and development will yield knowledge for the heavy-lift system, which is in the advanced concept phase.



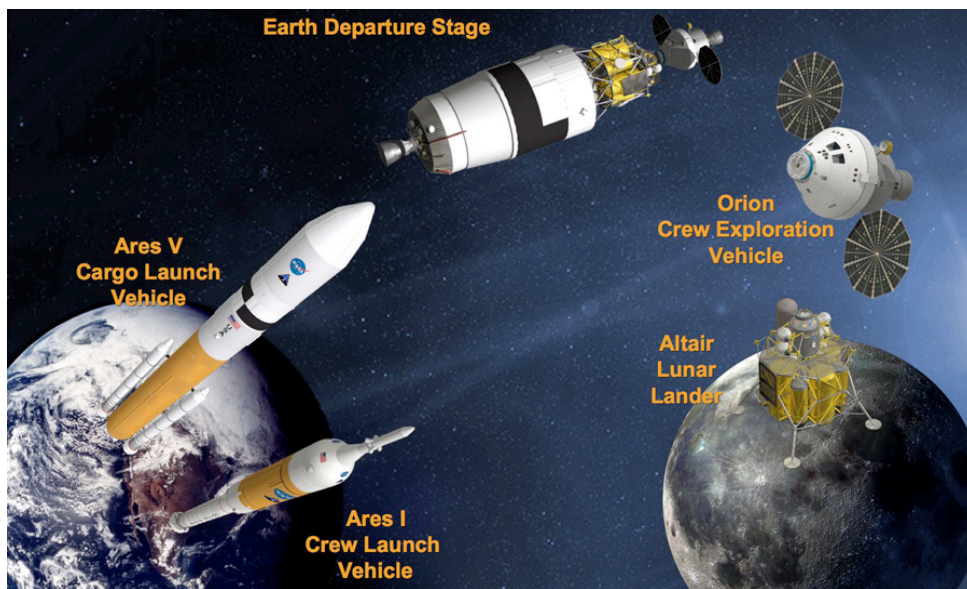
**Fig 4. The Ares I and Ares V have similar elements.**

This space transportation architecture leverages the knowledge and experience gained from tried-and-true systems, such as the Saturn V and Shuttle, while leveraging modern design tools, manufacturing processes, operational concepts, and systems engineering standards and practices (fig. 5). The Ares I first stage is an evolved 5-segment version of the existing Shuttle solid rocket motors/boosters, and the J-2X engine is based on the original J-2 utilized on the Saturn vehicles. Ares V will utilize a pair of the same 5-segment motors as the Ares I, and its EDS will employ the same J-2X engine as the Ares I upper stage. While the Ares I upper stage is a new, clean-sheet design, it will be leveraged in the design of the Ares V Earth departure stage. This programmatic and technical direction for commonality of hardware between the two vehicles is expected to reduce recurring costs for more sustainable operations, as well as reduce the risk of developing the Ares V.



**Fig. 5. The Ares I and Ares V are evolutionary space transportation solutions.**

The Constellation Program comprises multiple systems, including the Ares launch vehicles, Orion crew module, ground and mission operations, and the Altair lunar lander and supporting infrastructure (fig. 6). Systems engineering and integration between and among these systems is being performed in house using rigorous standards codified in NASA's Systems Engineering Processes and Requirements, Systems Engineering Handbook, and the Ares Projects Office's Systems Engineering Management Plan.<sup>4,5,6</sup> NASA is committed to applying systems engineering and systems management processes and standards to ensure that technical performance is accountably connected to budget allocations and schedule milestones.



**Fig. 6. NASA's Constellation Program manages the exploration architecture.**

The Ares I team consists of the range of engineering and business disciplines that come together formally and informally in working groups, integrated product teams, and governing councils and boards. In this way, decision-making is handled at the lowest possible level in most cases. The various industry partners are on board and the team is fully engaged in the design and development work now in progress (fig. 7).



**Fig. 7. The Ares nationwide team.**

For background, the Johnson Space Center is home to NASA's Constellation Program and the Orion Project; Kennedy Space Center is in charge of launch operations and first stage recovery; and Marshall is responsible for the design, development, test, and evaluation of the Ares launch vehicles. Other NASA locations are developing particular technologies and hardware for Constellation. For instance, Ames Research Center is leading the effort to develop the thermal protection system (heat shield) for Orion; Langley Research Center is leading the design of the Launch Abort System; and Glenn Research Center is building the segments for the simulated upper stage of Ares I-X flight test vehicle. These are a few examples of how the Agency is leveraging its unique strengths, in tandem with the U.S. aerospace industry, to derive safe, reliable, and cost-effective space transportation solutions for long-term exploration.

Many Department of Defense and NASA projects alike support the Government serving in the lead systems integrator role to enhance mission success, especially in a multi-decade effort such as fielding America's new space transportation system. As stated in a systems engineering article in NASA's Academy of Sharing Knowledge magazine: "A common misconception about systems engineering is that it is an up-front activity that takes place only in the requirements definition phase of a program or project life cycle. That view doesn't properly account for the complexity of engineering and integrating systems. As systems are added and modified over the course of development, the number and complexity of interfaces increases in a nonlinear fashion. Problems resulting from conflicting or missing interfaces are the norm, not the exception. The only way to deal with this type of dynamic environment is by adopting an end-to-end, logical systems approach that emphasizes robust modeling and simulation, verification, and validation testing. These rigorous systems processes must be repeated throughout the life cycle of a system to detect unexpected consequences that can flow from even small design changes."<sup>7</sup>

In the case of the Ares integrated vehicle, the systems engineering and integration function is performed by the Engineering Directorate in partnership with the Ares Projects' Vehicle Integration (VI) Element, which 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 (loads; thermal; guidance, navigation, and control; separation; and liftoff).

Engineering analyses are informed by a portfolio of integrated vehicle testing, from scale models in wind tunnels (fig. 8) to major full-up ground vibration testing in Marshall's Dynamic Test Stand (fig. 9). The testing strategy includes a series of developmental flight tests that will progress from uncrewed test flights, such as the Ares I-X mission discussed below, to those carrying crewmembers, prior to attaining initial operational capability.

Ares discipline engineers have conducted over 7,000 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. With facilities at Marshall, Langley Research Center (LaRC), 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.



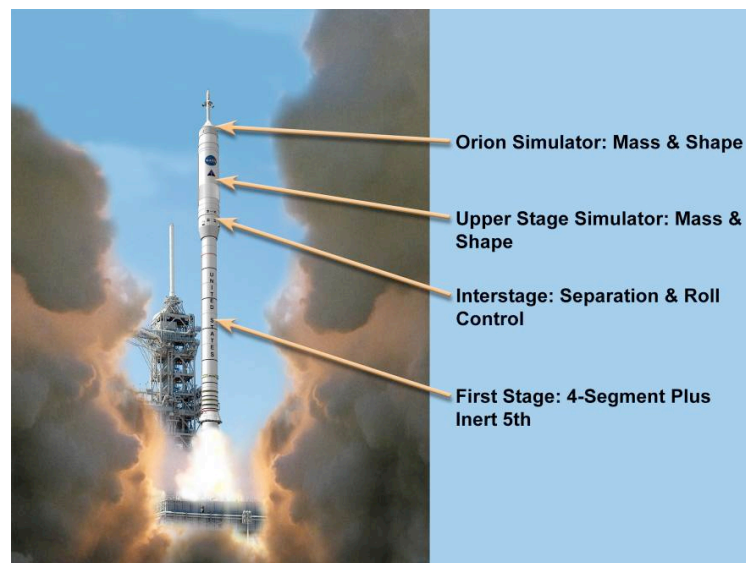
*Fig. 8. Sample Ares I wind tunnel testing configurations.*



*Fig. 9. The Ares I integrated vehicle will undergo vibration testing in Marshall's Test Stand 4550.*

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. 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.

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. 10), 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. 10. Ares I-X mission concept.***

While computer-aided design programs and modeling and simulation applications are vital engineering tools, three-dimensional testing in a variety of forms and formats is integral to refining the design and certifying the hardware for flight. These testing examples underscore the need to anchor digital data with real-world information that builds confidence in the components, subsystems (or elements), and the integrated system design.

The Ares Vehicle Integration Element, supported by Marshall's Engineering Directorate, is responsible for ensuring that consistent engineering practices and assumptions are implemented, in addition to solving technical challenges. VI also is responsible for confirming that requirements have been correctly validated, decomposed, and verified, and that the verification requirements are properly defined to ensure that the system design meets stakeholder and customer needs. In this overarching systems engineering capacity, VI coordinates technical activities across all participating NASA Centers to foster the integrated execution of essential design and analysis functions.

Leading the systems engineering and integration for Ares is an unparalleled effort for the current generation of NASA engineers. In order to mitigate that risk for a project of this scale, Ares is relying on expertise and experience at other NASA Centers to fill gaps, and utilizing outside experts (both experienced contractor personnel and "graybeard" former NASA personnel) to help train the existing NASA workforce and help reduce the experience gap.

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.

As a testament to this systems engineering network, which includes the Chief Engineers and Safety and Mission Assurance representatives assigned to the project, in October 2007, the Ares team completed the second major milestone in the integrated vehicle's path to fielding — the System Definition Review (SDR) — followed by an integrated vehicle technical interchange meeting, which uncovered several dynamic and weight challenges now being addressed by focus teams studying various options for resolution (fig. 11). The previous milestone — the System Requirements Review (SRR) — was completed in November 2006. This review was focused on requirements validation and verification, and risk identification and mitigation, as well as baselining the reference vehicle design from which to continue systems engineering work.

NASA Program/Project Lifecycle

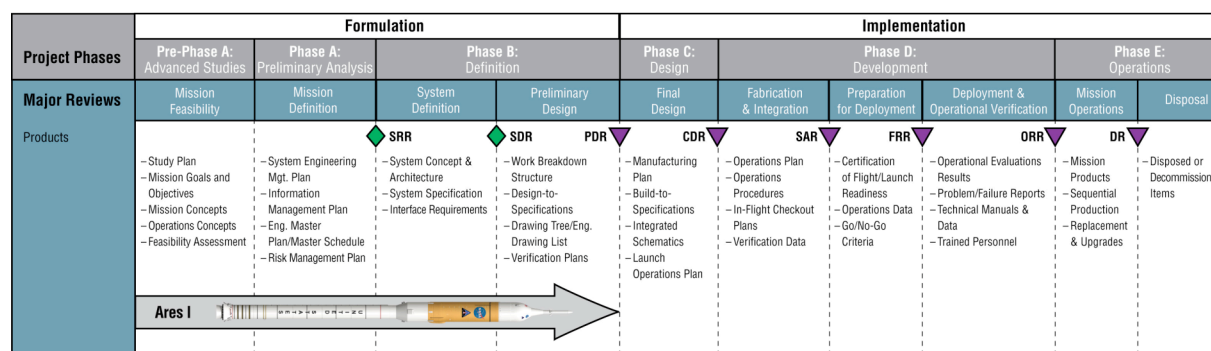


Fig. 11. Ares systems engineering reviews.

The next major milestone — the Preliminary Design Review (PDR) — will be conducted over the next few months. 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. 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.

Mission success demands a disciplined, innovative approach. A final example of systems engineering integration is the Engineering Information Center, where personnel who are assigned to various disciplines literally get on the same sheet of paper by providing status and issues on a range of set parameters. As NASA's fifth Administrator Robert Frosch, who was responsible for the development of the Space Shuttle, observed "Systems, even very large systems, are not developed by the tools of systems engineering, but only by the engineers using the tools."

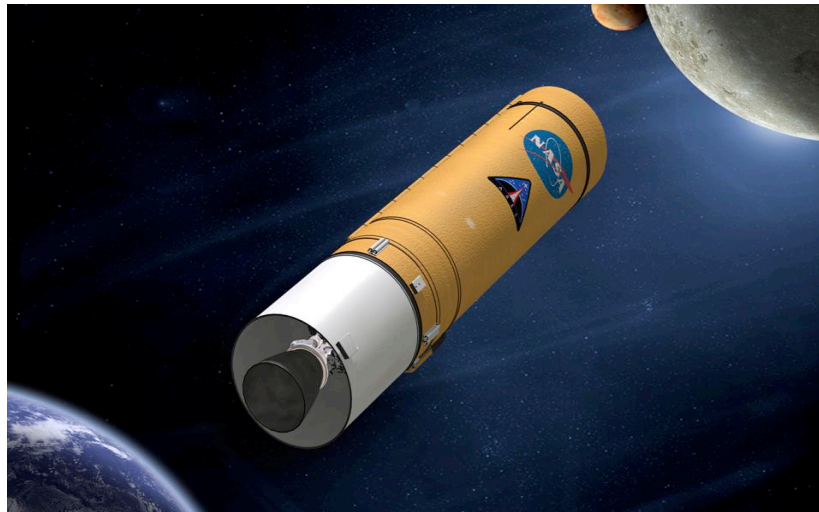
In many ways, the EIC is a representation of Frosch's observation that "engineering is an art, not a technique; a technique is a tool," as it is a tangible physical environment that is structured for dialogue and bottom-line understanding of the complexities of information that usually is relegated to Powerpoint charts and may, therefore, be lost in translation.<sup>8</sup> Participation in the EIC process sets the stage for the Engineering Directorate's 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 "war rooms" maintained by both the Ares Projects Office, which is integrating the vehicle elements, and the Upper Stage Element, which is being designed in house.

### III. Ares I Upper Stage Design

Whereas the Exploration Systems Architecture Study suggested evolving proven technologies — for example the 5-segment reusable solid rocket motor — where possible, it also recommended a clean-sheet design upper stage powered by an upper stage engine such as the Space Shuttle Main Engine (SSME). Subsequent trade studies found that developing the J-2X engine for expendable use would be more cost effective than revamping the SSME for a throw-away application. In short, the Ares I upper stage is a new system, rather than a modification of an existing one, though its manufacturing will be similar to that of the Saturn V's massive structure. This approach allows engineers to fully incorporate state-of-the-art materials, processes, and hardware; adapt to vehicle configuration changes; standardize replacement parts; and build the upper stage to evolve with technological advances.

The Ares I upper stage (fig. 12) is an aluminum-lithium alloy, self-supporting cylindrical structure that is 25.5 meters (84 ft) long and 5.5 meters (18 ft) in diameter. This second stage will provide the guidance, navigation, and control, while the J-2X upper stage engine will provide the thrust and propulsive impulse, required for the second phase of the Ares I ascent flight after the first stage separates from the launch vehicle. The upper stage includes the main propulsion system, thrust vector control, avionics and software, reaction control system for roll and attitude control, and the separation system required to perform the first stage separation. It also holds the liquid oxygen/liquid hydrogen propellants and provides the system for delivering the propellants for the J-2X engine operation. Most of the avionics will be housed in an instrument unit, which provides the mechanical and electrical interfaces between the Ares I and the Orion.

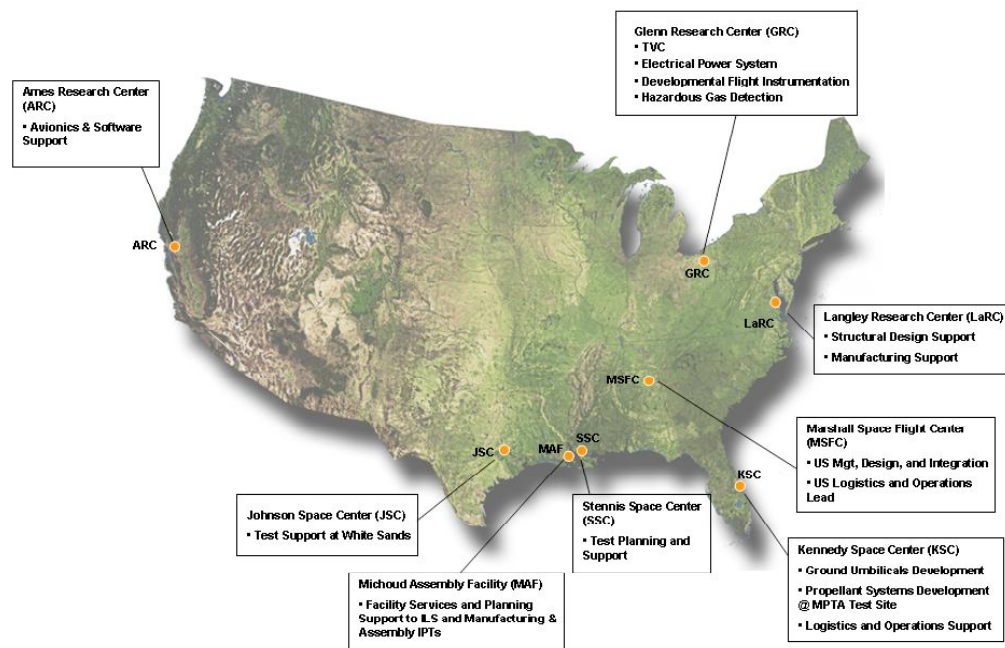


*Fig. 12. Concept of the Ares I Upper Stage.*

The Ares I upper stage is being designed by a NASA Design Team (NDT) and fabricated by the Upper Stage Production Contractor (USPC), The Boeing Company, at NASA's Michoud Assembly Facility (MAF) in New Orleans, Louisiana. NASA awarded the USPC contract to Boeing in August 2007 in a competitive procurement as part of an agreement that includes the assembly, checkout, and delivery of the completed integrated upper stage. NASA is responsible for all design, development, and test, including technical and programmatic integration of the upper stage system. NASA is reducing development risk and cost by incorporating current state-of-the-art technologies and minimizing the need for new technology development. The resulting system is designed to have minimal proprietary encumbrances.

The NDT is tasked to reduce the overall cost of ownership of the Ares I Upper Stage by considering early in the design process: (1) the input of the Boeing team that will fabricate the stage and (2) the operations team that will handle and operate the stage. Since the Ares Projects' inception, the NDT has been tasked to minimize the whole life-cycle cost of the Upper Stage. The team is implementing design-in supportability, which includes design input from the Boeing team on stage fabrication and design input from the operations team on how the stage will be processed, operated, and maintained. This is managed and controlled by an aggressive Integrated Logistics Support Plan (ILSP), which was developed early in the design life cycle and will directly affect and monitor design-in supportability.

The Marshall Center also is leading the in-house effort to develop the requirements and specification of the Ares I upper stage, the development plan and testing requirements, and all design documentation, manufacturing, logistics, and operations planning. Development, qualification, and acceptance testing will be planned based on derived requirements and risks identified by the NDT. The development process begins with component tests and advances to more integrated testing as the design matures. Similar to the approach of the Ares I integrated vehicle, the upper stage design is managed in design analysis cycles (DACs) that provide coordinated decomposition, detailed design at the component level, and reintegration of the system. The DACs are scheduled to support design reviews. In a truly “one mission/one team” approach, the final integrated upper stage will be the product of numerous partnerships among NASA and industry participants (fig. 14). For example, the Glenn Research Center is responsible for the thrust vector control system and the Stennis Space Center will contribute its one-of-a-kind engine and stage test facilities.



**Fig. 14. Upper Stage development approach.**

In addition to the USPC, NASA has also selected The Boeing Company as the prime contractor to produce, deliver, and install avionics systems for the Ares I upper stage. Boeing will support the NDT as the Instrument Unit Avionics Contractor (IUAC), leading the development of the Ares I avionics components. The company will also develop and acquire avionics hardware for the vehicle and will assemble, inspect, and integrate the avionics system components on the upper stage. Components will be manufactured by the prime contractor’s suppliers across the country. Final integration and checkout will also take place at MAF.

In 2007, the Ares I Upper Stage Element successfully completed its System Requirements and System Definition Reviews. The Element is currently conducting its Preliminary Design Review (PDR) to determine the adequacy, correlation, completeness, and risks associated with the allocated technical requirements for the Ares I upper stage. The PDR demonstrates that the preliminary design meets all system requirements with acceptable risk; shows that the correct design option has been selected, interfaces identified, and verification methods satisfactorily described; and establishes the basis for proceeding with detailed design.

The Upper Stage Element's Integrated Master Schedule (IMS) was developed and is maintained to support the Ares I Schedule Management System, and provides the Upper Stage Element with a maintainable IMS that:

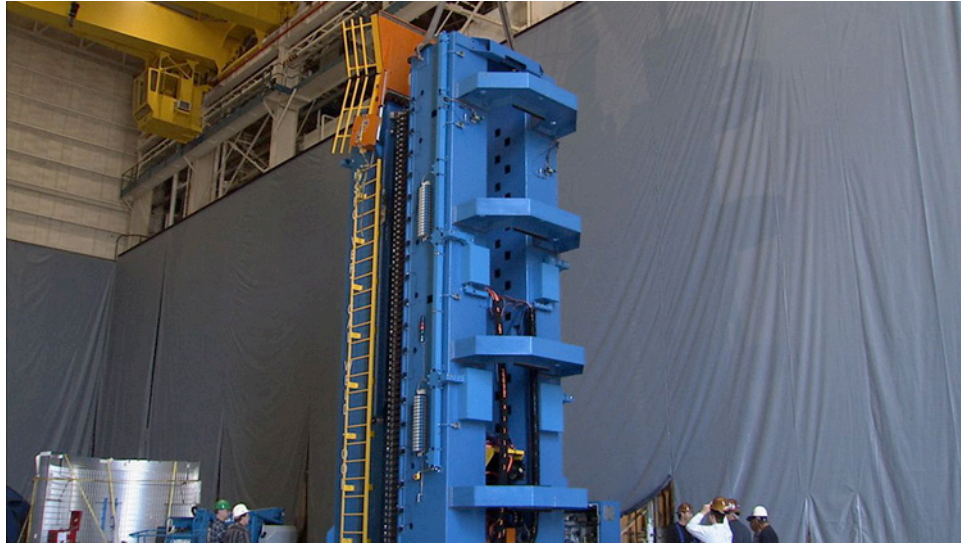
- Supports the ability to accurately track and assess the Upper Stage Element's schedule progress relative to the established baseline;
- Provides insight and integration of Element activities relative to major reviews and decision points; and
- Ensures integrated coordination between all aspects of the Project/Element activities and milestones that are critical to Project/Element and mission success.

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: 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. 15); and a Ground Vibration Test structure to support the overall crew transportation system and the Upper Stage/Orion configuration dynamic characterization tests. 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.



***Fig. 15. The Main Propulsion Test Article will be tested in Marshall's Test Stand 4670.***

In addition to these tests, the Upper Stage Element is also creating a number of process simulation articles and manufacturing demonstration articles to refine materials, procedures, and designs for the Ares vehicles. Utilizing a newly equipped Materials and Processes Lab with world-class friction stir welding capabilities (fig. 16), Upper Stage personnel will be able to refine the process for fabricating the upper stage structures and verify that the processes in place will result in the desired design specifications in the final flight hardware. By virtue of having this friction stir welding capability on-site at Marshall, engineers doing the design work for the Upper Stage Element can have first-hand experience of the fabrication processes, and account for those processes in their design. The Upper Stage Element also has created a full-scale interstage and instrument unit mock-up, allowing design engineers to consider ground operations and logistics concerns from the very beginning of the design process (fig. 17). These various simulators and demonstration articles provide engineers with an awareness of not only the final flight design, but also the processes for fabricating the hardware and the realities of operating the hardware as part of an integrated vehicle stack.



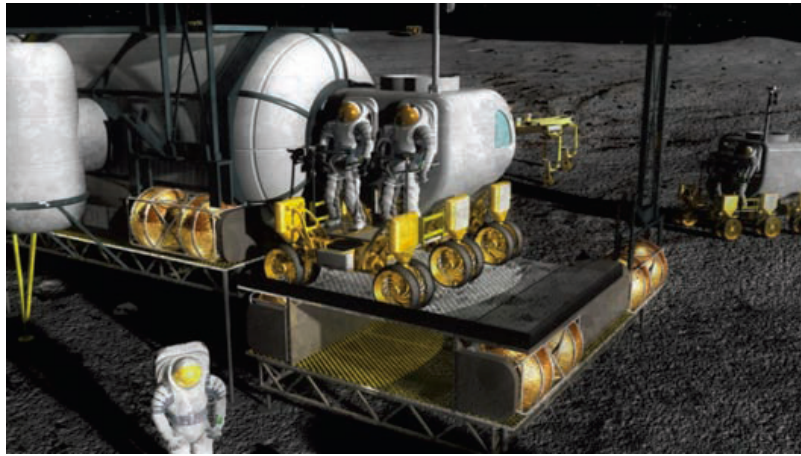
*Fig. 16. The Vertical Weld Tool installed in Marshall's Materials and Processes Lab.*



*Fig. 17. The Performance, Analysis, and Design Demonstrator (PADD) scale model installed at Marshall's Propulsion Research Development Lab.*

#### IV. Conclusion

NASA is revitalizing the Nation's space fleet for a new era of space exploration. It is seeking potential efficiencies across the Agency's mission portfolio by providing a routine, steady market for logistics and crew rotation services to the Space Station through the Commercial Orbital Transportation Services demonstration. Yet, while being flexible, the Agency has an overriding responsibility to assure U.S. access to space, as is evidenced in its methodical pursuit of a new human-rated transportation system that can be ready for crew transportation to low-Earth orbit no later than 2015, as well as cargo transportation to the Moon no later than 2020 (fig. 18). These systems will be extensible to future systems that one day will enable the first human footprint on Mars.



*Fig. 18. NASA lunar mission concept.*

Marshall's Ares Projects and Engineering Directorate are fully engaged in the task of delivering America's next human-rated space transportation system using the experience base and one-of-a-kind facilities offered by a government and industry collaboration, with NASA serving as the lead systems integrator. Throughout this design and development process, the basis for mission success comes from clearly understood requirements — including technical, schedule, and budget parameters — that translate into a safe, robust, and affordable exploration architecture. As a large percentage of the U.S. aerospace workforce prepares for retirement and the nation strives to maintain global competitiveness in science and technology, NASA's approach to integrating the Ares I vehicle stack and designing the Upper Stage in house will pay dividends through benefits such as an expanded experience base coupled with modernized infrastructure assets for testing, manufacturing, launching, and operating a new generation of space transportation for a new age of exploration beyond Earth orbit.

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