AIAA Joint Propulsion Conference, July 9 – 11, 2006
Paper due NLT June 15, 2006

NASA Exploration Launch Projects Overview: The Crew Launch Vehicle and the Cargo Launch Vehicle Systems

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Abstract

The U.S. Vision for Space Exploration (January 2004) serves as the foundation for the National Aeronautics and Space Administration's (NASA) strategic goals and objectives.[1] As the NASA Administrator outlined during his confirmation hearing in April 2005, these include:

- Flying the Space Shuttle as safely as possible until its retirement, not later than 2010.
- Bringing a new Crew Exploration Vehicle (CEV) into service as soon as possible after Shuttle retirement.
- Developing a balanced overall program of science, exploration, and aeronautics at NASA, consistent with the redirection of the human space flight program to focus on exploration.
- Completing the International Space Station (ISS) in a manner consistent with international partner commitments and the needs of human exploration.
- Encouraging the pursuit of appropriate partnerships with the emerging commercial space sector.
- Establishing a lunar return program having the maximum possible utility for later missions to Mars and other destinations.[2]

In spring 2005, the Agency commissioned a team of aerospace subject matter experts to perform the Exploration Systems Architecture Study (ESAS). The ESAS team performed in-depth evaluations of a number of space transportation architectures and provided recommendations based on their findings.[3] The ESAS analysis focused on a human-rated Crew Launch Vehicle (CLV) for astronaut transport and a heavy lift Cargo Launch Vehicle (CaLV) to carry equipment, materials, and supplies for lunar missions and, later, the first human journeys to Mars. After several months of intense study utilizing safety and reliability, technical performance, budget, and schedule figures of merit in relation to design reference missions, the ESAS design options were unveiled in summer 2005. As part of NASA's systems engineering approach, these point of departure architectures have been refined through trade studies during the ongoing design phase leading to the development phase that begins in 2008. Comprehensive reviews of engineering data and business assessments by both internal and independent reviewers serve as decision gates to ensure that systems can fully meet customer and stakeholder requirements. This paper provides the current CLV and CaLV configuration designs and gives examples of the progress being made during the first year of this significant effort.

Safe, reliable, cost-effective space transportation systems are a foundational piece of America's future in space and the next step in realizing the plan for revitalizing lunar capabilities on the passageway to the human exploration of Mars. While building on legacy knowledge and heritage hardware for risk reduction, NASA will apply lessons learned from developing these new launch vehicles to the growth path for future missions. The elements for mission success and continued U.S. leadership in space have been assembled over the past year. As NASA designs and develops these two new systems over the next dozen years, visible progress, such as that reported in this paper, may sustain the national will to stay the course across political administrations and weather the inevitable trials that will be experienced during this challenging endeavor.

I. Introduction

The U.S. Vision for Space Exploration and the U.S. Space Transportation Policy direct NASA to design and develop a new generation of safe, reliable, and cost-effective transportation systems to help fulfill the Nation's strategic goals and objectives relative to assured access to space.[4] These new launch vehicles will provide the capability for astronauts to conduct scientific exploration that yields new knowledge from the unique vantage point of space. American leadership in opening new frontiers will improve the quality of life on Earth for generations to come.

The Exploration Launch Projects (ELP) office was chartered in September 2005 by the Exploration Systems Mission Directorate (ESMD) and the Constellation Program to deliver operational CLV and the CaLV systems that meet or exceed customer and stakeholder requirements, fielded on time and within budget. Fig. 1 shows the CLV/CEV system concept as it leaves the launch pad. Fig. 2 shows the CaLV concept on its way to low-Earth orbit (LEO).

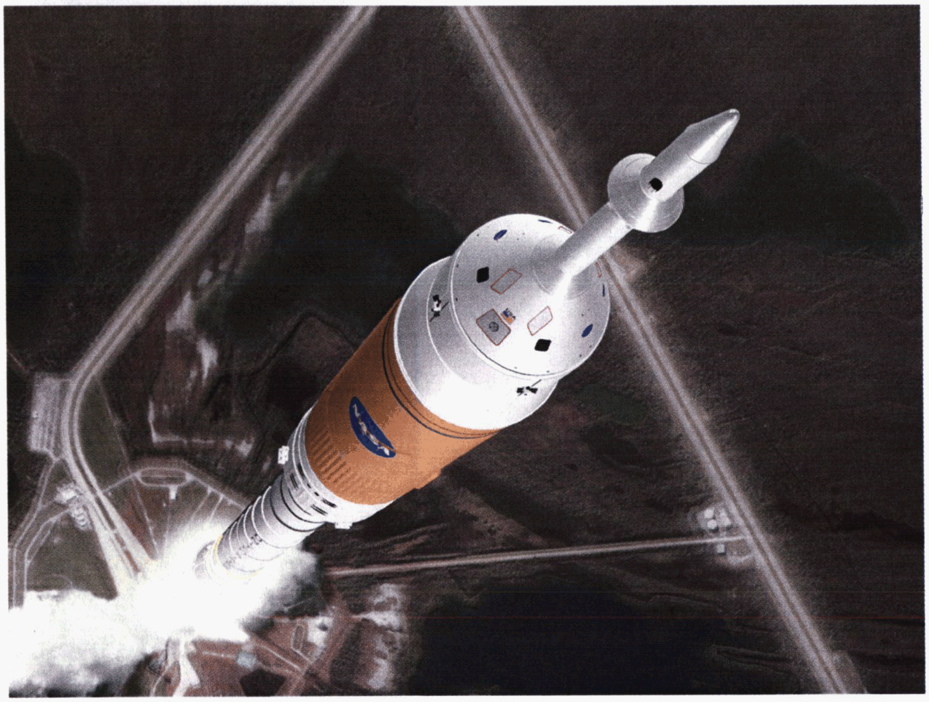


Fig. 1. The CLV will loft the CEV into LEO.

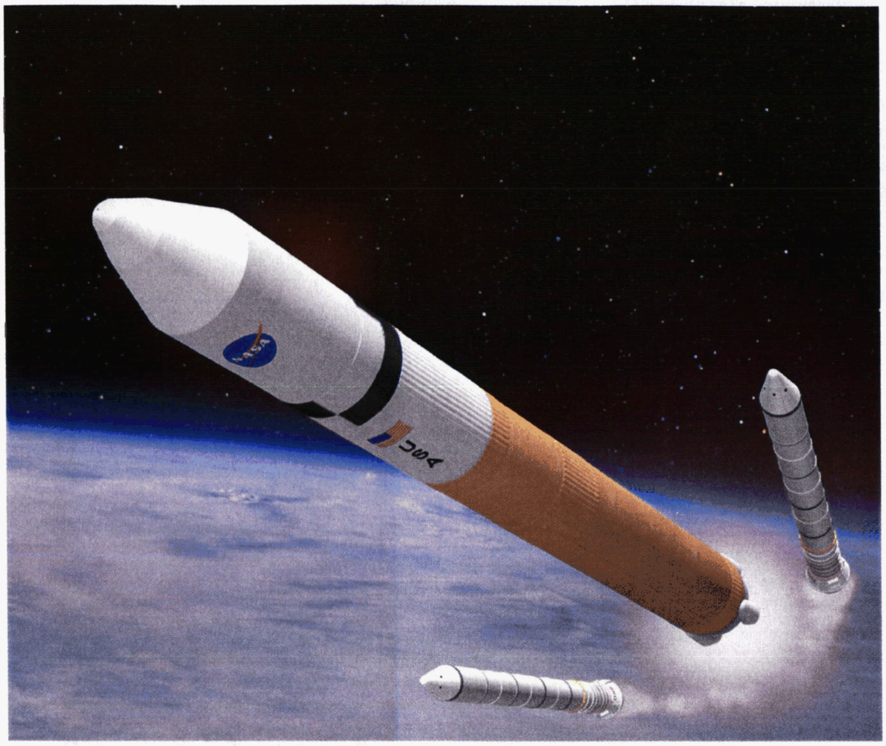


Fig. 2. The CaLV will carry the LSAM to LEO.

The Exploration Launch Projects office, located at NASA's Marshall Space Flight Center, is responsible for designing, developing, testing, and evaluating (DDT&E) the CLV that will loft the CEV into LEO, and the heavy lift CaLV, which will deliver the Lunar Surface Access Module (LSAM) to LEO, for astronaut return trips to the Moon in preparation for the eventual first human footprint on Mars. The lunar mission scenario (Fig. 3) begins with the CaLV delivering the Earth Departure Stage (EDS) carrying the LSAM to orbit, where the CEV, launched on the CLV, will rendezvous with the LSAM before beginning America's seventh trip to the Moon.

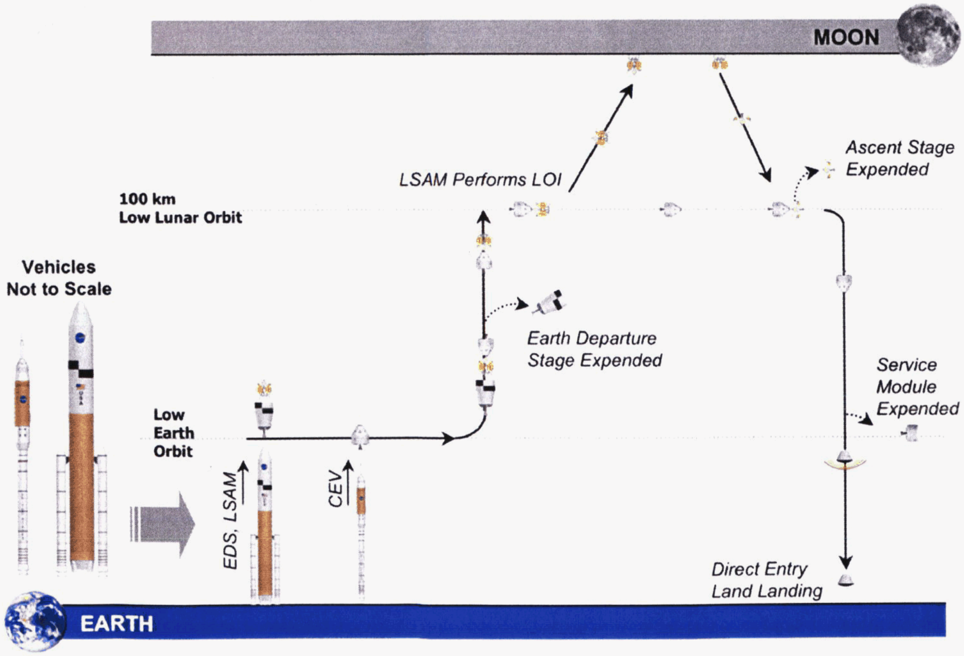


Fig. 3. Lunar mission scenario.

Working closely with NASA's Constellation Program and ESMD, the ultimate goal of the Exploration Launch Projects office is to deliver safe, reliable launch vehicle systems designed to minimize life-cycle costs so that NASA's budget can be more fully invested in the "why" of exploration, rather than on the "how". Applying almost 50 years of aerospace lessons learned, and building modern process and product improvements into proven legacy hardware, are prime strategies to ensure mission success. With the "test as you fly" philosophy, eventual flight-testing will prove the mettle of both hardware systems and operations staff, leading to fully operational launch vehicle fielding.

Given below is information about NASA's systems engineering approach to delivering hardware and operational solutions, along with a few of many success stories that have been documented over the past year. For example, during this time, the Exploration Launch Projects office has built a team with nationwide participation from across NASA Centers and the aerospace industry. As is outlined below, the ELP is systematically delivering measurable inch-stones along the path leading to well-defined milestone reviews by internal and independent panels. A series of NASA's Exploration Systems progress reports, along with other documents, provides regularly released news that is available through the NASA Web site.[5]

II. Systems Engineering Approach

The Exploration Launch Projects' formulation, or design, phase began in September 2005, using ESAS-recommended architecture options as points of departure for trade studies leading to the optimum vehicle designs to be developed in the implementation, or production, phase, which begins in 2008.[6] As a result of this systems engineering approach, in February 2006, the Agency streamlined its CLV DDT&E hardware plan so that the CLV first stage booster and upper stage engine are largely extensible to the CaLV booster stage and EDS propulsion elements, saving billions of dollars in nonrecurring investment. Hardware commonality between the two vehicles will help reduce the logistics footprint, including manufacturing, processing, and launch facilities, as well as decrease both recurring and nonrecurring operations expenses.

Furthermore, in May 2006, the ESAS-recommended CaLV configuration was updated to reflect the findings of engineering analyses and business planning conducted in spring 2006. As a result, the baseline CaLV configuration saves on DDT&E costs and reduces life-cycle expenses by changing from a proposed modified Space Shuttle Main Engine (SSME), which was designed for robust reusability, to a commercially available, expendable engine better suited for the CaLV mission; specifically, using the liquid oxygen/liquid hydrogen (LOX/LH2) RS-68 engine, which was developed by the U.S. Air Force and is currently flown on the Delta IV heavy lift vehicle. This is an example of how engineering analyses that are conducted in tandem with cost estimating and acquisition planning yield options that fulfill requirements while giving the best value for the investment made. Further details are given in the CaLV section below.

Current Vehicle Configurations

Fig. 4 shows expanded views of the current CLV and CaLV reference designs. The CLV will loft the 25 metric ton (55,000 pounds of mass (lbm)) CEV into orbit early next decade. This system is estimated to be 10 times safer than the Shuttle due to its in-line configuration, which places the crew above the rocket, and the integrated CEV launch abort system (LAS), which can rapidly move the crew away in case of an emergency. The CaLV system, slated for fielding late next decade, can lift 136 metric tons (300,000 lbm) to a 30-by-160 nautical mile (nmi) orbit inclined at 28.5 degrees, or 55 metric tons (120,000 lbm) to trans-lunar orbit. Preliminary schedules and flight profiles are shown in the CLV and CaLV sections below.

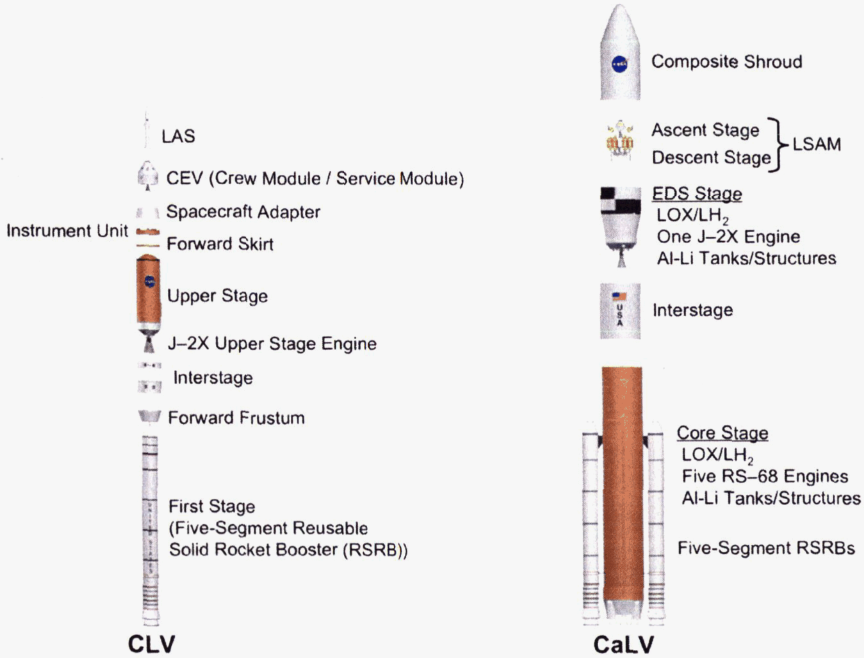


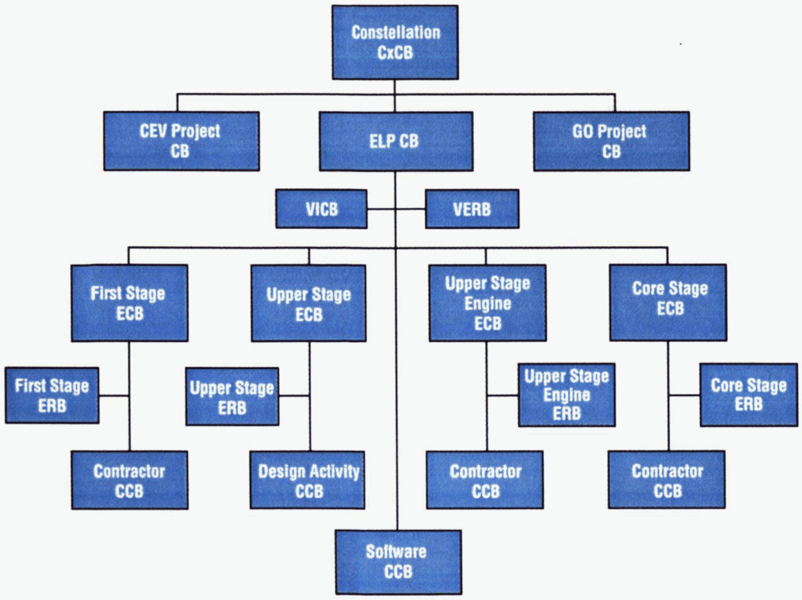
Fig. 4. CLV and CaLV expanded views.

Risk Reduction

Systems engineering reduces risk by providing a strong linkage between and among disparate engineering disciplines, from aerodynamics and avionics to mass properties and thermal control. The ELP Vehicle Integration Element understands the synergy that results when the pieces are integrated into the whole system and is invested with the methods and means to ensure correct and proper functionality. Through systems engineering, trade study analyses are performed to determine the optimum solutions that fulfill customer and stakeholder requirements, focusing on the "-ilities," such as reliability, maintainability, supportability, and operability.

The Exploration Launch Projects office implements stringent systems engineering standards to improve accuracy and reduce rework. A robust vehicle integration element facilitates communication via embedded touch-points throughout the various hardware offices, as well as through on-site resident staff members located at geographically dispersed business units, including contractor facilities. Following a rigorous configuration management process improves clarity across the various Government and contractor work in progress.

Within the systems engineering function, integrated product teams report through a board structure to the project- and program-level control boards (CB) (Fig. 5). This hierarchy is documented in the Exploration Launch Projects Systems Engineering Management Plan.[7] To spur innovation, decision-making is pushed to the lowest level possible. For example, the Vehicle Integration Control Board (VICB) defines and reviews the results of systematic design analysis cycles, during which trade studies are conducted and findings reported. The approval chain for decisions that must be made at higher levels, such as changes to the baseline vehicle configurations, is captured in the SEMP and in the Exploration Launch Projects Configuration Management Plan.[8]



Legend:
CxCB — Constellation Systems Control Board
CCB — Configuration Control Board
ECB — Element Control Board
ERB — Engineering Review Board
GO — Ground Operations
VERB — Vehicle Engineering Review Board

Fig. 5. NASA achieves configuration control through interrelated boards.

As specified in the NASA instruction on program and project management, a series of internal and independent reviews is conducted throughout the project's life cycle to serve as check-points for a number of engineering products, such as drawings and specifications, and to gauge technical progress against established funding guidelines and schedule milestones.[9] Non-advocate reviews survey technical and programmatic documentation and provide forums for interactive discussions relative to project progress. The series of CLV and CaLV top-level reviews is listed in Table 1 below.

Table 1. NASA project internal technical reviews.

Review Title	Review Purpose/Outcome
System Requirements Review (SRR)	Assures that requirements are properly defined, verifiable, and implemented, are traceable, and that the hardware and software are designed and built to the authorized baseline configuration.
Preliminary Design Review (PDR)	Provides completed design specifications, the identification and acquisition of long-lead items, manufacturing plans, and life cycle cost estimates; the design is 30% complete and element specifications are baselined.
Critical Design Review (CDR)	Discloses the complete system in full detail; ascertains that technical problems and design anomalies have been resolved; and ensures that the design maturity justifies the decision to begin fabricating/manufacturing, integration, and verification of mission hardware and software. The design is 90% complete.
Design Certification Review (DCR)	Serves as the control gate that ensures the system can accomplish its mission goals. Requirements are verified in a manner that supports launch operations.
Flight Readiness Review (FRR)	After the system has been configured for launch, the FRR process examines tests, demonstrations, analyses, and audits that determine the system's readiness for a safe and successful launch and for subsequent flight operations. The Project Manager and Chief Engineer certify that the system is ready for safe flight.

As is shown in Fig. 6, the ESMD Implementation Plan flows into the Constellation Architecture Requirement Document, which informs the CLV and CaLV System Requirements Documents. At lower levels, each launch vehicle system is governed by an Interface Requirements Document, which details the various linkage points (such as command and control, power, communications, and mechanical interfaces), and by an operations concept, which covers the multitude of aspects that go into integrating the vehicle subsystems, stacks, and payloads. Furthermore, a series of flight demonstrations — from simulators to high-fidelity vehicles — will provide the opportunity to validate modeling and simulation, test mission scenarios and the human/mechanical interface, and further influence integration decisions. These and other risk mitigation strategies are being employed to improve communication and increase the likelihood of mission success.

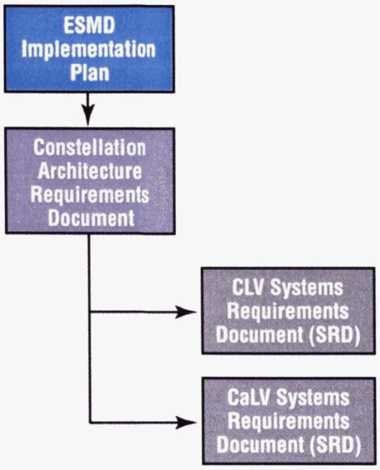


Fig. 6. High-level requirements flow down to system requirements to facilitate integration.

III. CLV Progress

As an integral part of NASA's design approach, CLV requirements are being validated by conducting rigorous systems engineering trades studies against the concept design through a series of design analysis cycles, leading to an SRR that is scheduled for 2006. The SRR is the first major milestone in CLV development; it assures that CLV requirements are properly defined and implemented, are traceable, and that the hardware and software will be built to the authorized baseline configuration requirements. The SRR confirms that the total CLV system — and the individual first stage, upper stage, and upper stage engine elements' design and interface requirements — are defined before proceeding to the PDR.

Completed design specifications will be provided at the PDR, planned for 2008. The Critical Design Review, projected for 2009, will verify that the CLV system design meets requirements, establish quality assurance plans, and baseline the "build to" specifications. The DCR, projected for 2012, is the control gate that ensures the CLV system can accomplish its mission goals. In addition to these documentation data reviews, the CLV path to flight includes verification flight-testing beginning in the 2009 timeframe, leading to the first flight of a crew to the ISS no later than 2014.

Fig. 7 provides the CLV preliminary integrated master schedule, which captures lower-level hardware element schedules. The notional CLV flight profile is shown in Fig. 8.

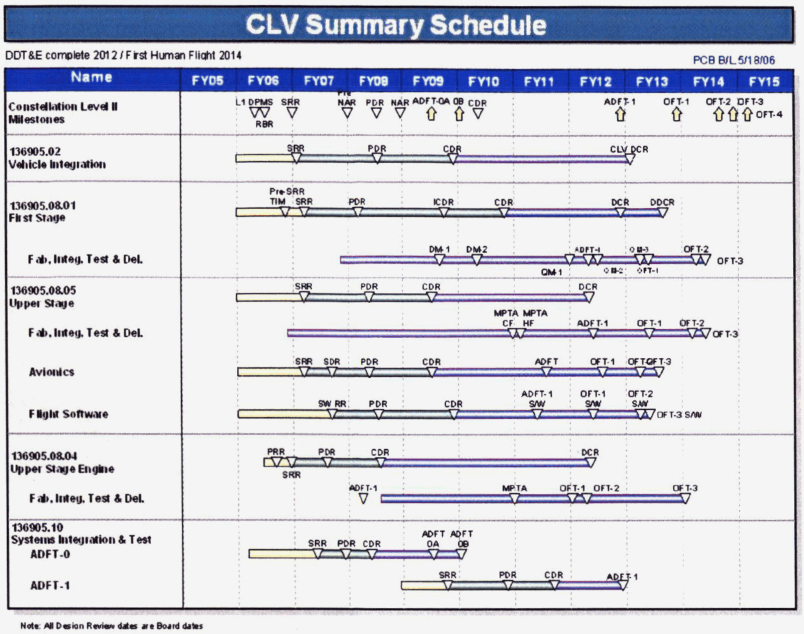


Fig. 7. Preliminary CLV schedule.

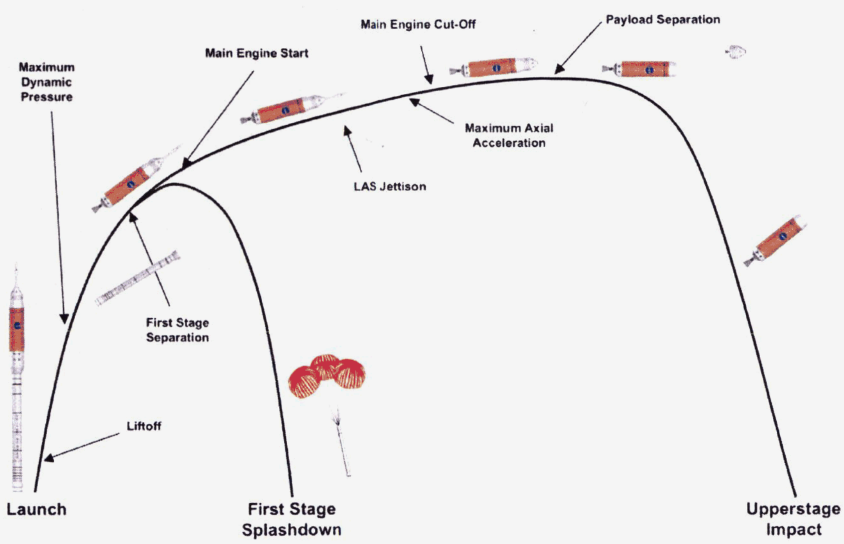


Fig. 8. Notional CLV flight profile.

Wind Tunnel Testing

Dozens of wind tunnel tests have been conducted on various-sized CLV scale models (see Fig. 9) to assess three-dimensional geometric configurations before more detailed engineering designs are produced. For example, in late 2005, the Aerodynamic Research Facility at the Marshall Space Flight Center provided data from 66 wind tunnel tests conducted using a 16.5-inch scale model, to help rocket engineers determine flight performance characteristics. The CLV scale model included the full take-off load, including the crew capsule, service module, and LAS tower.

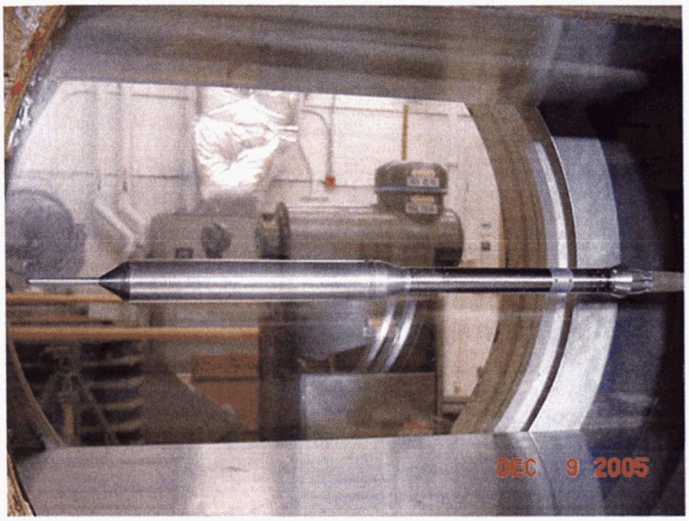


Fig. 9. Wind tunnel test.

Engineers also conducted flow visualization tests that identified shock waves and component expansion similar to that experienced during supersonic flight. It also provided CLV configuration data for guidance, navigation, and control (GN&C) subsystem analysis. This series of tests was performed over a range of 0.5 to 4.96 Mach. The data obtained provided the foundation for more detailed testing during the spring and summer 2006, using larger vehicle models in facilities such as those at the Langley Research Center and the Ames Research Center.

Static Test Firing

ATK Thiokol is the prime contractor for the CLV first stage. As the Shuttle Program made preparations to fly, a 2-minute test of the RSRB was performed at the ATK Launch Systems test facility (see Fig. 10). The flight support motor burned the same amount of time as that for an actual Shuttle launch. The test article had over 117 instrumentation channels to capture data for dozens of objectives. Analysis results have a dual benefit for the Shuttle Program and the CLV first stage element. As reported in Aviation Week and Space Technology, the extensibility from the Shuttle RSRB to the CLV first stage and the CaLV propulsion system "eliminates the need to start from square one. At the same time, it draws on workforce experience built up over the past quarter century."[10]

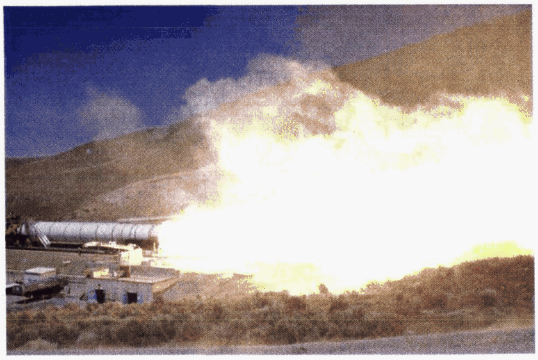


Fig. 10. RSRB static test firing, April 2006.

Upper Stage Request for Information

A series of well-planned acquisitions has kept CLV work moving at a brisk pace. To illustrate, in spring 2006, a request for information was issued to the aerospace community for strategic input on manufacturing the CLV upper stage, which is an in-house NASA design. Responses received addressed both technical and business challenges. In particular, approaches were sought to combining avionics or on-board electrical flight controls and guidance systems into the overall upper stage procurement. NASA also received feedback related to design and specification sharing among participants, commonality of design tools and software, methods of reducing component life-cycle costs, and seamless transition of contractual arrangements.

Following receipt of this information from interested parties, NASA conducted a well-attended open house at the Government-owned/contractor-operated Michoud Assembly Facility (MAF) — a one-of-a-kind facility where, currently, the Shuttle External Tank is manufactured and shipped to the Kennedy Space Center (KSC). The CLV upper stage and the CaLV EDS will be manufactured and assembled at MAF.

Upper Stage Engine Injector Performance Testing

Several candidate J-2X injector designs were tested in spring 2006, as a risk reduction strategy to increase confidence that the design can produce the specific impulse (Isp) needed for both the CLV and CaLV applications (see Fig. 11). The testing reflected the engine's operating conditions anticipated for the inaugural flights of both vehicles and yielded data that is helping engineers determine the simplest design that atomizes the propellant for the complete combustion with stable operation to meet performance requirements.

Fig. 11. J-2X injector performance test.

Several subscale candidate designs were investigated and anchored to current and historical engines to promote a highly reliable and affordable J-2X engine design to propel the CLV and CaLV. This test series, conducted at the Marshall Space Flight Center, verified how the C-star efficiency changes as a function of element density for the proposed injector designs. It also validated the system level power balance, for which C-star is the single most important variable. Although the CLV is due to be fielded first, this is an example of how common hardware, such as the J-2X engine, also is helping the CaLV effort progress.

Test as You Fly

Integrated flight-testing is a key risk mitigation strategy, and the plan includes both ascent (suborbital) flight development tests and orbital flight tests. In May 2006, the Constellation Program Control Board approved a proposed initial flight test to be conducted in 2009 to provide data that will be timely to the Critical Design Review. A sample of top-level CLV flight-test objectives include demonstration of:

- Ascent flight control system performance with dynamically similar first and upper stage CLV/CEV.
- Nominal first and upper stage separation and clearances.
- CEV/LAS performance during a post-staging abort from initiation to water landing and recovery.
- Significant reductions in launch processing time and required resources, as well as built-in test avionics.

Flight-testing of increasingly high-fidelity hardware configurations has a dual benefit of validating a multitude of launch vehicle processing, integration, and operations scenarios, while providing real-world mission training and problem-solving experience. Operability and supportability must be built into the systems and culture, knowing that two key CLV operations requirements are launch availability and fixed and variable recurring costs. In keeping with this business philosophy, the ELP effort includes early integration with operators and astronauts to ensure that they influence requirements and design.

IV. CaLV Progress

The current CaLV configuration is at an earlier design stage than is the CLV. However, recent studies have been conducted to determine mutual requirements between this system and the CLV system. Also, near-term technical work associated with modifying the RS-68 core stage engine is in progress. Both of these efforts are summarized below.

To provide a frame of reference, the preliminary CaLV integrated master schedule is shown in Fig. 12 and the concept vehicle notional flight profile is given in Fig. 13.

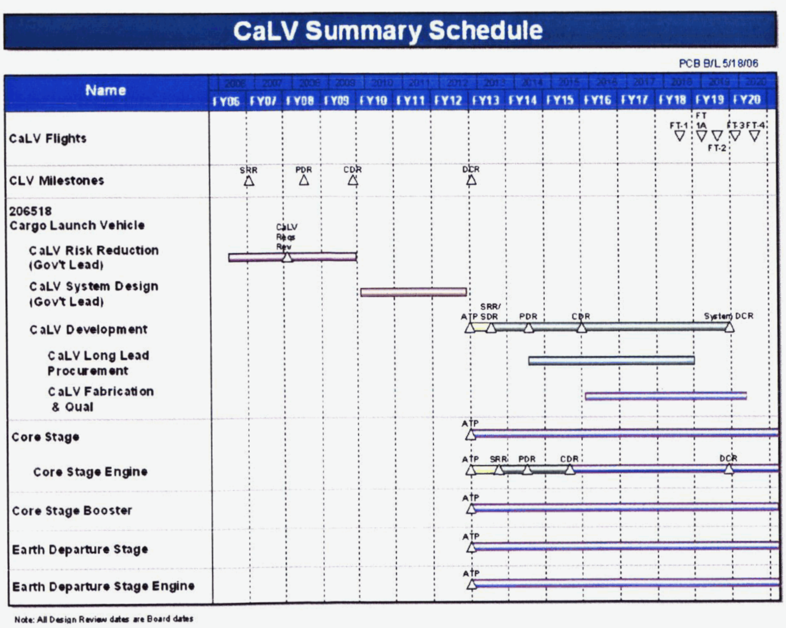


Fig. 12. Preliminary CaLV schedule.

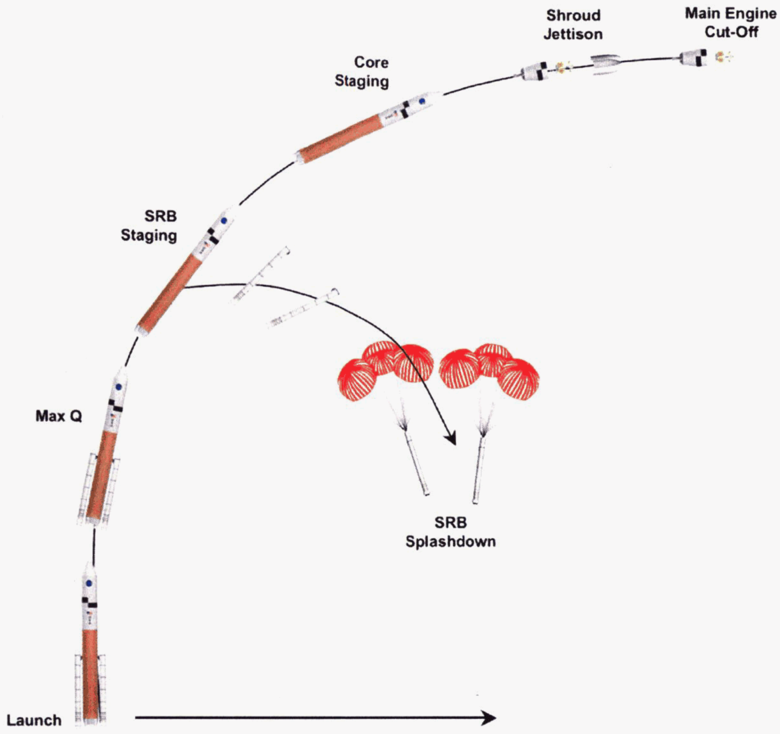


Fig. 13. CaLV flight profile.

Requirements Maturation

The Exploration Launch Project Crew Launch Vehicle/Cargo Launch Vehicle Commonality Assessment was conducted by a panel of aerospace experts in May 2006.[11] Personnel included all disciplines involved in the design, development, or integration of the vehicles, as well as representatives from contractors with experience in the various heritage Apollo and Shuttle systems that will be leveraged in the design of the new vehicles. With the impending concurrence of the CLV SRR and CaLV Initial Requirements Review, it was imperative to determine which CaLV requirements might have the most significant impact on the desired commonality between the two vehicles, major issues not covered by the CaLV concept, and major risks for the current concept based on expert opinion and qualitative analysis.

The panel's discussion of the RSRB revolved primarily around structural, avionics, and propulsion considerations. Structural risks included differences in the loads due to the single-stick CLV configuration versus the multiple-body geometry CaLV configuration. Different requirements for the forward and aft skirts may place some structural commonality at risk, but the conclusion was that significant commonality exists between the two vehicles. Avionics risks revolved around single booster requirements for the CLV, versus dual boosters on the CaLV. Propulsion risks included RSRB thrust mismatch requirements for the CaLV and performance penalties associated with using the CLV thrust trace. A session was conducted to address the CaLV core stage and core stage engine environments encountered during flight, and the potential for debris generation at RSRB ignition or liftoff. The session also addressed required RS-68 modifications, both for performance gains and safety improvements to maintain the vehicle's human-rating option. A number of modifications are needed, chiefly, reduction of free hydrogen at engine start and the engine's current excessive helium requirements for launch pad operations.

Configuration Refinements

As stated earlier, the Constellation Program Control Board approved refining the CaLV configuration in May 2006 to include the RS-68 engine, which was designed for low development and operations costs, and is in the process of being upgraded. Near-term NASA participation reduces Constellation Program schedule risk. In addition, high-level discussions are in progress with other Government agencies for potential collaboration, which may reduce cost risk. Subsequent flights of upgraded RS-68 engines on the Delta IV will yield valuable performance data that can be directly applied to the CaLV, reducing technical risk. By contrast, the SSME has not been built in over a decade, was estimated to be twice as expensive after modifications for expendability, and was rated highly complex compared to the relatively simple RS-68. The loss of mission estimate for the refined CaLV configuration is approximately equivalent to that of the previous ESAS design option.

The RS-68 engine is the most powerful liquid oxygen/liquid hydrogen booster now in existence. When modified to meet NASA's standards (see Fig. 14), the five-engine cluster will exceed Program requirements, delivering an additional 4 metric tons of cargo to space. Studies are being conducted to determine future human-rating potential.

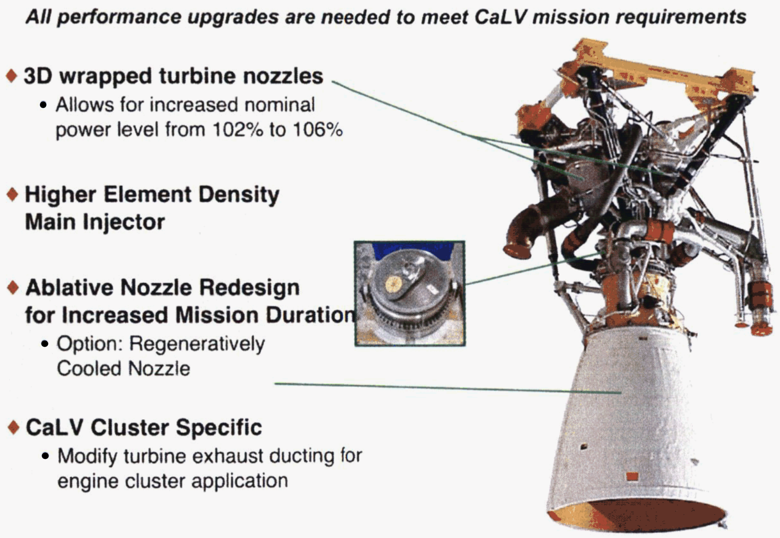


Fig. 14. A selection of RS-68 engine modifications.

A 33-foot-diameter core stage tank delivers the propellant needed for lunar missions. This Saturn-class tank also provides exhaust clearances for the larger RS-68 nozzle. This tank size should improve vehicle structural stiffness and controllability, as well. Manufacturing, testing, processing, and launch facility modifications will be required for any new tank, regardless of size. Trade studies included participants from KSC and those familiar with the MAF manufacturing and processing capabilities. Figure 15 shows the Saturn V stage being processed at MAF.

Table 2 below summarizes some of the work in progress for the CaLV, including the core stage and the EDS.

Fig. 15. Saturn V first stage (33-foot diameter) in the MAF horizontal processing facility.

Table 2. CaLV task summary.

Next Steps	Actions
Develop CaLV requirements.	• Allocation to Elements. • Validation (design analysis cycle). • Baseline requirements.
Perform engineering analyses.	• Computer Assisted Design modeling. • Induced environments (loads, structural dynamics, aerodynamic database, base heating and acoustics).
Perform manufacturing assessment.	• Impact of the 33-foot tank diameter on tooling requirements.
Perform further risk analyses.	• Technical • Schedule • Cost • Mitigation planning.
Perform ascent flight analysis.	• 3 degrees of freedom (DOF) and 6 DOF trajectory simulations. • Separation/staging maneuvers. • EDS impacts to J-2X restart conditions. • Options for circularizing the EDS/LSAM at 160-by-160 nmi. • Rendezvous orbit sensitivities.
Develop operations concept.	• With KSC participation.
Investigate acquisition strategies.	• For the integrated vehicle.

V. Conclusion: A New Era of Space Exploration

As the Exploration Launch Projects organization designs and develops systems capable of returning astronauts to the Moon, it marshals systems engineering methodology and tools to ensure that designs satisfy customer and stakeholder requirements. This approach builds on lessons learned from decades of aerospace knowledge and draws upon the experience of some of the Nation's top rocket engineers from Government and industry. In this way, technical, budget, and schedule risks are reduced, safety and reliability confidence is increased, and the probability of mission success is enhanced.

While NASA looks to the past for wisdom, it applies modern systems engineering and management practices and processes to ensure technical performance is accurately reflected in, and inextricably connected to, budget allocations and schedule milestones, with a primary focus on safety and reliability and reduced operations costs. Building on a foundation of legacy knowledge and heritage hardware increases the prospect of mission success in the complex business of space exploration. Sustainable transportation solutions will promote an industry that may be embraced by new generations of explorers on fresh journeys of discovery that will re-vector commonly held knowledge and open a frontier of infinite possibilities.

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