Progress on Ares First Stage Propulsion

Alex S. Priskos,[1] First Stage Element Manager
NASA Marshall Space Flight Center, MSFC, AL, 35812

and

Bruce Tiller,[2] First Stage Deputy
NASA Marshall Space Flight Center, MSFC, AL, 35812

Abstract

The mission of the National Aeronautics and Space Administration (NASA) is not simply to maintain its current position with the International Space Station and other space exploration endeavors, but to build a permanent outpost on the Moon and then travel on to explore ever more distant terrains. The Constellation Program will oversee the development of the crew capsule, launch vehicles, and other systems needed to achieve this mission. From this initiative will come two new launch vehicles: the Ares I and Ares V. The Ares I will be a human-rated vehicle, which will be used for crew transport; the Ares V, a cargo transport vehicle, will be the largest launch vehicle ever built. The Ares Projects team at Marshall Space Flight Center (MSFC) in Huntsville, Alabama is assigned with developing these two new vehicles. The Ares I vehicle will have an in-line, two-stage rocket configuration. The first stage will provide the thrust or propulsion component for the Ares rocket systems through the first two minutes of the mission. The First Stage Team is tasked with developing the propulsion system necessary to liftoff from the Earth and loft the entire Ares vehicle stack toward low-Earth orbit. Building on the legacy of the Space Shuttle and other NASA space exploration initiatives, the propulsion for the Ares I First Stage will be a Shuttle-derived reusable solid rocket motor. Progress to date by the First Stage Team has been robust and on schedule. This paper provides an update on the design and development of the Ares First Stage Propulsion system.

[1] First Stage Manager, Ares Projects, JP20, MSFC, AL, 35812.
[2] First Stage Deputy, Ares Projects, JP20, MSFC, AL, 35812.

Figure 1. Ares V cargo launch vehicle (left) and Ares I crew launch vehicle (right). (NASA artist's concept)

Nomenclature

BDM	=	Booster Deceleration Motor
BTM	=	Booster Tumble Motor
CDR	=	Critical Design Review
CEV	=	Crew Exploration Vehicle
CLV	=	Crew Launch Vehicle
CM/LAS	=	Command Module/Launch Abort System
	=	Simulator
DAC	=	Design Analysis Cycle
DDT&E	=	Design, Development, Test, and
	=	Evaluation
DFI	=	Developmental Flight Instrumentation
DM	=	Development Motor
EDS	=	Earth Departure Stage
FMEA	=	Failure Modes and Effects Analysis
FITO	=	Flight and Integrated Test Office
FSE	=	Forward Skirt Extension
FSM	=	Flight Support Motor
FTS	=	Flight Termination System
GSE	=	Ground Support Equipment
ICD	=	Interface Control Document
ICD	=	Interface Control Drawing
ISS	=	International Space Station
IS	=	Interstage
JSC	=	Johnson Space Center
KSC	=	Kennedy Space Center
LAS	=	Launch Abort System
LEO	=	Low-Earth Orbit
lbm	=	Pounds of Mass
LOC	=	Loss of Crew
LOM	=	Loss of Mission
Max G	=	Maximum Gravity
Max Q	=	Maximum Dynamic Pressure
MEOP	=	Maximum Expected Operating Pressure
MSFC	=	Marshall Space Flight Center
mT	=	Metric Ton (Tonne)
NASA	=	National Aeronautics and Space
	=	Administration
O&M	=	Operations and Maintenance
OML	=	Outer Mold-line
PBAN	=	Polybutadiene Acrylonitrile
PFI	=	Post Flight Inspection
PSA	=	Production Simulation Article
psf	=	Pounds Per Square Foot
psi	=	Pounds Per Square Inch
psia	=	Pounds Per Square Inch Absolute
RSRB	=	Reusable Solid Rocket Booster
SRB	=	Solid Rocket Booster
SRM	=	Solid Rocket Motor
SSME	=	Space Shuttle Main Engine
TLI	=	Trans-Lunar Injection
TPS	=	Thermal Protection System
TVC	=	Thrust Vector Control

I. Introduction.

For the first time in over thirty years, NASA is developing a new fleet (Figure 1) of human-rated space flight vehicles. NASA's Marshall Space Flight Center (MSFC) in Huntsville, Alabama, has been assigned that task. Charged with delivering new crew and cargo-launch capabilities, the goal is to build an outpost on the Moon in preparation for explorations elsewhere, to safely deliver a payload of crew and cargo to a specified ascent target, and to subsequently extend the boundaries of human exploration beyond low-Earth orbit (LEO). Reaching these goals, and extending these capabilities will entail two separate missions: (1) the new Ares I will continue in service to the International Space Station (ISS), transporting both people and payloads in a similar manner to Space Shuttle operations, which will be phased out and; (2) in parallel the new Ares launch vehicles will be the delivery of new transport and crew exploration vehicles. The crew exploration vehicle, named Orion, will have the capability to dock with the ISS or the Altair lunar lander and the Earth departure stage providing the ability to deliver both crew and cargo to the Moon and beyond. Equipped with a launch abort system, it will be capable of pulling the spacecraft and its crew to safety in the event of an emergency on the launch pad or during ascent. The Altair is the fleet's new lunar lander spacecraft. In addition to cargo, it will be able to deliver up to four crew members to the Moon's surface and serve as an initial base for exploration for up to a week, thereby providing the capability to reach further in the exploration of the Moon and beyond in subsequent lunar missions.

II. Design Overview.

The Ares I (Figure 2) vehicle consists of three major elements: a solid fuel first stage similar to a shuttle reusable solid rocket booster, an upper stage, and a liquid fuel upper stage engine. The new five-segment first stage will produce over 3.5 million pounds of thrust and provide safe reliable human rated propulsion technologies that reduce development costs and improve safety for future space missions. In addition to the solid rocket motor, the first stage includes several other structures and subsystems including the: aeroshell, which houses the parachute recovery system, forward skirt, and frustum—to structurally interface with the upper stage; the aft assembly includes the thrust vector control system; and an avionics subsystem to command stage functions.

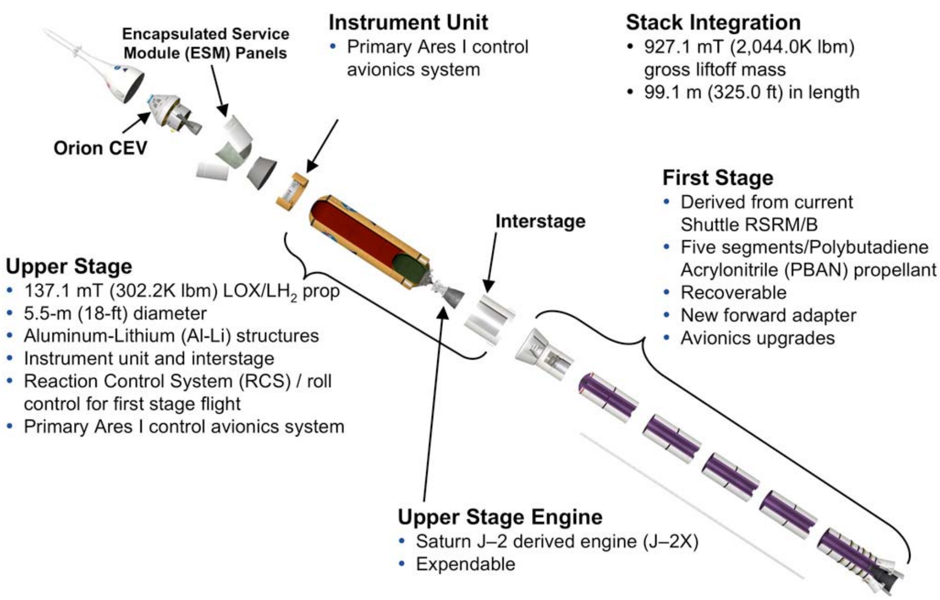

Figure 2. Ares I launch vehicle.

Ares V (Figure 3), which will begin full-scale development after the Shuttle's retirement, will be the largest launch vehicle ever built. With five commercial RS-68 engines and two five-segment solid rocket boosters, the Ares V cargo launch vehicle will generate over 10.5 million pounds of thrust at liftoff. Ares V launches the Earth departure stage (EDS) into orbit, where it will await the launch and docking of Orion to be delivered by Ares I before executing a trans-lunar injection (TLI) burn.

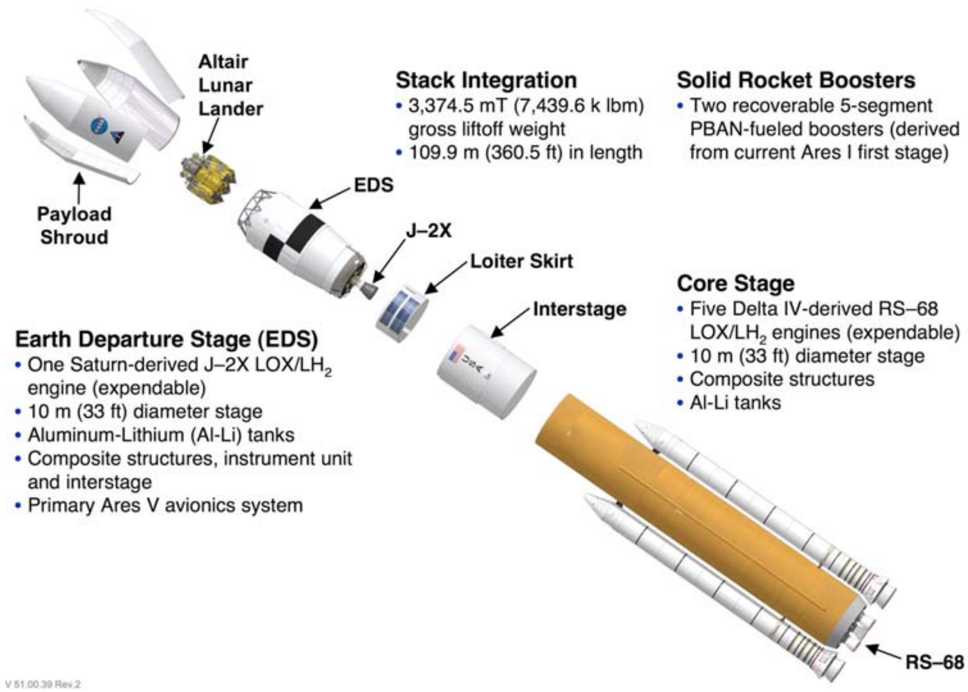

Figure 3. Ares V cargo launch vehicle.

III. Design Base.

Early studies recommended a two-vehicle approach separating crew from cargo for added safety. The Ares V cargo launch vehicle will go into orbit first, carrying Altair in the Earth departure stage. Once the Ares V is in orbit, the Ares I crew launch vehicle will loft the Orion crew exploration vehicle into orbit to rendezvous with the Earth departure stage, which then ignites for the trans-lunar injection burn.

- The five-segment first stage uses some Shuttle-derived hardware, allowing NASA to draw upon existing institutional knowledge and infrastructure, and existing tooling and manufacturing processes, but will fundamentally provide more total impulse to the system.
- The five-segment solid rocket motor will also be part of the Ares V core stage, so the Ares team can apply test data, hardware, and experience from Ares I to the future Ares V development.

Other factors that impact the Ares first stage design include a range of obsolescence issues (such as government regulations, supplier economics, industrial/safety hazards, natural disasters and obsolete technology), as well as objectives to enhance the reliability and operability of the vehicle.

IV. Motor.

Several first stage motor design modifications were required to meet Ares I operational requisites. These designs were driven by the need to meet several varying types of requirements including: ballistic performance, operability improvements, enhanced reliability, regulatory compliance, and replacement of obsolete materials and processes. These driving requisites were accommodated by changes to the following design features in the motor: total propellant, grain geometry and burn rate, nozzle throat and exit cone designs, materials used in the manufacture of the internal insulation, case bond liner, and the O-rings used to seal the joints between motor segments.

Figure 4. Ares I.

Ares first stage rocket motor casting tooling has been designed and built specifically to achieve a propellant grain geometry that produces the required ballistic performance. The configuration also must meet stringent structural requirements and be manufacturable, which adds further challenges to the grain design and tooling. The combination of grain surface area, propellant burn rate and nozzle geometry determine the thrust produced by the rocket motor. The complex fin, tapered bore, and chamfer geometry of the grain tooling establishes the initial surface area during solid propellant casting operations.

The number of "fins" at the forward end of the propellant chamber was increased, and the size of the "fin slots" between them reduced. This modification expands the initial aggregate burn surface area. The second and fourth middle segments will include chamfers (bevels) and inhibitors to ensure the propellant burns evenly from the axis to the outer casing, and will mitigate the risk of the bore choking.

A slightly different burn rate will be used, requiring minor changes to the propellant formulation. This variant of polybutadiene acrylonitrile incorporates a different, coarser grade of iron oxide. Because the new iron oxide formulation has a lower specific surface area, it is not as good a catalyst and consequently provides the capacity to lower the burn rate slightly, while maintaining the level of iron oxide. This modification allows for greater control of burn time and provides the ability to tailor the burn rate to achieve the desired burn time.

A nozzle throat area increase was essential to maintenance of the motor's maximum expected operating pressure consistent with the capabilities of the legacy cases that will be used.

This combination of modifications produces a significantly higher total impulse than the existing reusable solid rocket motor because of the additional mass flow rate and slightly longer burn time. The resulting design delivers a thrust-time profile consistent with the motor performance requirements.

A lighter, more environmentally friendly (asbestos-free) internal insulation will be incorporated into the design along with an asbestos-free case bond liner system. Structural and hot fire tests at subscale and full scale have already been conducted to ascertain that this insulation material could meet the required thermal and erosion requirements. In addition, this motor will incorporate new lower-temperature materials in the O-rings, enabling the removal of joint heaters and simplifying launch site operations.

To date the insulation manufacturing processes have been tested with two full-scale Ares process simulation articles (PSAs), which allowed the insertion of process improvements resulting in a lower void content. Additional efforts to date, which have been utilized to mitigate the incorporation of these new materials, include several hot fire testings from subscale articles up to and including the insertion of these materials into reusable solid rocket motor (RSRM) full-scale static fire units. Furthermore, a prudent and conservative approach for optimizing insulator thickness is planned. The DM-1 (first developmental motor) unit will incorporate a slightly thicker insulator and it will be reduced through the remainder of the development program leading up to the predicted flight configuration.

As previously mentioned, the nozzle throat area was increased to accommodate the motor burning more propellant over a longer period. This change ensures that more thrust can be generated and that the internal pressure within the combustion chamber can remain within the tolerances specified for the Shuttle motor casings. In addition, two designs of the aft exit cone will be carried through the development phase of the program. The objective is to design an exit cone that is less susceptible to a phenomenon known as ply-lifting. To address this issue, the project will carry one design similar to that being used on the RSRM and another design, which incorporates a higher ply-angle and is believed to be less prone to ply-lifting. The performance of these designs will be evaluated through the four planned DM tests with the best solution incorporated into the qualification motor test series. A process simulation article (PSA) of the first new first stage nozzle has been delivered. It will be used to verify that the new design fits together and that processes have been tested before a nozzle is built for hot-fire testing.

Process simulation articles are being used to help train the work forces in building the new hardware for the Ares I. These units are utilized to reduce development risk and avoid costly schedule delays later in the program. As of May 2008, a full five-segment pathfinder motor was completed through propellant casting. This unit was loaded with an inert propellant formulation and was used to verify processing techniques and new tooling. This unit will go on to be used to proof handling and stacking processes at MSFC and KSC and will be used as a test article in the vehicle ground vibration test.

V. Structures.

Although much of the reusable solid rocket booster consists of legacy hardware, because of Ares I's unique in-line configuration (Figure 4), the first stage will require an extended systems tunnel, as well as entirely new forward structures. This will include the frustum, the forward skirt extension, and the forward skirt. Trade studies have been completed regarding the use of metal versus composite materials for the new forward structures. Those studies focused on reusability, ease of manufacture, structural durability, and weight.

A. Frustum.

The physical transition between the smaller diameter first stage to the larger diameter upper stage is accomplished through the use of a frustum. Although performance and weight are obvious considerations, the frustum is designed for strength. Although the frustum for the Ares I-X will be metal (Figure 5), to prevent buckling and develop robustness in the design, the frustum for the Ares I will be composed of composite materials. The use of composites facilitated a change in the geometry, which in turn afforded the ability to focus strength where it is needed, without additional mass. Shortly after separation, booster tumble motors located on the frustum ignite to start the first stage tumbling. The frustum-interstage assembly is jettisoned in a secondary separation at a separation plane located near the aft end of the frustum. As the first stage begins to tumble, the centrifugal force will be sufficient to propel the frustum-interstage assembly away from the first stage without re-contact. Several notable achievements have been accomplished to date. Composite panels have been manufactured with a fiber placement process and design allowable values are being characterized for the various lay-ups. The frustum end ring has already been manufactured and will be utilized in upcoming separation tests.

Figure 5. Ares I-X frustum.

Figure 6. Forward skirt extension.

B. Forward Skirt Extension.

The forward skirt extension (Figure 6) houses the main parachute support system and the main parachutes, which will be needed for recovery of the first stage. The drogue and pilot parachutes sit on top of the forward skirt extension and are protected by the legacy nose cap, which is used on the current solid rocket booster.

C. Forward Skirt.

The first stage avionics controls for ignition, thrust, and separation commands are housed in the forward skirt. The forward skirt is an aluminum-grid-stiffened structure with aluminum end rings.

The first test of the Ares I separation system was recently conducted and it was successful. The test involved a replicated Ares I first stage forward skirt extension and forward skirt stacked, and suspended two feet above the ground. In this joint severance test, a linear-shaped charge was detonated to horizontally detach the two pieces of hardware. This was the first of a series of three tests. In the second test, the first stage forward skirt extension will be separated from the first stage frustum and in the third, the forward skirt extension will be tested.

VI. Thrust Vector Control System (TVC).

The First Stage Element Office and ATK Launch Systems formed a team to investigate four Pre-phase A design concepts to mitigate thrust oscillations. The Ares Thrust Oscillation Focus Team (TOFT) is evaluating solutions to the problem. Possible changes may include the following:

- Dynamic dampening using parachute mass cancels the mass benefit of shortening the forward skirt extension and impacts the reliability of the deceleration system. Directly adding minor mass may ameliorate this effect.
- Changes to castable inhibitors may negatively impact the reliability prediction, so that confidence in an improvement is not easily justified.
- The addition of the Axial RCS system on the aft skirt, which may replace baseline solid BSMs, may be prevented by structural limits of the aft skirt.

VII. Avionics.

Significant progress has been made in the development of first stage avionics and control systems. Ares I will use modern electronics in the first stage avionics and thrust vector control (TVC) systems. The Shuttle thrust vector control system is the baselined system for the Ares. The architecture has been defined and a preliminary assessment of the thrust vector control system's performance requirements made. Although progress on avionics design and development is on schedule, the design is not as mature as that in other areas.

VIII. Deceleration/Recovery.

A. Parachute Tests.

Wind tunnel tests were used to help calibrate the Ares I first stage altitude switch assembly (ASA) or "baroswitch," which deploys the parachute recovery system during reentry. Other tests have been conducted to collect performance data on a pilot parachute, the first to be unfurled in a three-part recovery system being developed for first stage. The Ares system will include a pilot, drogue, and three main parachute system, which is derived from the reusable solid rocket booster (RSRB) recovery system. The first two pilot parachute drop tests have been completed successfully.

An analysis to determine optimum inflation reefing percentages of full open for the Ares I-X flight test was completed recently. Inputs into this analysis included booster sequence mass properties, drogue parachute inflation curves optimized to minimize the drogue peak load and the main parachute inflation curves that produce balanced peak loads based on the opening load factors determined from the single main drop tests. Based on these analyses, a small increase was made to the previous reefing percentages. Preparations are under way for drogue chute drop testing. (Figure 7)

Figure 7. Completed parachute in Mississippi facility.

B. Booster Tumble Motors/Booster Deceleration Motors.

During separation, the booster deceleration motors (BDMs) on the aft skirt are fired in forward motion to pull the booster away from the upper stage. Shortly after separation, booster tumble motors (BTMs) on the frustum ignite to initiate tumbling in the first stage. As the first stage begins to tumble, the frustum-interstage assembly is jettisoned in a secondary separation at a separation plane near the aft end of the frustum The centrifugal force will be sufficient to propel the frustum-interstage assembly safely away from the first stage. The frustum and interstage are not reused.

IX. Preliminary Design Review (PDR).

The first stage preliminary design review (PDR) cycle has been completed successfully. The current state of the first stage design largely exceeded PDR maturity. The PDR data package was complete as specified by first stage element guidance. The review was extensive, comprehensive, and thorough. Although some areas are slightly more mature than others, no surprises were identified. Areas of lesser maturity were thoroughly scrutinized to understand the risk potential to the progression of the stage design. Issues of concern included the RSRM's maximum expected operating pressure (MEOP) during flight; inappropriate tailoff thrust requirement; and forward skirt purge requirements. The go-forward plan for maturing the avionics component designs was also a point of focus.

Any required new technology has been developed to an adequate state of readiness, or back-up options exist, and are supported to make them viable alternatives. The project risks are understood, and plans, process, and resources exist to effectively manage them. Safety and Mission Assurance (S&MA—safety, reliability, maintainability, quality, and parts) have been adequately addressed in preliminary designs and any applicable S&MA products (Hazard Analysis, and Failure Modes and Effects Analysis) have been approved. The operational concept is technically sound, it includes (where appropriate) human factors that apply, and requirements for its execution flow down.

On 5 June 2008, the PDR board determined that all PDR exit criteria had been met and recommended that the First Stage Element continue progressing the design toward the Critical Design Review (CDR).

X. Ares I-X Test Flight.

NASA has long understood that operating costs can be reduced through early, incremental, and thorough testing in the design and development of its launch vehicles. The primary objectives of the Ares I-X and I-Y test flights are to demonstrate the controllability of the vehicle, to demonstrate that the stages can be separated safely, and that the five-segment booster can be successfully recovered.

The Ares I-X, a suborbital development flight scheduled for 2009, will provide the opportunity to gather critical data about the flight dynamics of the integrated launch vehicle stack, understand how to control its roll during flight, better characterize the severe stage separation environments that will be experienced during flight, and demonstrate the first stage recovery system. The Ares I-X will incorporate a mix of flight and mockup hardware; the mass and weight will be similar to that of the operational Ares I to obtain data on controlling the long narrow crew launch vehicle configuration.

The Ares I-X will use a four-segment RSRM from the Shuttle inventory and a fifth spacer segment to simulate the size and weight of the five-segment motor that will be used on later flights. The upper stage, Orion, and launch abort system will all be replaced with simulator hardware on the test vehicle. Atlas V avionics are being adapted to control the I-X first stage. That hardware has already undergone hardware-in-the-loop testing in a contractor-provided systems integration laboratory. Its critical design review was completed in 2007. Drogue and main parachute drop tests have been conducted successfully at Yuma Proving Grounds, allowing the First Stage Element Team to proceed with fabricating parachutes for Ares I-X. The Ares I-X flight test will be the first flight test for the parachutes, as well.

Data collected during the I-X and I-Y flights will influence the end design of the Ares vehicles. Although conditions will not be matched 100 percent, and the trajectory will not be exactly the same, it will closely match the dynamic pressure and velocities at separation of the Ares I vehicle and that will provide a real-time indication of the controllability of the vehicle, separation safety, and recoverability of the five-segment booster.

Progress on manufacturing continues. The frustum conic sections have been assembled, and manufacturing is underway on the main parachute system, the forward hub, fifth segment simulator, and aft skirt. SDA flight units are progressing, and the thermal protection system has been completed on the forward motor segment.

XI. First Stage Conclusion and Technical Status.

Ares first stage design progress is robust. The system requirements review (SRR) was completed in December 2006. The Preliminary Design Review (PDR) is complete. Ares I–X hardware is in the midst of fabrication. The first Ares I development motor (DM–1) is in the manufacturing process with the first DM–1 static firing is slated for April 2009. The Ares I and Ares I–X First Stage Teams are pursuing the design and development of propulsion hardware for America's next generation of human-rated launch vehicles. The Ares I–X First Stage Team has already conducted sub-element and component-level major design reviews and critical design reviews to ensure that the vehicle specifications meet the stage and vehicle requirements. Drogue and main parachute tests continue in 2008. Recovery system testing is well underway. Separation testing has begun. The Ares I–X launch is scheduled for 2009 and the Ares I Critical Design Review (CDR) will follow.