Ares Launch Vehicles Development Awakens Historic Test Stands at NASA's Marshall Space Flight Center

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Abstract

This paper chronicles the rebirth of two national rocket testing assets located at NASA's Marshall Space Flight Center: the Dynamic Test Stand (also known as the Ground Vibration Test Stand) and the Static Test Stand (also known as the Main Propulsion Test Stand). It will touch on the historical significance of these special facilities, while introducing the requirements driving modifications for testing a new generation space transportation system, which is set to come on line after the Space Shuttle is retired in 2010.

In many ways, America's journey to explore the Moon begins at the Marshall Center, which is developing the Ares I crew launch vehicle and the Ares V cargo launch vehicle, along with managing the Lunar Precursor Robotic Program and leading the Lunar Lander descent stage work, among other Constellation Program assignments.[1]

An important component of this work is housed in Marshall's Engineering Directorate, which manages more than 40 facilities capable of a full spectrum of rocket and space transportation technology testing — from small components to full-up engine systems. The engineers and technicians who operate these test facilities have more than a thousand years of combined experience in this highly specialized field. Marshall has one of the few government test groups in the United States with responsibility for the overall performance of a test program from conception to completion. The Test Laboratory has facilities dating back to the early 1960s, when the test stands needed for the Apollo Program and other scientific endeavors were commissioned and built along the Marshall Center's southern boundary, with logistics access by air, railroad, and barge or boat on the Tennessee River.[2]

NASA and its industry partners are designing and developing a new human-rated system based on the requirements for safe, reliable, and cost-effective transportation solutions.[3] Given below are summaries of the Dynamic Test Stand and the Static Test Stand capabilities, along with an introduction to the new missions that these sleeping giants will be fulfilling as NASA readies the Ares I for service in the 2015 timeframe, and plans the development work for fielding the Ares V late next decade (fig. 1). Validating modern computer design models and techniques requires the sorts of data that can only be generated by these one-of-a-kind facilities.

I. Dynamic Test Stand

The Dynamic Test Stand was used in 1966-67 for ground vibration testing of the Saturn V launch vehicle and the Apollo spacecraft. Dr. Werner von Braun credits this facility for providing rocket scientists with the data that identified and helped solve the oscillation problem known as "pogo," keeping the Apollo 8 mission on track.[4] Completing this testing program was the final step prior to the launch of Apollo 11, the first manned lunar landing mission. In 1972-73, the stand was used for tests involving the Skylab Space Station, and in 1978-79 for ground vibration testing of the complete Space Shuttle vehicle (fig. 2).

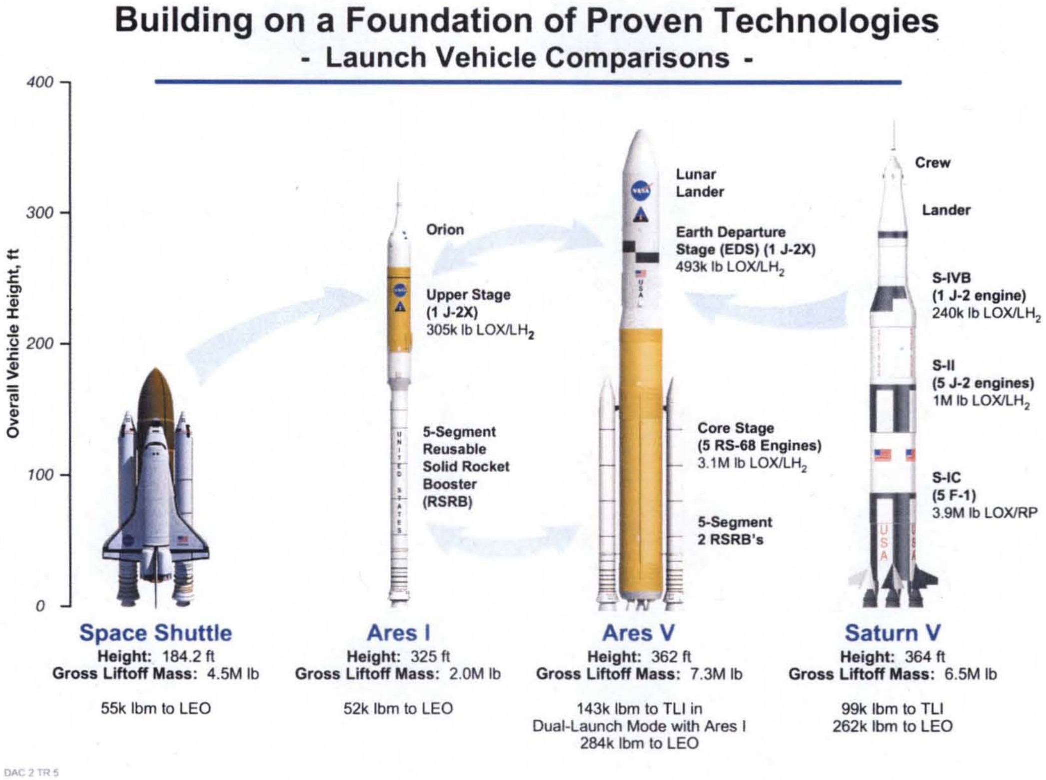

Fig. 1. The Ares I and Ares V build on knowledge gained from the Saturn V and the Space Shuttle.

Fig. 2. Marshall's Dynamic Test Stand was used to gather ground vibration test data prior to flying the new space transportation system.

The integrated Ares I is an in-line configuration comprised of a 5-segment reusable solid rocket booster and an upper stage powered by a J-2X engine. The Orion crew exploration vehicle is the payload, with its launch abort system tower on top (refer to fig. 1). In the Dynamic Test Stand, the integrated vehicle will be supported on a soft suspension system to simulate free-free boundary conditions. Facility modifications, such as installation of an external access stairwell, are in progress, with structural work that is planned to be completed in 2008. A sampling of modifications includes the installation of a 100-ton mobile crane, as well as relocating a rail head and pouring a concrete foundation pad for hardware delivery.

Currently, 6 tests of the Ares I are planned, including 2 full stack and 4 upper stage with J-2X engine tests. Ares I hardware delivery begins in 2009, the 5-segment first stage will be delivered in late 2010, and the J-2X engine is expected in 2011. Test data collected will be available to inform the Ares I Design Certification Review milestone for the Orion 2 flight test mission slated for July 2013.

II. Static Test Stand

The Static Test Stand is a vertical engine firing test stand with its foundation keyed into the bedrock approximately 40 feet below grade. It was constructed in 1962 to develop and test the first stage of the Saturn V launch vehicle, which used five F-1 engines that produced 7.5 million pounds of thrust, or 180 million horsepower (fig. 3). This facility includes a water-cooled deflector with a flow rate of 135,000 gallons per minute.

Fig. 3. Marshall's Static Test Stand accommodates large rocket engine testing, such as the Saturn V cluster of five F-1 engines.

This is the only place aside from the launch site where the entire Saturn V vehicle was assembled. Dynamic testing was used to determine the bending and vibration characteristics to verify vehicle design. The 364-foot assembly was placed on a hydraulic bearing, which acts as a floating platform, and electromechanical shakers caused vibrations similar to those expected from flight forces.[5] More recently, in 1998, this stand was used to test fire the RD-180 Russian-built rocket engine under a Space Act Agreement with Lockheed Martin for its Atlas III vehicle.[6]

For the Ares I, this facility is being refurbished and modified to accommodate the main propulsion test article, comprised of the upper stage and the J-2X engine. The upper stage is a "clean sheet" design, while the J-2X is an updated version of the powerful J-2 engine used to launch the Saturn V rocket upper stages during the Apollo Moon program in the 1960s and 1970s. This same stage will be used for the Ares V in an Earth departure mode for translunar injection, so Ares I testing has the dual benefit of informing the heavy-lift launch vehicle system, as well.

Ares test objectives are to verify main propulsion system design performance, as well as to validate the performance algorithms, system, and subsystem models. The test article 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. Currently, main propulsion test article drawings are being created, and the stage will be fabricated at Marshall in the 2010 timeframe, followed by J-2X engine delivery in mid-2011. Testing conducted in 2011 will produce data that will inform the upper stage Design Certification Review in 2012.

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Abstract

This paper chronicles the rebirth of two national rocket testing assets located at the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center: the Static Test Stand (also known as the Main Propulsion Test Stand and TS 4670) and the Dynamic Test Stand (also known as the Ground Vibration Test Stand and TS 4550). It will touch on the historical significance of these special facilities, while introducing the requirements driving modifications for testing a new generation space transportation system, which is set to come on line after the Space Shuttle is retired in 2010. In many ways, America's journey to explore the Moon, Mars, and beyond begins at the Marshall Center, which is developing the Ares I crew launch vehicle and the Ares V cargo launch vehicle, along with leading the Altair lunar lander descent stage work, among other Constellation Program assignments. An important aspect of this work is housed in Marshall's Engineering Directorate, which manages more than 50 facilities capable of a full spectrum of rocket and space transportation technology testing — from small components to full-up engine systems. Marshall has one of the few government test groups in the United States with responsibility for the overall performance of a test program from conception to completion. The Engineering Directorate's Test Laboratory engineers and technicians who operate these facilities have more than a thousand years of combined experience in this highly specialized field. Some facilities date back to the late 1950s and early 1960s, when the test stands needed for the Apollo Program and other scientific endeavors were commissioned and built along the Marshall Center's southern boundary, with logistics access by air, railroad, and barge or boat on the Tennessee River. Given below are summaries of the Dynamic Test Stand and the Static Test Stand capabilities, along with an introduction to the new missions that these once slumbering giants will be fulfilling as NASA readies the Ares I for service in the 2015 timeframe and plans the development work for fielding the Ares V late next decade. Validating contemporary engineering computer design models and techniques requires the types of data that can only be generated by these one-of-a-kind facilities.

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I. Ares I and Ares V Introduction

This section gives background for the new missions that Marshall's historic test stands will be supporting. NASA and its industry partners are in the process of designing and developing a new human-rated system based on the requirements for safe, reliable, and cost-effective transportation solutions.[1] The exploration architecture is managed by NASA's Constellation Program, with a number of projects such as the Orion crew exploration vehicle, the Ares launch vehicles, and the Altair lunar lander. The Ares I and Ares V are evolutionary systems that will work in combination to replace the Space Shuttle when it is retired later this decade (fig. 1) as one of NASA's strategic goals.[2]

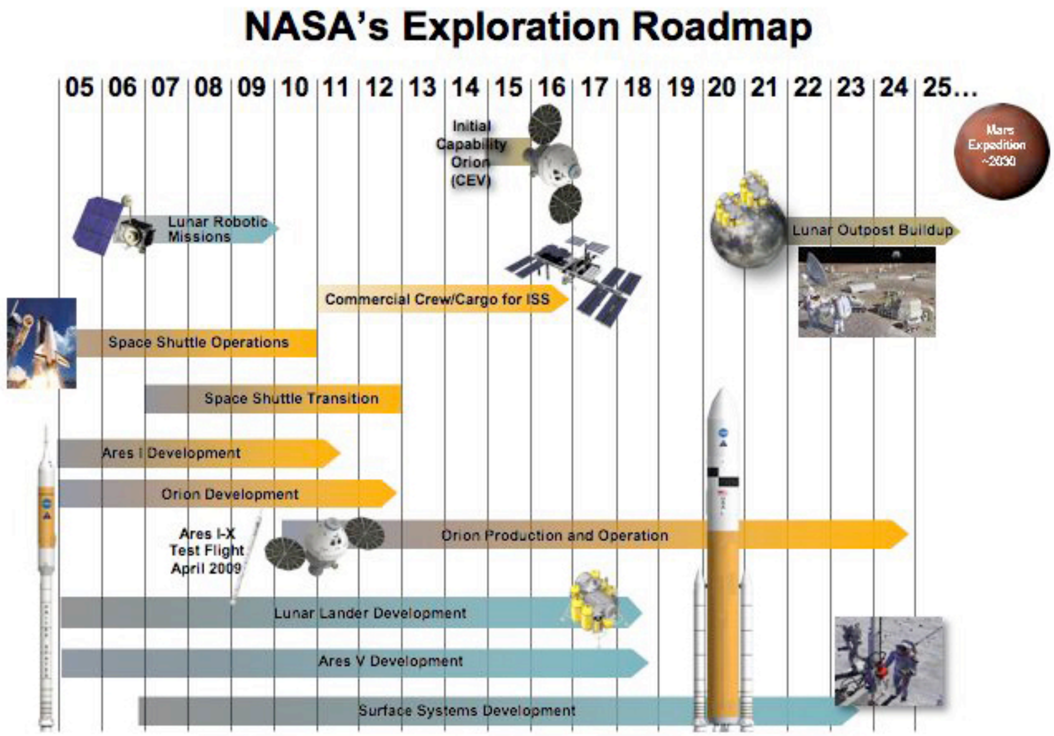

Fig. 1. NASA's exploration strategy is a multi-decade endeavor.

The Ares I is slated to loft the Orion to orbit in its first test flight in 2013, with initial operational capability by 2015, while the heavy-lift Ares V test flights are projected for 2018 in preparation to deliver the Altair to orbit for trips to the Moon by 2020. These systems are being designed to empower America's renewed exploration initiative beyond Earth orbit to prepare for the first astronauts on Mars.

The new architecture reflects almost 50 years of hard-won experience gained from the Saturn's missions to the Moon in the late 1960s and early 1970s, and from the venerable Shuttle, which has been in operation for almost 30 years (fig. 2). Building on NASA's experience in the design, development, testing, evaluation, and operation of complex space transportation systems, the Marshall Center houses the skilled workforce and unique facilities needed to field new exploration systems that are being designed for long-term sustainability across the years ahead.[3]

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 (LEO) (fig. 3). Orion can carry up to six crewmembers to the International Space Station or four astronauts to the Moon.

The Ares I design is an in-line, two-stage configuration with a Launch Abort System (LAS) on top of Orion, to move the crew quickly away from the launch vehicle in case of an emergency. The Ares I first stage is a 5-segment solid rocket booster (SRBV) based on the heritage Shuttle SRB design and, like the Shuttle SRBs, is designed to be recoverable and reusable. The clean-sheet design upper stage is powered by the liquid oxygen/liquid hydrogen (LOX/LH_2) fueled J-2X engine, which is derived from the Saturn's second-stage J-2 engine.

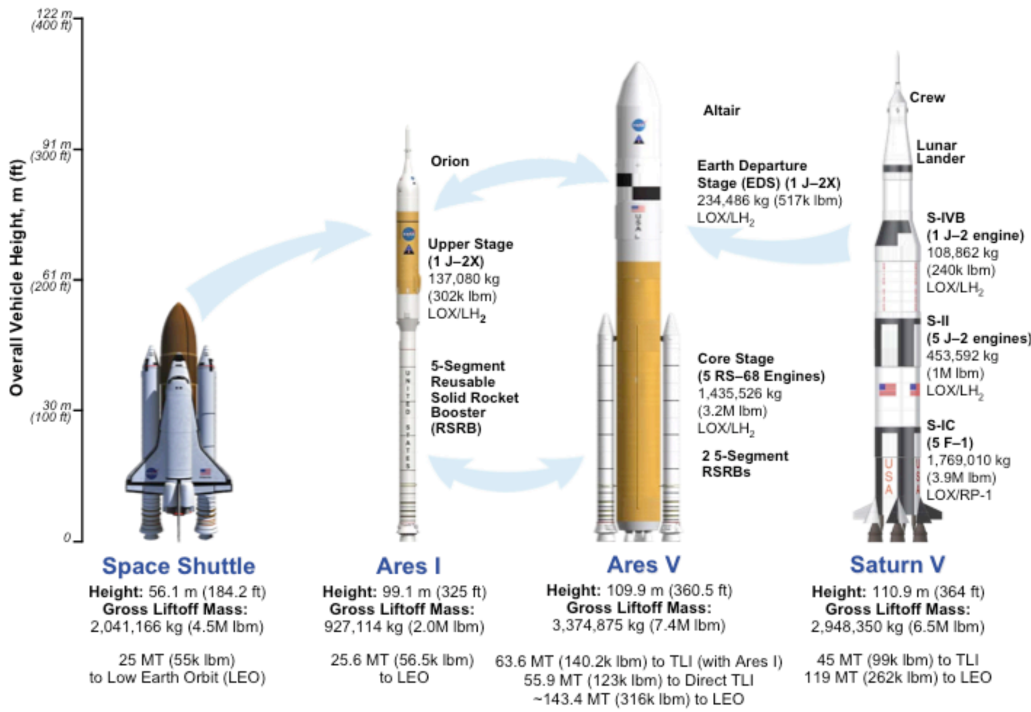

Fig. 2. The Ares I and Ares V build on knowledge gained from the Saturn V and the Space Shuttle.

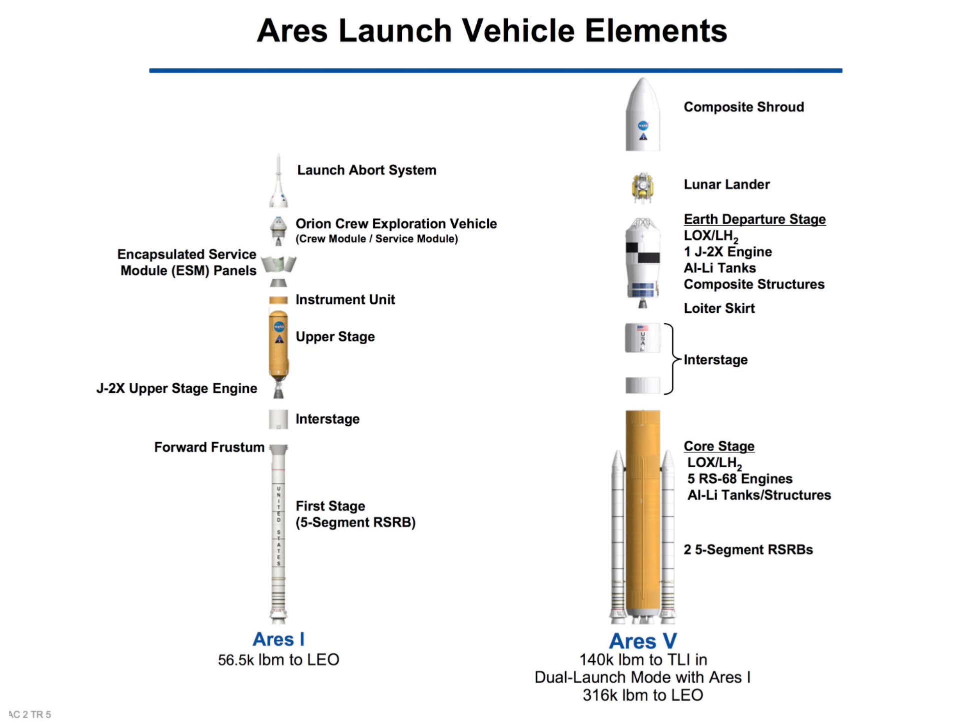

Fig. 3. The Ares I and Ares V have common elements.

The Ares V will be 360 feet tall, weigh 7.4 million pounds at launch, and be capable of lifting about 316,000 pounds to LEO or 140,200 pounds to trans-lunar injection (TLI) in combination with the Ares I. The Ares V core stage will be powered by five RS-68 LOX/LH_2 engines similar to those currently used by the Delta IV evolved expendable launch vehicle. Two five-segment solid rocket boosters, like those used for the first stage of the Ares I, will also provide power during ascent. The second stage, or Earth departure stage (EDS), will be powered by a single J-2X engine — the same as that used for the Ares I second stage. In addition, the EDS structure will be very similar to the Ares I's upper stage.

Although the Ares V is still in the advanced concept stage, it is anticipated that hardware commonality between the two vehicles will offer economies of scale, while engineering lessons gained from the Ares I experience will be applicable to the larger cargo carrier.

The lunar mission scenario calls for the Ares I to transport Orion to Earth orbit to rendezvous and dock with the Ares V's Earth departure stage transporting the Altair. After mating, the EDS upper stage 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 (fig. 4). 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. 4. Concept of Altair lunar landing.

II. Role of Testing in the Ares I Space Transportation System Development

Engineering America's next space fleet requires that safety, reliability, and operability are maximized for missions to the Space Station, as well as for extended lunar exploration. Sound systems engineering and business best practices are employed to effectively create sustainable transportation solutions, while effectively integrating the many subsystems and components that form a system that is robust and cost-effective, thus reducing the technical and business risks that are inevitable in such a complex undertaking.

NASA's Systems Engineering Handbook provides guidance on the major reviews to be followed in the delivery of flight hardware, from concept studies to operation and retirement.[5] Since its inception in late 2005, following NASA's Exploration Systems Architecture Study, the Ares I Project has completed several major systems engineering reviews and is preparing for the Preliminary Design Review, at which time the vehicle's requirements will be set and the design will be 10 percent complete.

Computer aided design programs and modeling and simulation applications are vital engineering tools; however, three-dimensional testing in a variety of forms and formats is integral to refining the design and certifying the hardware for flight. NASA's Systems Engineering Handbook also prescribes testing objectives throughout the design and development phases, as well as during operations. Steps on the path to fielding the Ares I include a series of validation and verification tests, including scale model wind tunnel testing, component-level testing, and flight testing, such as the Ares I-X mission that is slated for 2009 to inform the Ares Critical Design Review in 2010.

The series of wind tunnel tests for the Ares I has given early insight into configurations resulting from requirements solutions based on trade studies during design analysis cycles. Thousands of wind tunnel tests have been conducted on various-sized scale models to assess three-dimensional geometric configurations before more detailed engineering designs are produced (fig. 5). For example, in late 2005, Marshall's Aerodynamic Research Facility provided data from wind tunnel tests conducted using a 16.5-inch scale model, to help rocket engineers determine flight performance characteristics. The Ares scale model included the full take-off load, including the Orion and Launch Abort System tower. This is one of many examples of where early testing of three-dimensional models has contributed to design studies.

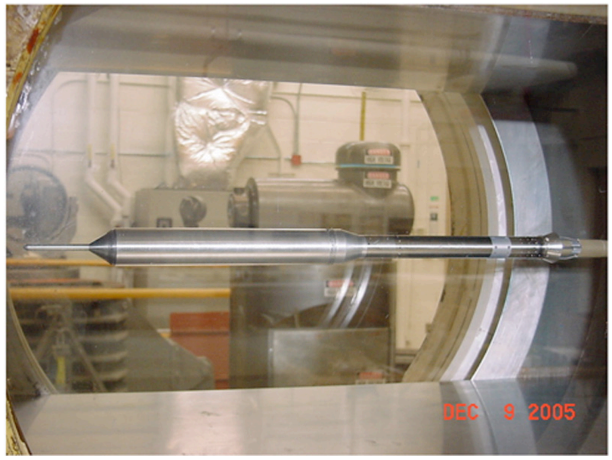

Fig. 5. Wind tunnel test.

As an example of how the Agency is leveraging its unique facilities, the first J-2X engine test series was completed in 2008, using 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.[5] 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. 6). 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 6. J-2X subscale main injector hot-fire testing at Marshall.

Progress also has been made toward planning the first flight of the integrated system — a mission known as Ares I-X, which is scheduled for 2009 (fig. 7). The Ares I-X vehicle will be composed of flight-like and high-fidelity mockup hardware to simulate the anticipated aerodynamics and loads of the full-up Ares I mission. The first stage will be a Shuttle inventory 4-segment booster with a mass simulator fifth segment, and the mock upper stage will simulate the mass, center of gravity, and outer mold line of the final flight hardware in development. Atop the mock upper stage, a mass simulator will represent the Orion crew exploration vehicle, designed to accurately reflect the aerodynamics of the planned crew capsule.

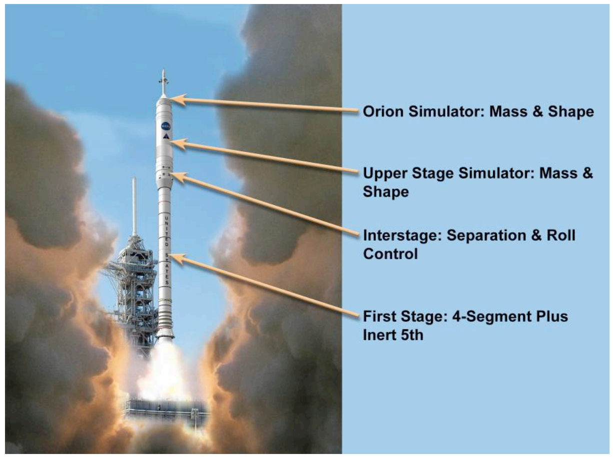

Fig. 7. The Ares I-X flight test is planned for 2009.

During this suborbital developmental flight test, data will be collected by on-board vehicle sensors, such as accelerometers, and from ground systems, such as cameras. Critical data will be telemetered to the ground and all data will be recorded on board the vehicle. The on-board data recorder will be retrieved from the first stage after recovery. These data will be processed in accordance with the flight test objectives.

Data gathered from this initial suborbital flight 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 hardware, which will be evolved and repurposed for the Ares application, as well as to gather data about the dynamics and controllability of the integrated launch vehicle stack. In addition, as the Kennedy Space Center transitions from Space Shuttle to the Ares/Orion system, the Ares I-X mission provides an excellent starting point from which to perfect ground operations scenarios, including modifications to Launch Complex 39B.

These are just a few examples of risk-reduction testing that is in progress to inform the Ares I design process. Add to this the planned tests of the Main Propulsion Test Article (MPTA) and the Integrated Vehicle Ground Vibration Test (IVGVT) activities, among others, and a wealth of information will be available on which to base final decisions relative to fielding America's next human-rated space transportation system.

Marshall's Test Laboratory has been involved in the testing of all human-rated fight vehicles since NASA was established. The Test Lab provided critical test support to the Shuttle Program throughout the early phases of development and has historically provided critical, quick turnaround response for anomaly resolution and Shuttle return-to-flight testing. In addition, the Test Lab supports the Shuttle and Space Station programs as those designs have matured. As the Shuttle test rate tapers down, Ares work continues to increase. Research and development testing is performed to support other NASA Centers, as well as other government agencies and commercial customers. In addition, preparations are underway to retrofit facilities for several major Ares tests, including the Upper Stage Common Bulkhead structural strength testing in the croygenic test facility, as well as the Main Propulsion Test Article's static hot-firing and the Integrated Vehicle's dynamic structural test.

Following are top-level details about the Main Propulsion Test Article/Static Test Stand and the Integrated Vehicle Ground Vibration Test/Ground Vibration Test Stand, both of which are to be conducted by Test Lab personnel at Marshall to generate and collect data for the Ares Projects' Flight and Integrated Test Office, using the unique facilities that made possible the success of the Apollo and Shuttle Programs. Included in the content below are historical details and capability summaries, along with information on driving requirements and modifications in progress to support development of the Ares I.

III. Static Test Stand for Main Propulsion Test Article Testing

NASA conducts static testing on its spacecraft propulsion systems to ensure suitability for the severe conditions experienced during launch and to verify the ability of the engine to sustain the thrust level needed to meet mission requirements. The Ares I Main Propulsion Test Article will be a validation test of the Upper Stage mated with the J-2X Upper Stage Engine. This testing will be conducted in a timeframe to both validate the materials and processes used in Upper Stage construction, as well as the integrity of the system when subjected to the forces of the powerful J-2X.

A. Historical Significance and Capabilities

The Static Test Stand, whose formal name is the Advanced Engine Test Facility, is a National Historic Mechanical Engineering Landmark, which is better known as TS 4670 and often referred to as the Technology Test Bed. TS 4670 is a vertical engine firing test stand with its foundation keyed into the bedrock approximately 40 feet below grade. Construction began in 1963 and was completed in 1965 to develop and test the first stage of the Saturn V launch vehicle, which used five F-1 engines that produced 7.5 million pounds of thrust, or 180 million horsepower (fig. 8). This one-of-a-kind facility includes a water-cooled deflector with a flow-rate capability of around 260,000 gallons per minute. The stand has two test positions and accommodates three propellant types: LOX/LH_2 Space Shuttle Main Engine class and LOX/Rocket Propellant-1 RD-180 class.

Fig. 8. Marshall's Static Test Stand (TS-4670) accommodates large rocket engine testing, such as the Saturn V cluster of five F-1 engines.

This stand, which was used throughout the 1960s, was envisioned as a capability to test the Nova booster, which was planned to replace the Saturn V. The stand was modified in 1974 to add a liquid hydrogen capability for testing the Space Shuttle External Tank, which was conducted between 1978 and 1980. The stand was modified again to allow single-engine testing with advanced components on the Space Shuttle Main Engine. Testing was conducted as part of NASA's Technology Test Bed Program, which evaluated new engine technology modifications. More recently, in 1998, this stand was used to hot fire the RD-180 Russian-built rocket engine under a Space Act Agreement with Lockheed Martin for its Atlas III vehicle.[6]

B. Driving Requirements and Modifications

As stated earlier, the Ares I MPTA will consist of the Upper Stage mated with the J-2X engine (fig. 9). The Upper Stage is a clean-sheet design, which is now in Preliminary Design Review, while the J-2X is an updated version of the powerful J-2 engine used to launch the Saturn V rocket upper stages during the Apollo Moon program in the 1960s and 1970s. A similar stage will be used for the Ares V in an Earth departure mode for trans-lunar injection, so Ares I testing has the dual benefit of informing the heavy-lift launch vehicle system design process.

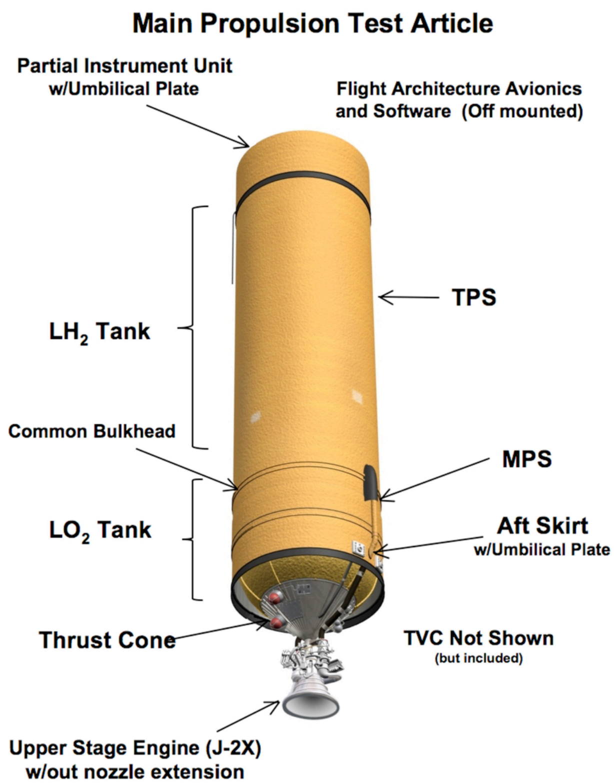

Fig. 9. MPTA concept.

The Upper Stage test article is being designed and developed in house at Marshall in the Engineering Directorate's Materials and Processes Lab, using capabilities such as the country's largest friction-stir welding machine to fuse aluminum-lithium alloy into a 33-foot cylindrical structure that is 84-feet long. The Boeing Company, under contract to NASA, will be responsible for the overall manufacturing of this stage, as well as the integrated vehicle's avionics.

The largest components of the Upper Stage will be two insulated tanks for liquid oxygen and liquid hydrogen, separated by a common bulkhead. Located between the Ares I instrument unit and the common bulkhead, the liquid hydrogen tank will be almost 51-feet long and will provide storage for 11,620 cubic feet of unpressurized fuel at minus 423-degrees Fahrenheit (F), or around 11,800 cubic feet of unpressurized fuel at 72-degrees F. Located on the other side of the common bulkhead is the liquid oxygen tank, which provides insulated storage for the J-2X engine's oxidixer. The 9-foot-long tank will provide 3,825 cubic feet of unpressurized liquid storage volume at minus 297-degrees F and 3,868 cubic feet of unpressurized storage volume at 72-degrees F.[7]

Upper stage testing, including the MPTA and structural modal and vibration testing, will be conducted in government-owned facilities, including the Marshall Center and Stennis Space Center's test stands, which also were used in the design and development of the Saturn V and the Shuttle. The Ares I Upper Stage element provides a case in point for streamlining not only processing and on-pad activities, but of using lean manufacturing process flows to dramatically reduce recurring costs. Its flight hardware traffic model includes manufacturing at NASA's Michoud Assembly Facility in New Orleans, with handoff from Michoud to Stennis in Mississippi for mating with the engine and acceptance testing prior to shipping to Kennedy for launch processing and mission operations.

The J-2X engine is being developed under contract to NASA by Pratt & Whitney Rocketdyne (fig 10). This hardware system is in its Critical Design Review phase and on track for delivery for testing in 2011. The verification and validation matrix includes testing requirements. The development effort focuses on four goals that reflect a building-block approach to gaining empirical knowledge as the engine design matures:

- Early risk mitigation, including characterization of heritage turbomachinery and valves.
- Design risk mitigation, including characterization of various design features prior to component testing.
- Component and subassembly tests.
- Engine system tests, including development and certification, as well as support to the Ares I Upper Stage Main Propulsion Test Article.

Fig. 10. Concept of the J-2X engine.

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.

Currently, MPTA drawings are being created, and the stage will be fabricated in the 2010 timeframe, followed by J-2X engine delivery in mid-2011, as covered above. Testing conducted in 2011 will produce data that will inform the Upper Stage Design Certification Review in 2012.

TS 4670 is being refurbished and modified to accommodate this test series. Requirements are in development and the preliminary schedule for deliverables is in work. Modification plans for TS 4670 has included careful coordination with the Stennis Space Center and the Kennedy Space Center over the past year. Preparation for TS 4670 modifications include stand maintenance activities described below. Reactivation construction will be completed prior to the hardware deliveries.

The LOX storage area components have been serviced. Some piping has been cleaned in house; reinstallation of these items will begin as soon as pipe support painting is completed. Storage vessels and the remaining pipe will be cleaned when funded. Purge panels have been refurbished and are back in service. Solenoid cabinets have been mechanically refurbished, and electrical work is underway.

In the LH_2 storage area, some components have been serviced. Modifications to storage vessel vent piping to support installation of new relief valves and vent valves has been completed. Modifications to the pressurization system for both vessels is in progress. New pressure regulator panels and trickle purge panels have been completed and are in service. A new solenoid cabinet has been built. Main pressure regulator panels for gaseous helium, gaseous nitrogen, and gaseous hydrogen have been refurbished. Most old control and instrumentation cabling and hardware has been removed and will be replaced at a later date.

IV. Dynamic Test Stand for Integrated Vehicle Ground Vibration Testing

NASA has conducted dynamic tests on each of its major launch vehicles during the past 45 years. Each test has provided invaluable data to correlate and correct analytical models used to predict structural responses to differing dynamics for these vehicles and for the control of the vehicles. With both Saturn V and Shuttle, hardware changes were also required to the flight vehicles to ensure crew and vehicle safety.

The Ares I IVGVT will provide similar valuable data to support mission success. The IVGVT will provide information on natural frequencies, mode shapes, and damping. This testing will support controls analysis by anchoring computer models. The value of this testing has been proven by past launch vehicle successes and failures. Performing dynamic testing on the Ares vehicles will provide confidence that the launch vehicles will be safe and successful in their missions.

A. Historical Significance and Capabilities

The Dynamic Test Stand (TS 4550) was used in between 1966 and 1967 for ground vibration testing of the Saturn V launch vehicle and the Apollo spacecraft (fig 11). Designated as a National Historic Landmark, this is the only place aside from the launch site where the entire Saturn V vehicle was assembled.

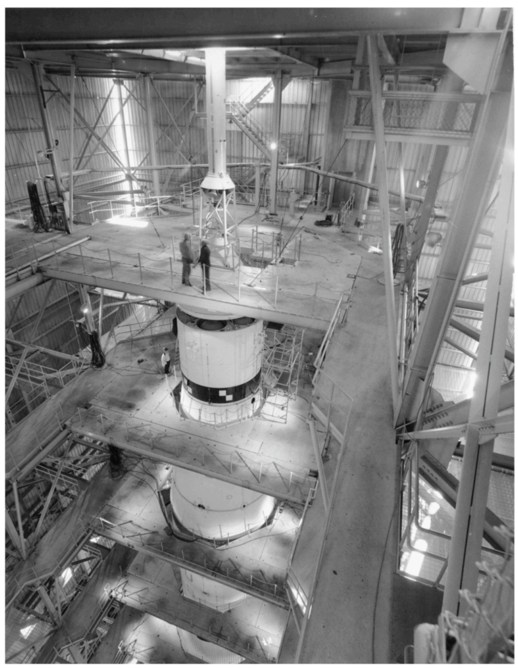

Fig. 11. Saturn V installed in TS 4550 (1967).

Dynamic testing was used to determine the bending and vibration characteristics to verify vehicle design. The 364-foot assembly was placed on a hydraulic bearing, which acts as a floating platform, and electromechanical shakers caused vibrations similar to those expected from flight forces.[8] Dr. Werner von Braun was the Marshall Center's first Director and architect of America's journeys to the Moon. He credits this facility with providing rocket scientists the data that identified and helped solve the oscillation problem known as "pogo," keeping the Apollo 8 mission on track.[9] Completing this testing program was the final step prior to the launch of Apollo 11, the first manned lunar landing mission. In 1972 and 1973, TS 4550 was used for tests involving the Skylab Space Station. In 1978 and 1979, TS 4550 was the site of ground vibration testing of the complete Space Shuttle vehicle (fig. 12).

Fig. 12. TS 4550 with the Space Shuttle Enterprise test article (1978).

B. Driving Requirements and Modifications

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. Plans to perform the Ares I tests began in early 2006. The Ares IVGVT will be conducted from mid-2011 to mid-2012.

As covered above, the integrated Ares I is an in-line configuration comprised of a 5-segment reusable solid rocket booster and an upper stage powered by a J-2X engine. The Orion crew exploration vehicle is the payload, with its Launch Abort System tower on top. In the Dynamic Test Stand, the integrated vehicle will be supported on a soft suspension system to simulate free-free boundary conditions.

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.

The current plan is for the Ares I IVGVT to test six configurations in three unique test positions (TP) that correlate to the launch vehicle at different time points during flight (figs. 13 and 14). Position 1 consists of the full launch stack at first stage burnout, using empty first-stage segments. Position 2 consists of the full launch stack at liftoff, using inert first-stage segments. Position 3 is the "short stack," consisting of the Upper Stage and Orion crew module. Four test configurations will be tested. These are J-2X ignition, post Launch Abort System jettison, critical slosh mass, and J-2X burn-out. The vehicle will be instrumented with hundreds of accelerometers before the dynamic shakers vibrate the test article. This information will be used to determine the modes of vibration in response to dynamic forces.

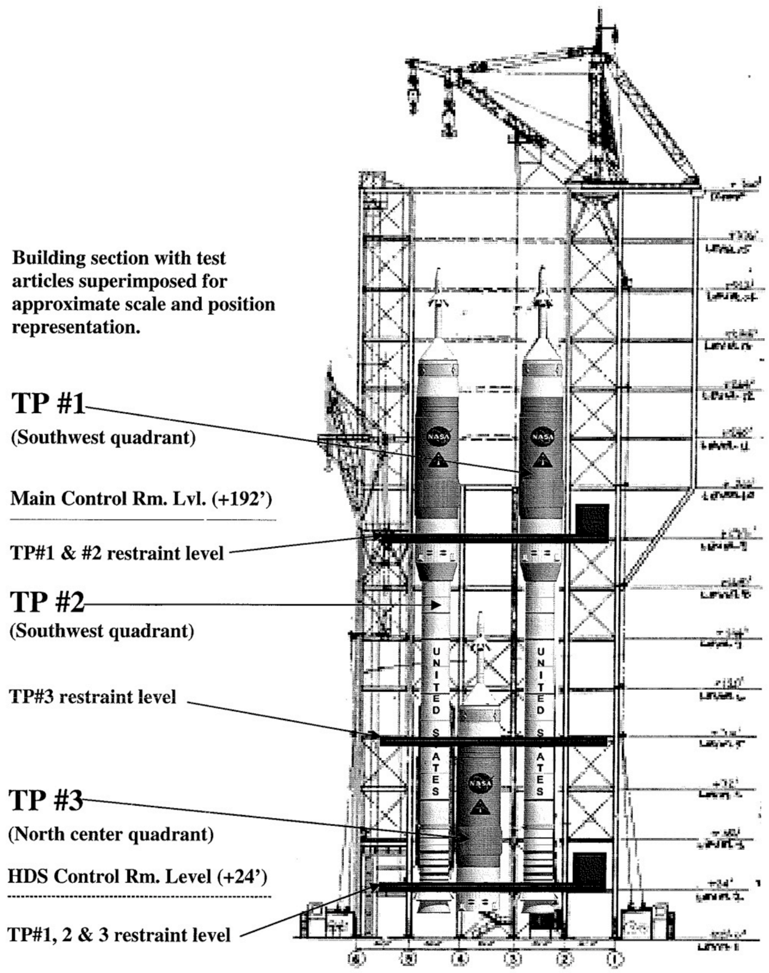

Fig. 13. Notional drawing of test positions for Ares I.

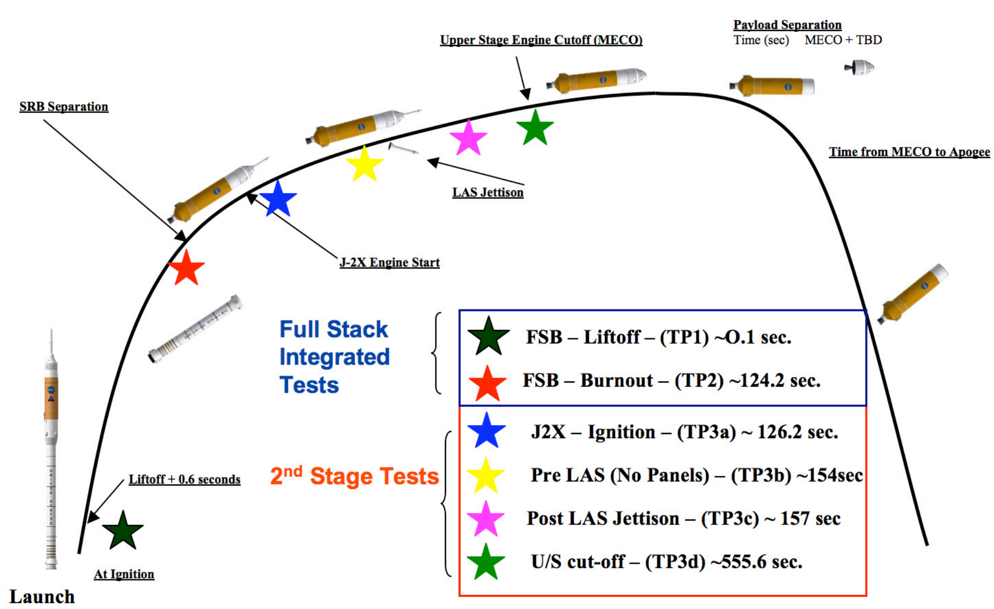

Fig. 14. Test positions correlated to mission scenario trajectories.

It has been more than 25 years since the Shuttle's integrated ground vibration test. In 1987, the United States Department of the Interior's National Park Service designated TS 4550 a national historic landmark. NASA conducted an historical study of the stand, including a review of the original design and subsequent modifications, which were submitted to the Department of the Interior, Historic American Building Survey. This study ultimately will be part of the Library of Congress collection. As required by Federal law, an environmental impact study was performed and posted for public review. This study was approved by NASA in January 2008.[10]

Facility modifications are in progress, with structural work that is planned for completion in 2008 (fig. 15). The 200-ton derrick crane on top of the stand has undergone significant repairs, including installation of a new motor. In March 2008, the crane was used to remove the roof panels and lower the door for the first time since the Shuttle's ground vibration tests in the late 1970s.[11]

Fig. 15. TS 4550 is being modified for Ares I testing in 2011.

Currently the Shuttle-era platforms are being removed. They will be replaced with mast climbers that provide ready access to the test articles and can be moved easily to support different test positions within the test stand. Two new cranes are being procured, a jack/gantry crane and a 100-ton mobile crane, which will be used to aid in moving test articles both at the test stand and at the Redstone Arsenal railhead where first stage segments will be received. The Marshall Center is located on the U.S. Army's Redstone Arsenal, so permission was received to relocate the railhead and to pour a new concrete pad by mid-2009.

V. Conclusion

NASA has had many recent successes in space, from the long-running Mars rovers Opportunity and Spirit, to the recent touchdown of the Phoenix spacecraft at the Mars North Pole, to the Shuttle's delivery of some of the final modules of the Space Station construction project. New Horizons is on its way to image Pluto at the farthest edge of our solar system, and the Chandra and Hubble space telescopes continue to provide data from stars that are billions of years old. It is against this backdrop that Marshall's Test Lab readies for the massive power that will be generated by the Ares I and Ares V launch vehicles.

The Ares I and Ares V duo (fig. 16) will propel U.S. space endeavors to the next level. Parallel design and development activities, as well as investments in modernizing one-of-a-kind infrastructure assets, are on track to field a new space transportation system for the human exploration of space. A nationwide team of Agency and industry partners are taking development to the next level. As the Ares I–X mission prepares to fly in 2009, the Marshall Center's once silent test stands are being revitalized in anticipation of their roles in mission success. Both progress and planning are on track to deliver America's space fleet for assured access to space exploration for generations to come.

Fig. 16. Ares I (right) and Ares V concepts.

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National Aeronautics and Space Administration

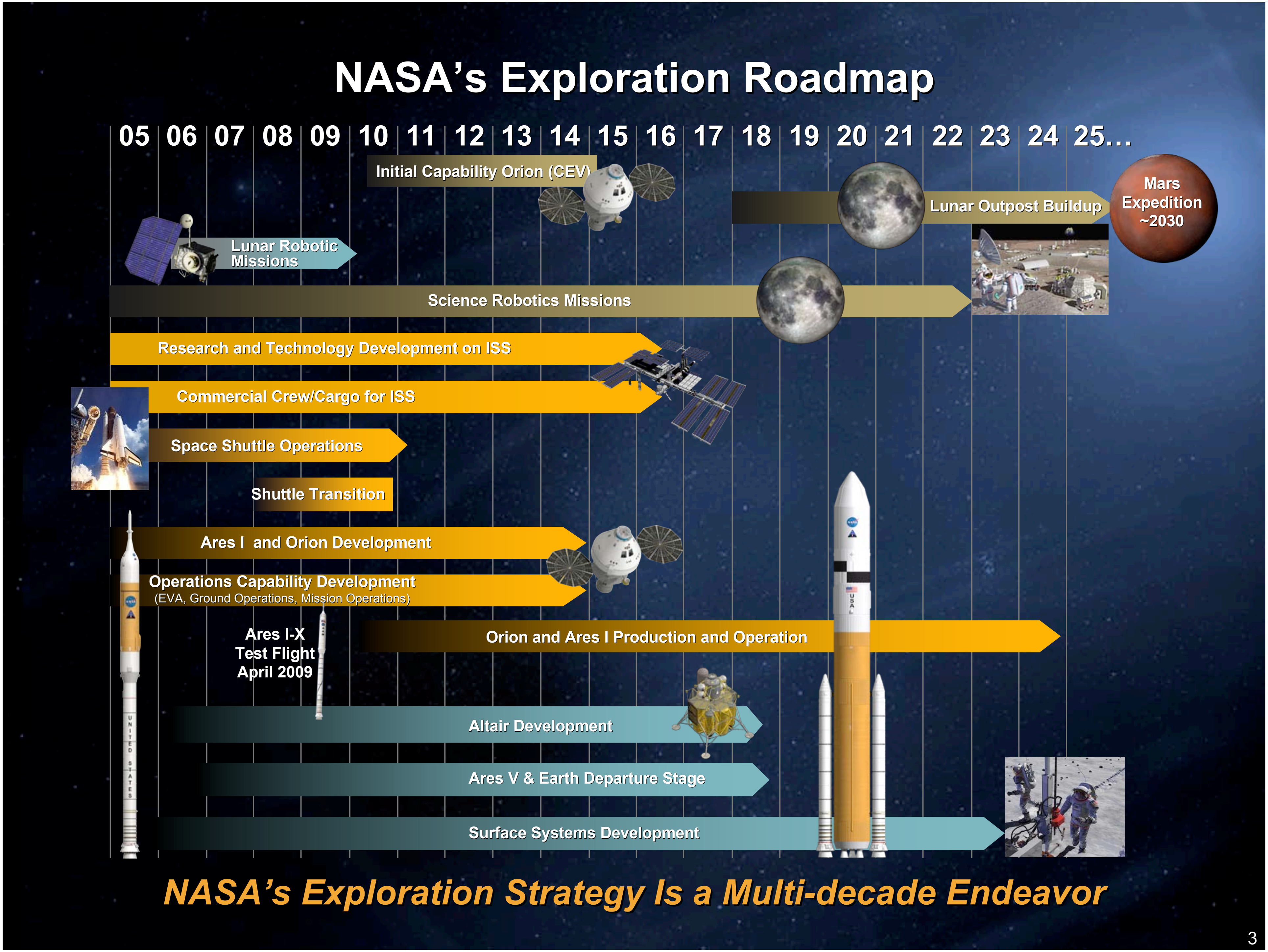
Ares Launch Vehicles Development Awakens Historic Test Stands at NASA's Marshall Space Flight Center

John M. Hammond
Deputy Manager
Test Laboratory
Engineering Directorate
NASA Marshall Space Flight Center

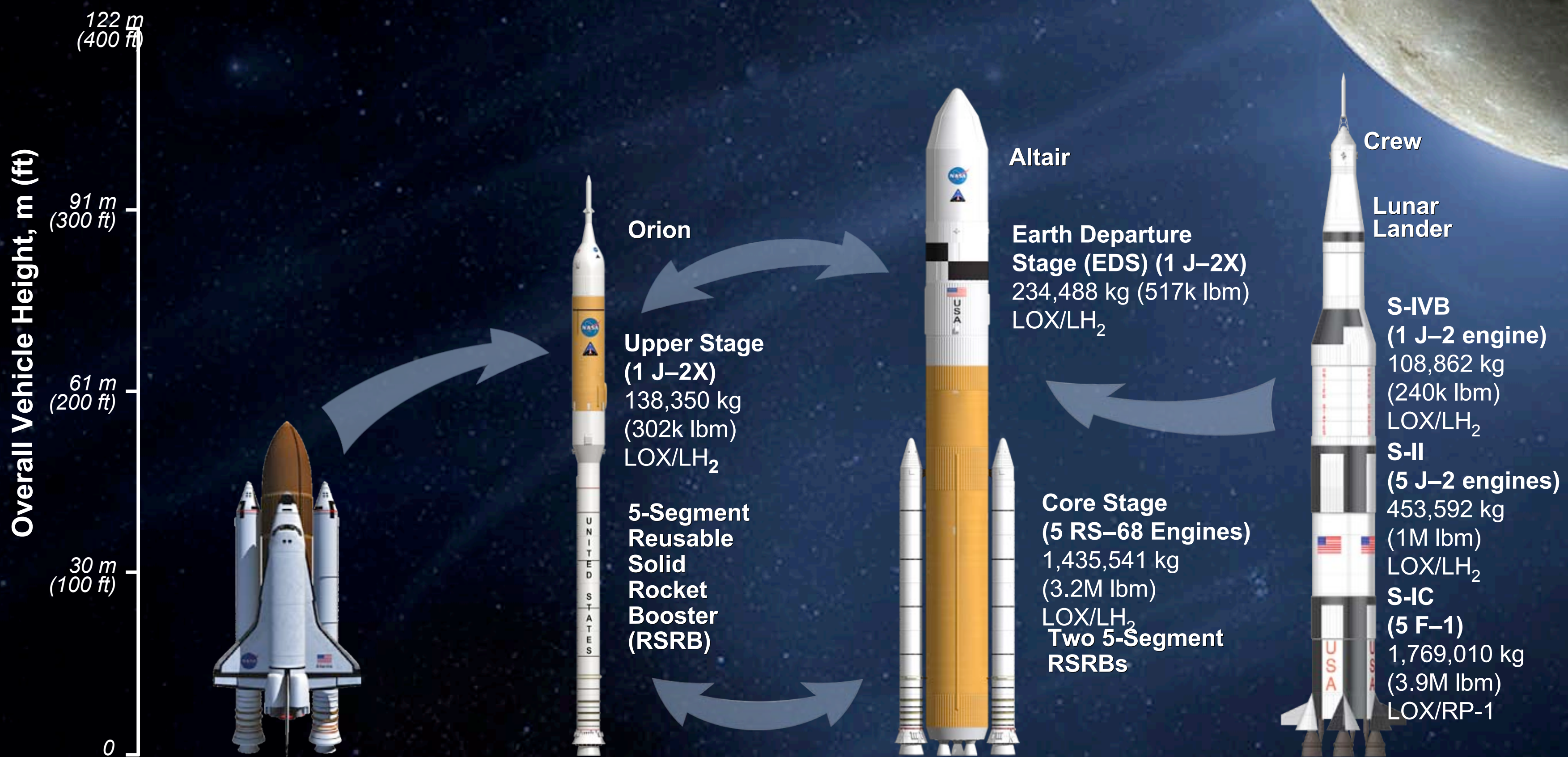
July 23, 2008

Agenda

- NASA's Exploration Roadmap
- Launch Vehicle Comparisons
- Ares Launch Vehicle Elements
- Testing Validates Computer Design and Modeling and Simulation Tools
- Static Test Stand (TS 4670) for Ares I Main Propulsion Test Article Testing
- Main Propulsion Test Article
- Dynamic Test Stand (TS 4550) for Ares I Integrated Vehicle Ground Vibration Testing
- TS 4550 Modifications in Progress
- TS 4550 Test Positions for Ares I
- Summary


NASA's Exploration Roadmap
05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25…
Initial Capability Orion (CEV)
Lunar Outpost Buildup
Mars Expedition ~2030
Lunar Robotic Missions
Science Robotics Missions
Research and Technology Development on ISS
Commercial Crew/Cargo for ISS
Space Shuttle Operations
Shuttle Transition
Ares I and Orion Development
Operations Capability Development
(EVA, Ground Operations, Mission Operations)
Ares I-X Test Flight April 2009
Orion and Ares I Production and Operation
Altair Development
Ares V & Earth Departure Stage
Surface Systems Development
NASA's Exploration Strategy Is a Multi-decade Endeavor
3

Launch Vehicle Comparisons



Space Shuttle

Height: 56.1 m (184.2 ft)
Gross Liftoff Mass: 2,041,166 kg (4.5M lbm)
Payload Capability: 25 mT (55k lbm) to Low Earth Orbit (LEO)

Ares I

Height: 99.1 m (325 ft)
Gross Liftoff Mass: 907,185 kg (2.0M lbm)
Payload Capability: 25.6 mT (56.5k lbm) to LEO

Ares V

Height: 116.2 m (381.1 ft)
Gross Liftoff Mass: 3,704.5 mT (8,167.1k lbm)
Payload Capability: 71.1 mT (156.7k lbm) to TLI (with Ares I)
62.8 mT (138.5k lbm) to Direct TLI
~187.7 mT (413.8k lbm) to LEO

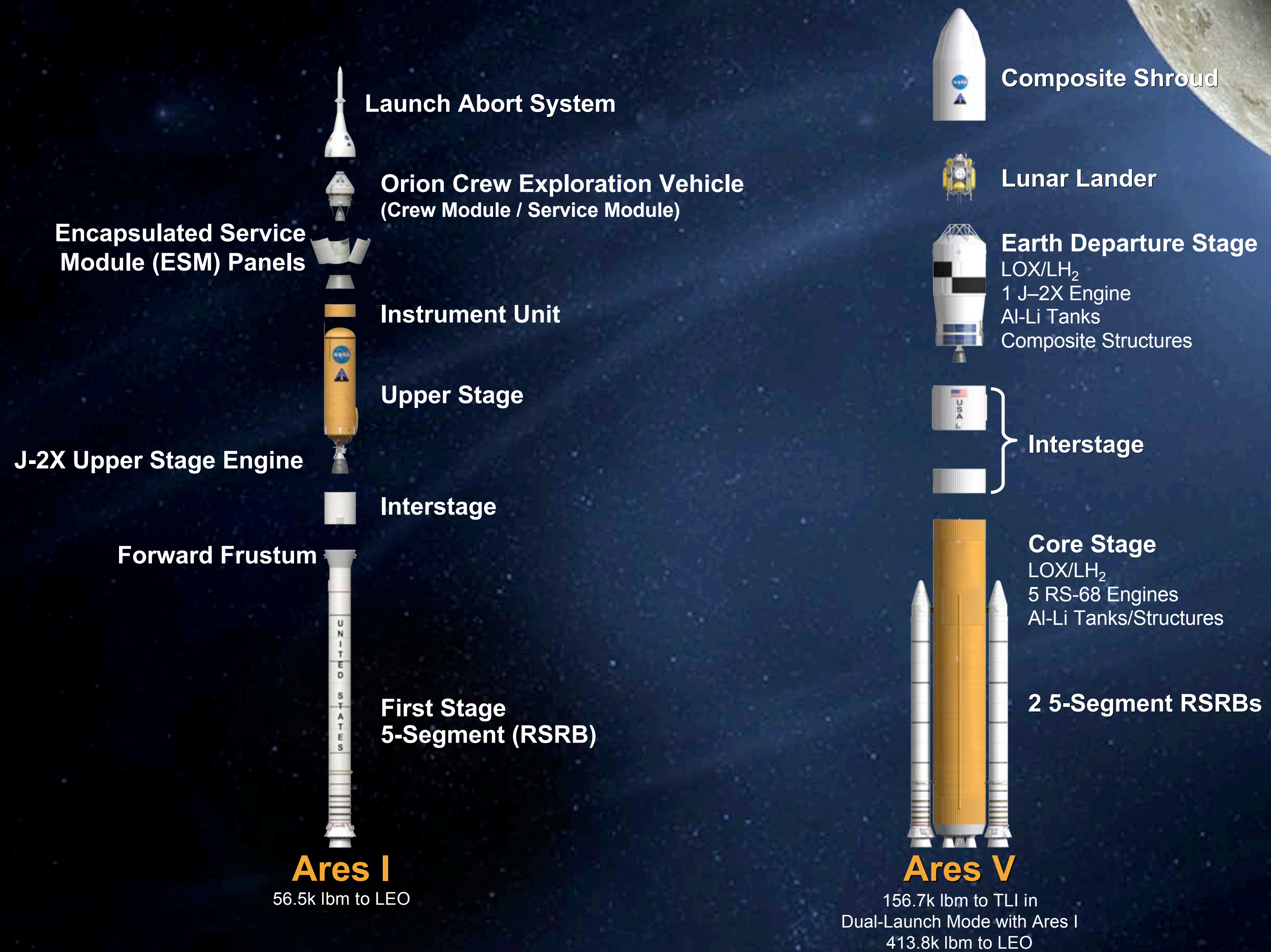
Saturn V

Height: 110.9 m (364 ft)
Gross Liftoff Mass: 2,948,350 kg (6.5M lbm)
Payload Capability: 45 mT (99k lbm) to TLI
119 mT (262k lbm) to LEO

DAC 2 TR 5

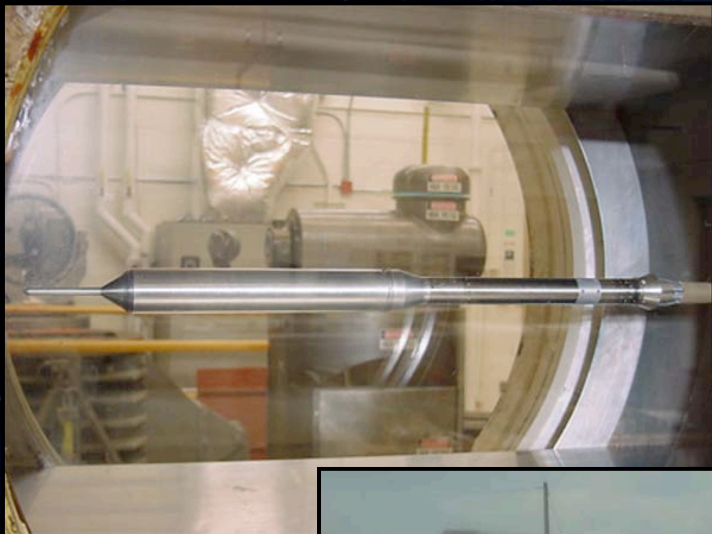
The Ares I and Ares V Build on Knowledge Gained from the Saturn V and Space Shuttle

Ares Launch Vehicle Elements



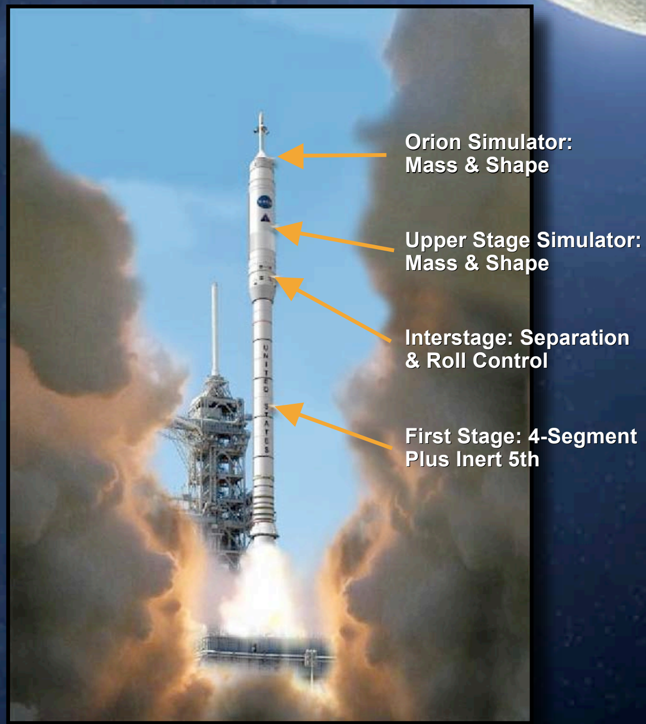
Lessons From the Ares I Crew Launch Vehicle
Will Be Applied to the Ares V Cargo Launch Vehicle

Testing Validates Computer Design and Modeling and Simulation Tools



Ares I wind tunnel test

J-2X upper stage engine injector test

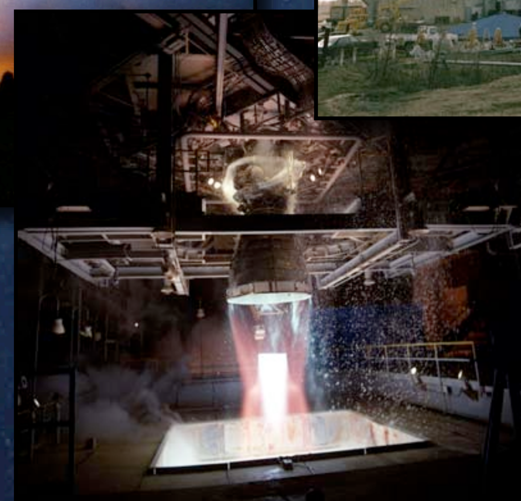


Ares 1-X demonstration test flight April 2009

NASA's Strategy Includes Component, Subsystem, and System Testing

Static Test Stand (TS 4670) for Ares I Main Propulsion Test Article Testing

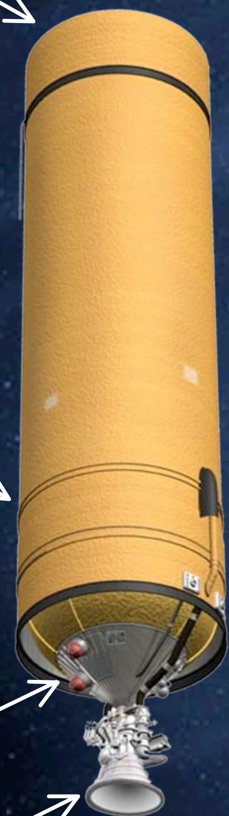
- **Advanced Engineering Test Facility was originally designed for Saturn-1C stage static test.**
- **Two test positions currently on stand:**
  - LOX/LH2 Space Shuttle Main Engine-class position
  - LOX/RP-1 RD-180-class position
- **Capabilities:**
  - 7.5M pounds of Thrust (Foundation designed for 12M)
  - Propellants: LOX, LH2, & RP-1



Saturn- and Shuttle-era Infrastructure Transformation for New Missions

Main Propulsion Test Article

Testing in 2011 informs Upper Stage design certification review in 2012.



Test Objective: Verify Design Performance and Validate Computer Models

Dynamic Test Stand (TS 4550) for Ares I Integrated Vehicle Ground Vibration Testing


Saturn V in 1967

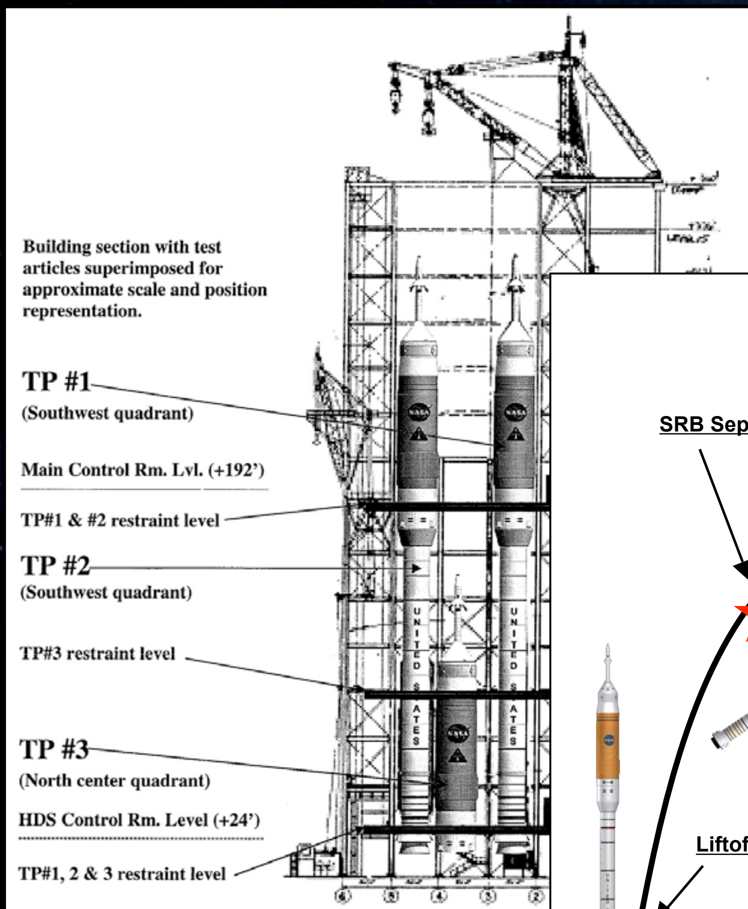

Space Shuttle in 1978

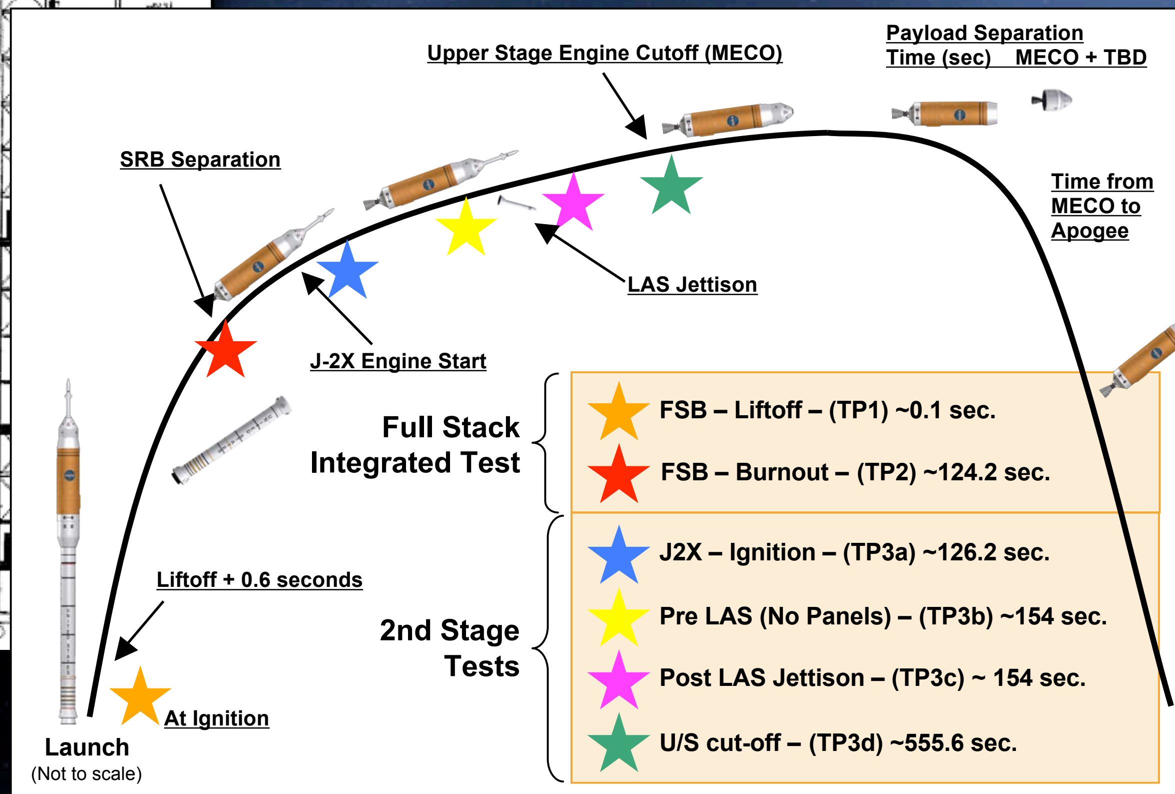
One-of-a-Kind Infrastructure Asset

TS 4550 Modifications in Progress

Ares I Integrated Vehicle Testing 2011–2012

TS 4550 Test Positions for Ares I





Test Objective: Simulate Ares I Mission Scenario Flight Profiles

Summary

- **The Ares I Main Propulsion Test Article and Integrated Vehicle Ground Vibration tests will:**
  - Validate computer modeling and simulation
  - Anchor computer models with real-world data
  - Give confidence in designs
  - Provide data for systems engineering reviews

- **One-of-a-kind test stands:**
  - National infrastructure assets
  - Proven value for generating flight-like data
  - Modifications in progress
  - Team making progress on test plans

Testing Takes Development to the Next Level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