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Foundation for Heavy Lift – Early Developments in the Ares V Cargo Launch Vehicle

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The Ares V Cargo Launch Vehicle (CaLV) is NASA's primary vessel for safe, reliable delivery of the Lunar Surface Access Module (LSAM) and other resources into Earth orbit, as articulated in the U.S. Vision for Space Exploration.[1] The Ares V launch concept is shown in Figure 1. The foundation for this heavy-lift companion to the Ares I Crew Launch Vehicle (CLV) is taking shape within NASA and with its government and industry partners. This paper will address accomplishments in the Ares V Launch Vehicle during 2006 and 2007 and offer a preview of future activities.

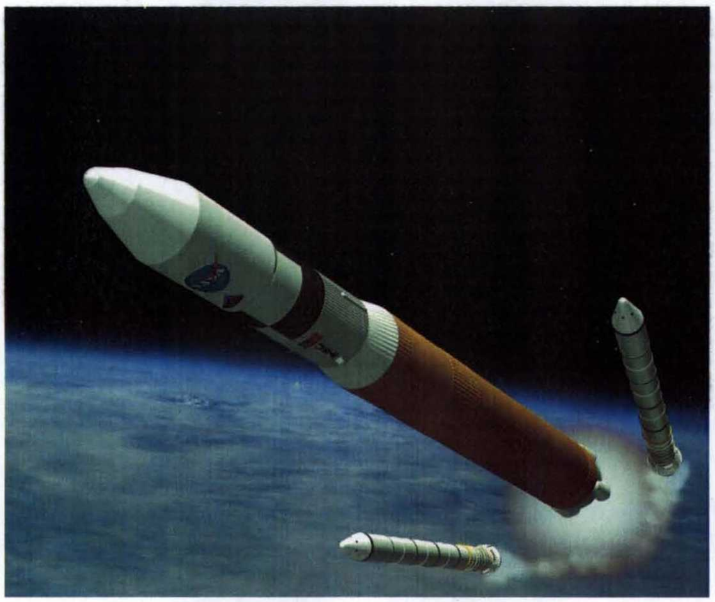

Figure 1. Ares V launch concept.

When it stands on the launch pad at Kennedy Space Center late in the next decade, the Ares V stack will be almost 360 feet tall (Figure 2). It will lift 136 metric tons (300,000 pounds) to a 30-by-160 nautical mile orbit at 28.5-degrees inclination, or 55 metric tons (120,000 pounds) to trans-lunar injection. As first envisioned by the Exploration Systems Architecture Study (ESAS) in summer 2005, the Ares V consisted of two 5-segment Reusable Solid Rocket Boosters (RSRB) flanking a 27.5-foot-diameter Space Shuttle-derived External Tank (ET) delivering liquid hydrogen/liquid oxygen (LOX/LH2) to a cluster of five RS-25 Space Shuttle Main Engines (SSME), redesigned to be low-cost and expendable.[2] The upper stage, known as the Earth Departure Stage (EDS), would be powered by two LOX/LH2 J-2S engines, evolved from the J-2 engine used in the Saturn launch vehicle upper stages.

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Figure 2. NASA concept of the Ares V on the launch pad.

As part of NASA's systems engineering approach, Marshall Space Flight Center's Exploration Launch Projects Office in early 2006 streamlined its Ares I design, development, test, and evaluation (DDT&E) hardware plan so that the first stage booster and upper stage engine are largely extensible to the Ares V booster stage and EDS propulsion elements, saving billions in nonrecurring costs. Figure 3 shows the launch vehicles' common elements. The RS-25 also was replaced by the LOX/LH2 RS-68 engine, developed by the U.S. Air Force and currently in use on the Boeing Delta IV heavy-lift vehicle, reducing technical, schedule, and cost risk. The benefits and challenges of using common hardware are documented in the CLV/CaLV Commonality Assessment.[3]

The RS-68 is the most powerful liquid oxygen/liquid hydrogen booster in existence, capable of producing 650,000 pounds of thrust at sea level. In contrast, the SSME is capable of producing 420,000 pounds of thrust at sea level, although it operates at a higher level of efficiency than the RS-68. The ESAS had initially rejected the RS-68 because its lower specific impulse (Isp) and size were not compatible with the 27.5-foot core stage propellant tank and payload requirements of the reference Ares V. The ESAS theorized that the high-performance RS-25 might be redesigned as an expendable model (RS-25F) to reduce manufacturing costs by roughly half. However, current estimates suggest that the RS-68 modified to meet NASA standards will cost significantly less than a modified SSME. This represents a major savings on recurring costs, especially considering that each Ares V mission will use five main engines at a nominal rate of two missions annually over a decade.

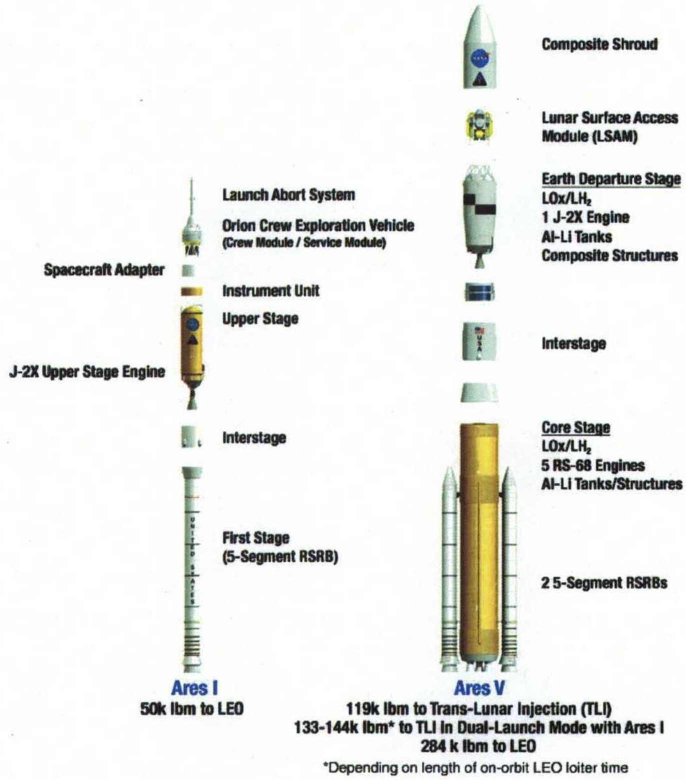

Figure 3. Expanded views of Ares I and Ares V show common hardware.

Further analyses show the cost, technical, schedule, and safety and reliability risks associated with redesigning and mass-producing the RS-25 are greater than the risks and costs associated with scaling up the Ares V Core Stage from 27.5 feet to 33 feet to hold the additional propellants needed to accommodate the RS-68 engine's reduced Isp and make room for the larger nozzle and exhaust clearances needed for the five-engine cluster. Analyses also noted that the RS-68 production line was developed with a goal of delivering 40 engines annually and is currently delivering 7 per year for Department of Defense and commercial missions. Additionally, improvements proposed by Boeing will make it feasible for the RS-68 to exceed the Ares V payload requirements.

Due to schedule and budget priorities, Ares V design remains at an earlier stage in development than Ares I. Many of the technical successes of the Ares I during the past year involving the 5-segment RSRB and J-2X engine are shared by the Ares V because of the decision to maximize commonality between the two launch vehicles. NASA has completed studies to determine mutual requirements between the Ares I and Ares V systems. Engineering analyses have been conducted on induced loads, structural dynamics, aerodynamics, base heating, and acoustics. Additionally, studies have examined on how the switch to a 33-foot tank will affect manufacturing tooling at Michoud Assembly Facility and operations at Kennedy Space Center. However, most of the Ares V activity to date is related to the RS-68 engine.

NASA and the U.S. Air Force Space and Missile Center entered discussions in 2006 on reaching an interagency agreement to develop RS-68A and RS-68B variants, respectively, of the RS-68 engine for the Delta IV and Ares V, leveraging the work of each organization in a synergistic fashion (Figure 4). For example, the Air Force is investigating process and design

changes that result in improved overall reliability of the engines, while NASA is seeking modifications such as reducing free hydrogen around the Core Stage base at ignition, reduced helium usage, and development of a long-duration nozzle. This arrangement would reduce NASA's DDT&E investments and provides a unique opportunity to obtain early flight data from Delta IV missions, reducing technical and schedule risk. The Air Force would benefit from additional risk reduction testing and NASA-funded performance improvements.

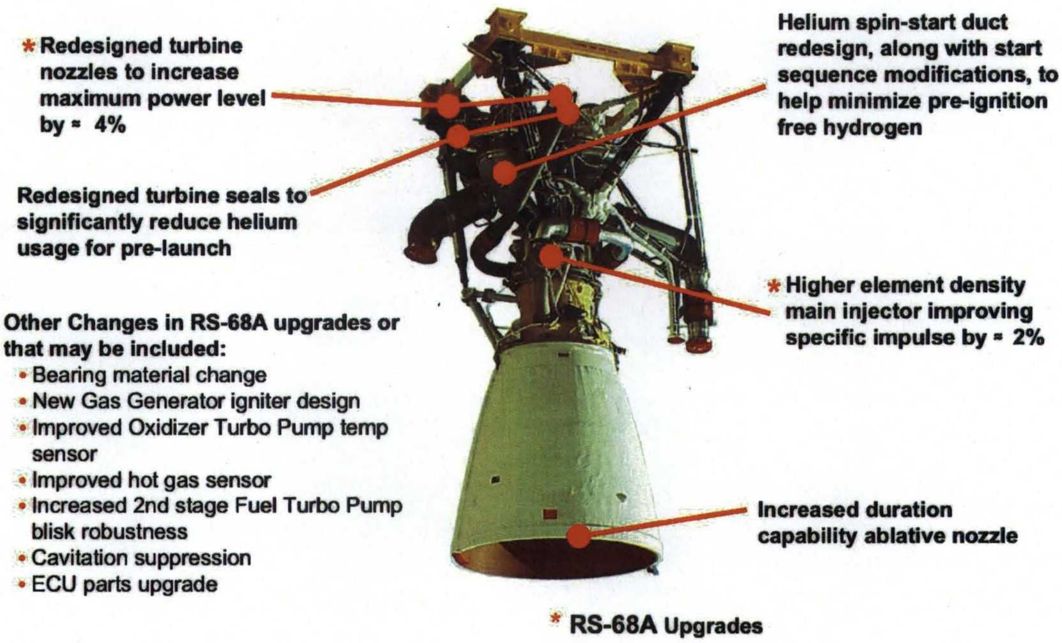

Figure 4. RS-68 engine, showing major planned modifications.

The U.S. Vision for Space Exploration sets a goal of returning to the Moon no later than 2020 and extending the human presence across the solar system and beyond. The work already conducted on the Ares V Core Stage advances progress toward meeting that commitment.

I. Introduction

THE strategic goals outlined in the U.S. Vision for Space Exploration (January 2004) guide NASA's challenging missions of scientific discovery.[4] In addition, the U.S. Space Transportation Policy (December 2005) directs America's civil space agency to provide launch vehicle systems for assured access to space.[5] The Vision provides specific guidelines for relatively near-term human exploration of the Moon to prepare astronauts for longer journeys to Mars. It also commits the United States to completing the International Space Station and retiring the Space Shuttle by 2010. New space transportation systems will provide new capabilities for the human exploration of space beginning as soon as possible after the Shuttle is retired.

The Ares I is slated to fly the Orion CEV in the 2014 timeframe, while the Ares V is slated to fly the Lunar Surface Access Module (LSAM) by 2020. Both are shown in Figure 5. These systems are being designed for safe, reliable, and sustainable space transportation by building on a foundation of legacy knowledge and heritage hardware, while reflecting modern engineering and business best practices that meet stringent standards and deliver maximum value for the investment. Together, these space transportation systems will replace the Space Shuttle for the human exploration of Earth's cosmic neighborhood and beyond.

Figure 5. Ares V (left) and Ares I in flight (artist's concept).

II. Risk-based Technical and Management Approach

The Exploration Launch Projects Office has been chartered by the Constellation Program, located at NASA's Johnson Space Center, and the Exploration Systems Mission Directorate, located at NASA Headquarters, to deliver safe, reliable crew and cargo launch vehicles designed to minimize life-cycle costs so that NASA can concentrate its resources, both budget and personnel, on missions of scientific discovery. To that end, the Space Shuttle follow-on systems are being designed and developed to maximize safety and reliability margins, with an eye on affordability of near-term development and long-range operations activities.

Toward that end, engineers and managers are working to transfer hardware, infrastructure, workforce, and decades of experience from the Space Shuttle Program to the new launch systems. The Ares government/industry team also has tapped into Saturn databases and sought insights from Apollo-era veterans. Learning from its successes and failures, NASA is using rigorous systems engineering and systems management processes and principles to further improve the possibility of mission success.

With a "test as you fly" philosophy, the Exploration Launch Projects Office draws on analysis from computer-aided modeling and simulation applications that test integrated avionics software and simulate vehicle dynamics. The Exploration Launch Projects team also gains insight into three-dimensional configurations from subscale wind tunnel model testing. These preliminary analyses lead to real-world testing with increasingly flight-like hardware to gain confidence in the systems before orbital flight tests that will yield even more information on which to base critical hardware and operations decisions.

Using rigorous systems engineering standards and guidelines provides a framework for both internal and external independent reviews, with clearly defined entrance and success criteria on which to base decisions.[6] Major milestone reviews help guide engineers to a configuration that that fulfills customer and stakeholders requirements on time and within budget.

III. The Ares V Design Concept and Mission Scenario

The Ares V has undergone a series of concept studies to determine the most appropriate vehicle design for the requirements levied by the missions ahead. The Ares V consists of two Shuttle-derived 5-segment Reusable Solid Rocket Boosters (RSRBs) using polybutadiene acrylonitrile (PBAN) propellant, similar to the Ares I first stage. The

Ares V core stage is a 33-foot-diameter tank delivering liquid oxygen and liquid hydrogen (LOX/LH2) to a cluster of five RS-68 engines. The Ares V Earth Departure Stage (EDS), which carries payloads such as the Lunar Lander, employs the same J-X Upper Stage Engine as the Ares I Upper Stage. The LOX/LH2 J-2X is a derivative of the Saturn upper stage engines. This hardware commonality is expected to reduce both development and operations costs.

The lunar mission scenario is shown in Figure 6. During ascent, the Reusable Solid Rocket Boosters separate from the Core Stage. After separation from the spent Core Stage, the EDS will ignite and place the vehicle into a circular orbit, discarding its payload shroud and exposing the LSAM. The Orion CEV, delivered to orbit by the Ares I, will dock with the EDS/LSAM. The EDS J-2X engine will re-ignite to start Trans Lunar Injection. The EDS will be jettisoned when the mated crew and lunar modules are on course for the Moon. Once the astronauts arrive in lunar orbit, they will check out systems, transfer to the lunar lander, and descend to the Moon, while the crew module remains in orbit. At the end of their lunar stay, the astronauts will return in the lunar lander and rendezvous with the crew module to return to Earth.

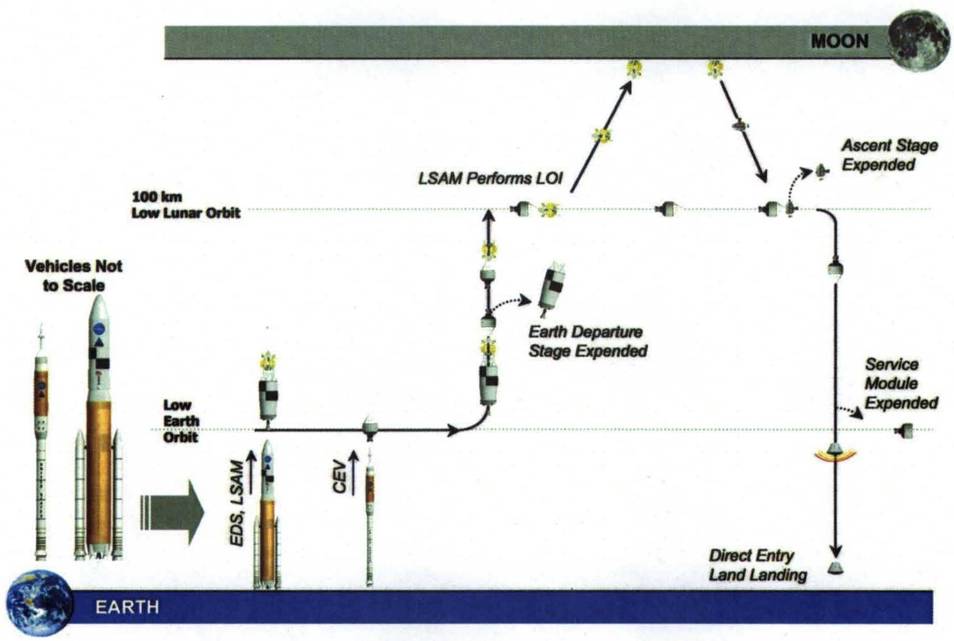

Figure 6. Lunar mission scenario.

IV. Exploration Systems Architecture Study Initial Recommendations

To provide a frame of reference for the current Ares V baseline configuration, it is useful to review the genesis and evolution of the concept over the past two years. The Exploration Systems Architecture Study (ESAS) team was chartered in spring 2005 to develop and assess viable launch system configurations for a Crew Launch Vehicle and a Cargo Launch Vehicle to support lunar and Mars exploration and provide astronaut access to the International Space Station.

The ESAS team, which was comprised of government aerospace experts, developed potential launch vehicle design concepts; assessed dozens of candidate concepts against figures of merit (safety, cost, reliability, and extensibility); identified and assessed vehicle subsystems and their allocated requirements; and developed viable development plans and supporting schedules to minimize the gap between Shuttle retirement and the Orion's initial operational capability. The study team explored concepts derived from elements of the existing Evolved Expendable Launch Vehicle (EELV) fleet and the Space Shuttle.

In fall 2005, the Exploration Systems Architecture Study team released a report that recommended a heavy-lift launch vehicle configuration.[7] This point-of-departure vehicle was based on two 5-segment Reusable Solid Rocket

Boosters and five Space Shuttle Main Engines (SSMEs) modified to be expendable rather than reusable, a 27.5-foot-diameter core tank derived from the Shuttle's External Tank, and the J-2S+ upper stage engine.

V. Bottom-up Review Refines Concept

Following the Exploration Systems Architecture Study, in spring 2006, the Constellation Program tasked the Exploration Launch Office with performing follow-on studies of technical scope as it relates to budget guidelines and schedule targets.

As a result of this comprehensive bottom-up review, the Constellation Program adopted a revised vehicle configuration based on analyses performed by rocket engineers and business professionals, which gave clear evidence that the RS-68 engine could offer significant savings over redesigning the reusable Space Shuttle Main Engine — a complex, reusable, human-rated engine — for this Ares V expendable application.[8]

Developed by Boeing (now Pratt & Whitney Rocketdyne) for the U.S. Air Force's EELV Program, the RS-68, shown during development in Figure 7, now powers the Delta IV launch vehicle family. The RS-68 is the most powerful liquid oxygen/liquid hydrogen engine in existence. When modified to meet NASA's standards, the five-engine cluster/33-foot-diameter tank will exceed the Constellation Program's payload lift requirements. Building on lessons learned from the SSME Project, the development time for the relatively new RS-68 was cut in half and the parts count was reduced by 80 percent. Touch labor for the RS-68 was reduced by 92 percent over the labor-intensive SSME processing, and non-recurring costs were cut by 20 percent.[7] Collaborating with the U.S. Air Force on RS-68 engine upgrades will reduce cost and risk to the Constellation Program. Flights of upgraded RS-68 engines on the Delta IV will provide performance data that will further reduce technical risk.

The review also validated the use by both vehicles of similar Reusable Solid Rocket Boosters and upper stage engines, which offers multiple benefits, including reduced recurring and nonrecurring operations costs.

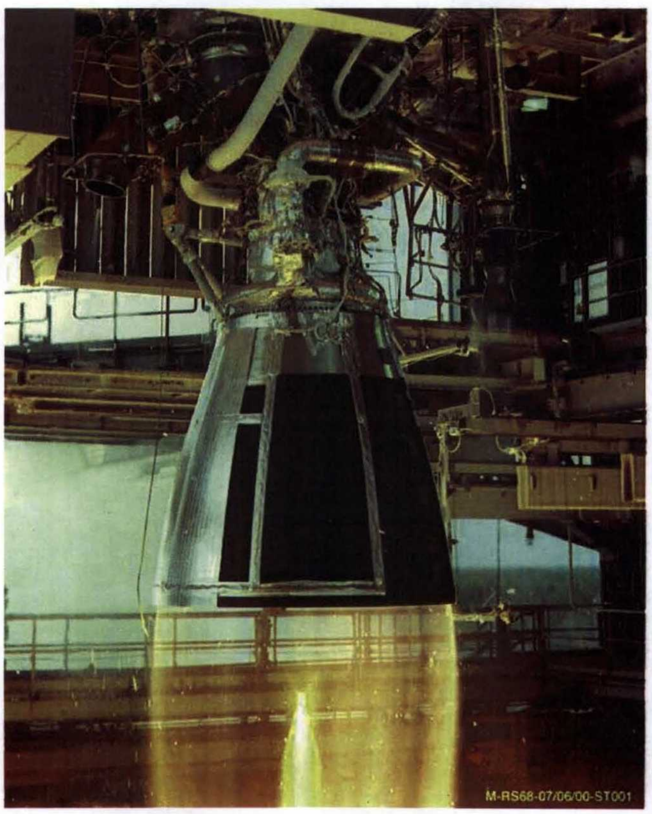

Figure 7. RS-68 engine test at Stennis Space Center in 2000.

VI. Commonality Assessment

The Commonality Assessment, conducted in May 2006, brought together a multi-disciplined panel of aerospace experts, some with Saturn and Shuttle experience, to assess potential synergy points and design challenges between the Ares I and Ares V vehicles.[9] Driven by the upcoming Ares I System Requirements Review (SRR) and Ares V Initial Requirements Review (IRR), the panel was chartered to help determine which Ares V requirements might have the most impact on the desired commonality of hardware systems and components between it and the Ares I. Challenges and risks identified during the process led to follow-on analyses to support the Design Analysis Cycle leading to the Ares I System Requirements Review in fall 2006.

The Commonality Assessment Report results were used to perform advanced concept studies using the Vehicle Integrated Performance Analysis (VIPA) modeling and simulation capability, along with other systems engineering tools and activities, to further validate the design configuration.

Mission considerations evaluated by the commonality assessment included the three potential payloads for the Ares V: the LSAM for lunar missions, cargo to orbit, and the potential for a single-launch solution to the Moon in which the Orion and LSAM are both launched aboard the Ares V. Each payload will require different interfaces, servicing, ground and mission operations, and induced environment analyses.

The commonality assessment also examined the key goal of common hardware. There is great potential for commonality between the Ares I and Ares V Reusable Solid Rocket Boosters, including case, joint, and seal hardware; parachute and recovery systems; documentation; planning, inspection, and verification procedures; design tools; full-scale test facilities; manufacturing processes, tooling, and facilities; ground support equipment, and so forth. However, the Ares V team will have to account for several major differences: physical stresses due to different physical configurations and flight profiles, thrust trace, tail-off and separation, potential thrust imbalance, thermal protection systems, and the sequencing of booster recovery.

The Commonality Assessment panel discussed modifying the off-the-shelf RS–68 engine for use in the Ares V Core Stage, both for performance gains and for safety improvements. A number of changes are necessary to mitigate or eliminate known issues — chiefly, reduction of free hydrogen at engine start and the engine's current excessive helium requirements for operations.

The assessment also highlighted the possibility for the RS-68 and J-2X engines to utilize common components and software for the engine controller, as well as instrumentation, pyrotechnic igniters, and ancillary components such as check valves, solenoid valves, and so forth. In addition to subsystem components, the two engines could pursue common manufacturing processes.

VII. Progress and Plans

This section highlights a range of accomplishments in 2006 and 2007 that advanced the Ares V design. Although it will be a number of years before the Ares V begins flying missions to the Moon, the initial planning effort has received "seed money" to begin the lengthy process of designing, developing, and fielding a new heavy-lift launch vehicle system. The element schedule as of May 2007 is provided in Figure 8. Because the Ares V launch vehicle shares common hardware with the Ares I, as discussed above, it benefits from work currently being performed on those elements as part of the Ares I design, development, testing, and evaluation process.

Throughout 2006, the Ares V team performed comprehensive programmatic and technical planning, including developing a preliminary integrated master schedule and projecting resources — personnel, facilities, and budget. It also kicked off a number of in-house tasks and business development activities related to the RS-68 engine and the 33-foot-diameter core stage tank. The team drafted its concept of operations document as a foundational piece of information upon which trade studies aimed at defining and refining mission scenarios will build. The team visited the Michoud Assembly Facility and the Stennis Space Center test stands to gain a firsthand understanding of capabilities and constraints, such as transitioning from SSME testing to J-2X engine testing, followed by RS-68 engine testing, which will overlap with the earlier J-2X engine development, qualification, and certification.

In spring, 2006, a request for information was issued to the aerospace community for strategic input on manufacturing the Ares I Upper Stage, an in-house NASA design that also will inform and influence the Ares V Earth Departure Stage design. Responses received addressed business and technical challenges relevant to both Upper Stage and EDS design, including procurement of combined avionics, on-board electrical flight controls and guidance systems, commonality of design tools and software, ways of reducing component life-cycle costs, etc.

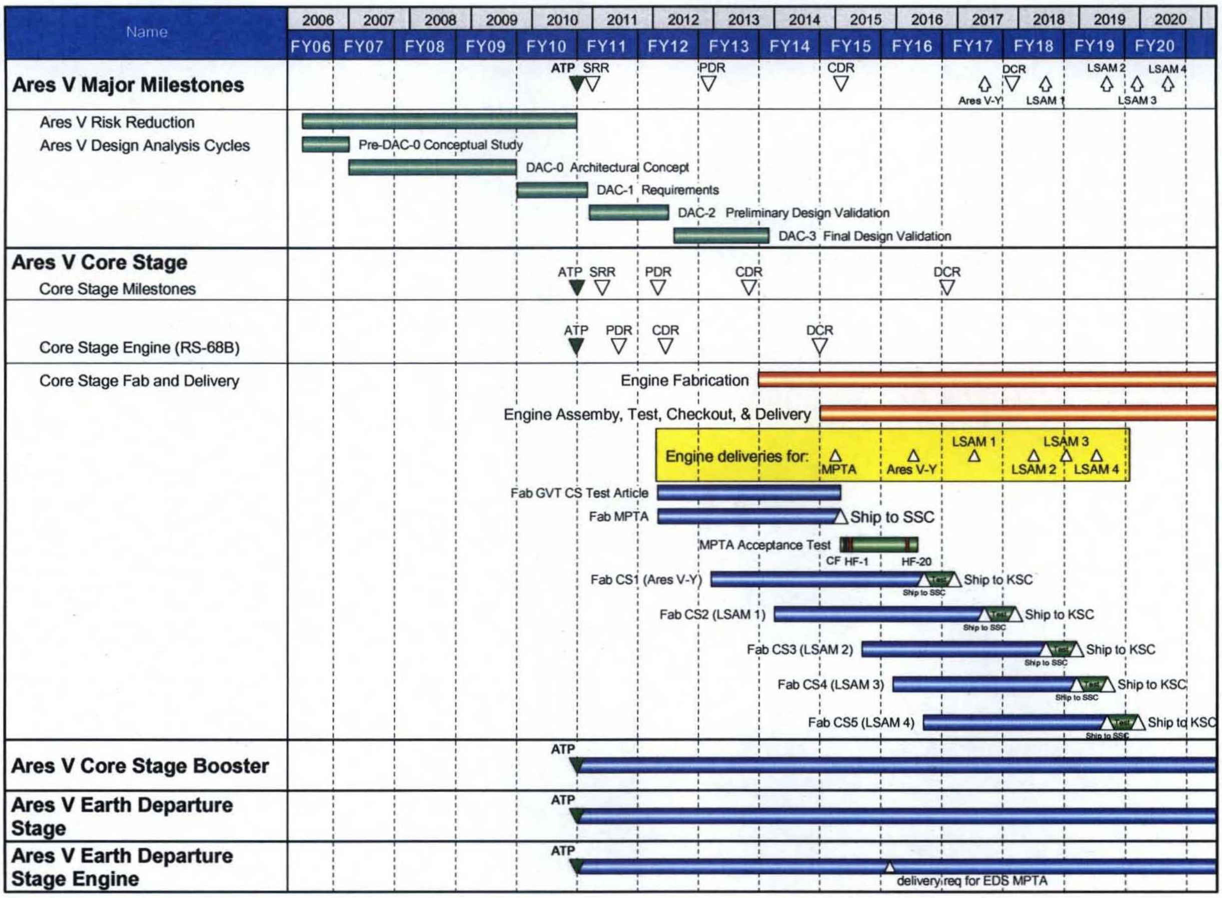

Figure 8. Ares V Summary Schedule.

In April 2006, a 2-minute test of a Space Shuttle Reusable Solid Rocket Booster was performed at the ATK Launch Systems test facility.[10] The test article had over 117 instrumentation channels to capture data for dozens of objectives. In addition to benefiting the Shuttle program, it also benefited the Ares V. As reported in Aviation Week and Space Technology, the extensibility from the Shuttle Reusable Solid Rocket Booster to the Ares V first stage "eliminates the need to start from square one. At the same time, it draws on workforce experience built up over the past quarter century."[11] Another 2-minute booster test was conducted in November 2006 with instrumentation that will help analyze motor-induced roll-torque.

To facilitate RS-68 engine upgrade activities, the Ares V team in 2006 finalized a technical directive with Pratt & Whitney Rocketdyne (PWR) to evaluate the Core Stage Engine requirement and review technical options, culminating in an Upgrades Requirement Review in October 2006. NASA and the engine contractor met to determine the best options for helium-use mitigation and to plan for analysis and testing. As an integral part of this engine effort, the Ares V team established a formal working relationship with the U.S. Air Force to collaborate on the RS-68 engine work, which is already in progress. An upgraded variant is in development for a single mission. From that engine, NASA plans to work with the Air Force to develop a common RS-68B version for use on both the Ares V and the Delta IV, featuring upgrades required by NASA for operability and changes planned by the Air Force for its Assured Access To Space (AATS) program to improve robustness. Planned modifications to the current RS-68 are:

1. Increased power level of roughly 4 percent.
2. Main injector changes to improve Isp roughly 2 percent.
3. New bearing material to decrease stress corrosion susceptibility.

4. Redesigned turbopump pump inlets to incorporate tip vortex suppression.

5. Redesigned fuel turbopump second stage blisk to increase robustness.

6. Redesigned gas generator igniter that eliminates potential foreign object debris.

7. Higher reliability oxidizer turbopump bearing chill sensor.

8. Higher reliability hot gas sensor.

9. Redesigned oxidizer turbopump to reduce pre-start and operational helium usage.

10. Modified engine start sequence/configuration to reduce free hydrogen on the pad during engine start.

11. Redesigned ablative nozzle to accommodate the longer-duration Ares V mission profile.

The increased power level and main injector modifications are included in an engine upgrade program that PWR is implementing under a contract with United Launch Alliance for the RS-68A variant. Changes 3 through 8 are currently conducted under the Air Force Assured Access to Space (AATS) Program. NASA will work with the Air Force to combine the AATS upgrades with changes 9-11 above, required for Ares V, to produce a common RS-68 B engine variant.

The J-2X Upper Stage Element was responsible for several important milestones in maturing the Ares V design in 2006. Engineers created many of the necessary planning and design documents needed to develop budgets, schedules, and design decisions. The Element completed a Preliminary Requirements Review in summer 2006 that concluded that engine requirements were mature enough to begin developing subsystem and component requirements and begin engine conceptual design. The team identified all existing J-2 engine hardware from the Apollo and X-33 programs and transferred them to the J-2X for refurbishment and testing. Test engineers conducted tests of a subscale main injector[12], an augmented spark igniter, J-2 heritage valves, and subscale tests of 40- and 58-element main injectors. The historic A-1 test stand at Stennis Space Center was transferred from the Space Shuttle Program to the Constellation Program for J-2X testing.

In November, the J-2X Element completed a combined System Requirements Review/System Definition Review that encompassed requirements, conceptual design, and planning to meet the exploration mission. Among the major decisions resulting from those reviews were discontinuation of a 274,000-pound thrust option to concentrate on the baseline 294,000-pound thrust option, selection of helium spin start over solid propellant gas generators, open loop control mode, pneumatic valve actuation, ball sector valves over heritage butterfly valves, and a baseline engine test plan.

That same month, NASA completed a milestone first review of all systems for the Orion spacecraft and the Ares I and Ares V rockets during a Constellation Program System Requirements Review, the first system requirements review of a human rated spacecraft since the Space Shuttle in 1973.[13]

A series of engineering studies in 2006 and early 2007 served as the basis for an Ares V Integrated Vehicle Design Definition Document marking the completion of Design Analysis Cycle 0. This document, in turn, will serve as the starting point for one or more formal design analysis cycles to follow. This DAC focused on refining the concept for the Core Stage. Refinements to the entire stack were made primarily where understanding the stack helped refine the Core Stage. Inputs to those studies included detailed computer aided design work (Figure 9).

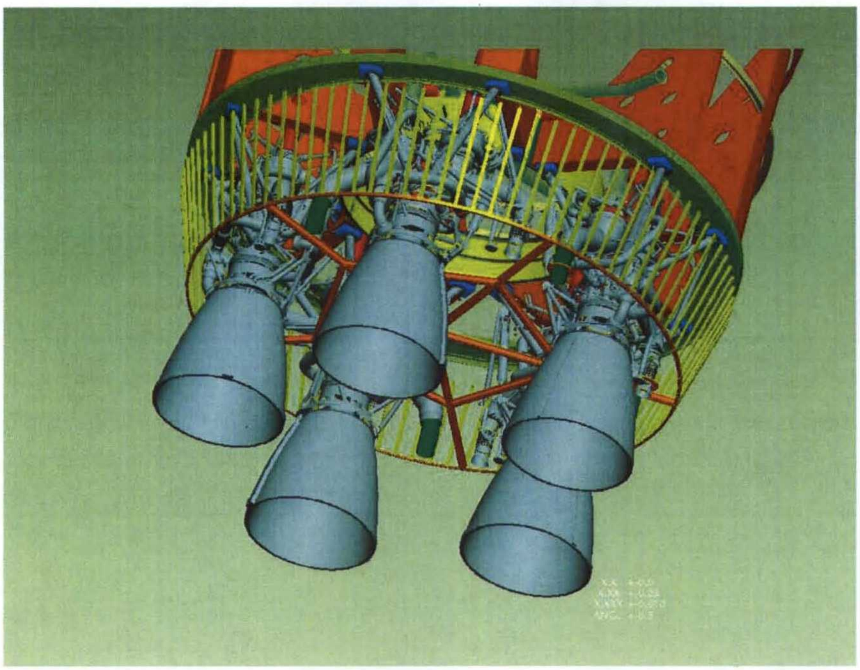

Figure 9. CAD concept art of Ares V Core Stage 5-around RS-68 engine configuration.

The Core Stage Element conducted an Upgrades Requirements Review (URR) board on the engine modifications on Oct. 31, 2006. The Turbopump Upgrade Critical Design Review (CDR) board occurred on Nov. 30, 2006. In early 2007, Pratt&Whitney Rocketdyne completed computational fluid dynamics (CFD) analyses of free hydrogen accumulation around Pad 39 during launch, examining no changes, start sequence changes only, and start sequence changes plus helium spin start changes. The 5-second point for the baseline RS-68 is shown in Figure 10 below.

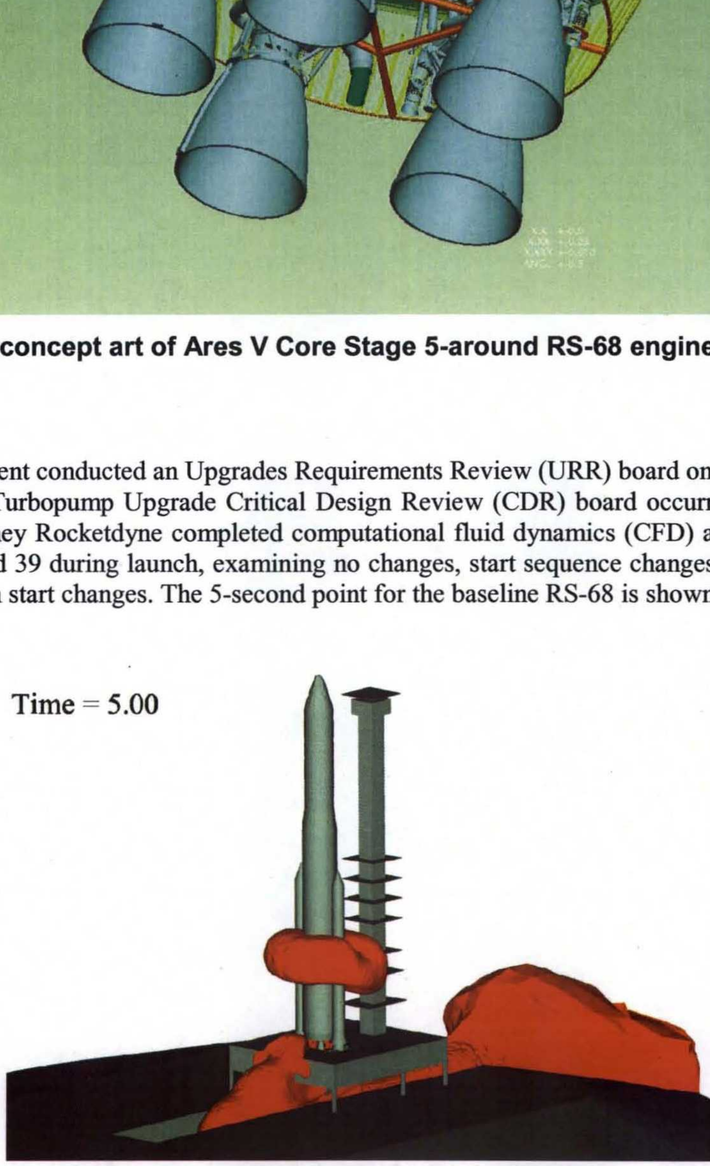

Figure 10. CFD analysis of launch pad free hydrogen 5 seconds after engine start.

An analysis of Michoud Assembly Facility was completed in March 2007 by the Austin Company. This study included manufacturing and assembly for Ares I Upper Stage, Ares V EDS and Ares V Core Stage. A planned follow-up study would assess surge capacity, manufacturing flow, tooling, and support equipment.

Between February and April 2007, Marshall Center engineers conducted a series of tests on subscale injector hardware for the RS-68 engine in support of the Ares V Core Stage Element office (Figure 11). The injector channels liquid hydrogen and liquid oxygen into the engine's main combustion chamber, where it burns to produce thrust. The injector plays a key role in determining the efficiency and overall performance of the engine. Engineers completed some 14 hot fire tests on 40- and 58-element injectors. The test series focused on modifications to the injector tips to improve performance. The series also sought to determine an element density that represents the best balance of performance versus manufacturability and cost. Firings of roughly 7 to 20 seconds generated between 15,000 and 20,000 pounds of thrust over a range of chamber operating temperatures and pressures. The results of the tests will benefit the RS-68A and B engines, as well as the J-2X, which will use the same injector.

Figure 11. Subscale 40-element injector test at MSFC.

The Core Stage Element completed its work under 2006 and 2007 Congressional funding on May 18, 2007, and work was transferred to the MSFC Advanced Planning Manager. NASA's initial exploration plans in 2005 called for development of the Ares V to begin in 2012. However, Congressional conferees noted in their 2006 Appropriations Bill that "the Heavy Lift Launch Vehicle is critical to NASA's exploration plans" and that "human exploration beyond low Earth orbit is not achievable without an operational capability." They provided $5 million in FY 2006 and $3.2 million in FY 2007 as seed money to support early development of a heavy lift launch capability. Following trade studies that changed the Core Stage engine from the SSME to the RS-68, NASA, accordingly, invested the seed money in identifying detailed requirements for modifying the RS-68, conducting initial risk mitigation testing on engine components, and initiating a cooperative relationship the U.S. Air Force to develop a common engine to satisfy the needs of both agencies.

VIII. Summary and Conclusion

The Ares V Cargo Launch Vehicle will deliver large-scale hardware and provisions to space for establishing a permanent Moon base and extending a human presence beyond the International Space Station and low-Earth orbit. Working in tandem with the Ares I/Orion combination, this heavy-lift vessel will provide a replacement for the venerable Space Shuttle. While NASA looks to the past for wisdom, it applies modern systems engineering and management practices and processes to ensure technical performance is delivered on time and within budget. Building on a foundation of legacy knowledge and heritage hardware increases the prospect of mission success in the complex business of space transportation.

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