NASA Crew and Cargo Launch Vehicle Development Approach Builds on Lessons from Past and Present Missions

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The United States (U.S.) Vision for Space Exploration, announced in January 2004, outlines the National Aeronautics and Space Administration's (NASA) strategic goals and objectives, including retiring the Space Shuttle and replacing it with new space transportation systems for missions to the Moon, Mars, and beyond. The Crew Exploration Vehicle (CEV) that the new human-rated Crew Launch Vehicle (CLV) lofts into space early next decade will initially ferry astronauts to the International Space Station (ISS). Toward the end of the next decade, a heavy-lift Cargo Launch Vehicle (CaLV) will deliver the Earth Departure Stage (EDS) carrying the Lunar Surface Access Module (LSAM) to low-Earth orbit (LEO), where it will rendezvous with the CEV launched on the CLV and return astronauts to the Moon for the first time in over 30 years. This paper outlines how NASA is building these new space transportation systems on a foundation of legacy technical and management knowledge, using extensive experience gained from past and ongoing launch vehicle programs to maximize its design and development approach, with the objective of reducing total life cycle costs through operational efficiencies such as hardware commonality. For example, the CLV in-line configuration is composed of a 5-segment Reusable Solid Rocket Booster (RSRB), which is an upgrade of the current Space Shuttle 4-segement RSRB, and a new upper stage powered by the liquid oxygen/liquid hydrogen (LOX/LH2) J-2X engine, which is an evolution of the J-2 engine that powered the Apollo Program's Saturn V second and third stages in the 1960s and 1970s. The CaLV configuration consists of a propulsion system composed of two 5-segment RSRBs and a 33-foot core stage that will provide the LOX/LH2 needed for five commercially available RS-68 main engines. The J-2X also will power the EDS. The Exploration Launch Projects, managed by the Exploration Launch Office located at NASA's Marshall Space Flight Center, is leading the design, development, testing, and operations planning for these new space transportation systems. Utilizing a foundation of heritage hardware and management lessons learned mitigates both technical and programmatic risk. Project engineers and managers work closely with the Space Shuttle Program to transition hardware, infrastructure, and workforce assets to the new launch systems, leveraging a wealth of knowledge from Shuttle operations. In addition, NASA and its industry partners have tapped into valuable Apollo databases and are applying corporate wisdom conveyed firsthand by Apollo-era veterans of America's original Moon missions. Learning from its successes and failures, NASA employs rigorous systems engineering and systems management processes and principles in a disciplined, integrated fashion to further improve the probability of mission success.

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I. Introduction

The United States Vision for Space Exploration directs NASA to retire the venerable Space Shuttle in 2010 and to develop safer, more reliable, and more cost-effective transportation systems in a timely manner to continue the journey of discovery from the unique vantage point of space.[1] With this policy as its guidepost, NASA is in the process of developing a human-rated CLV capable of lifting 25 metric tons (Fig. 1) and a heavy-lift CaLV capable of lifting 125 metric tons (Fig. 2) for missions that will return astronauts to the Moon as the first step toward the eventual human exploration of Mars. These systems are based largely on evolutions of Apollo and Space Shuttle legacy hardware to maximize extensive aerospace databases and collaborative utilization of existing highly specialized resources with proven reliability.

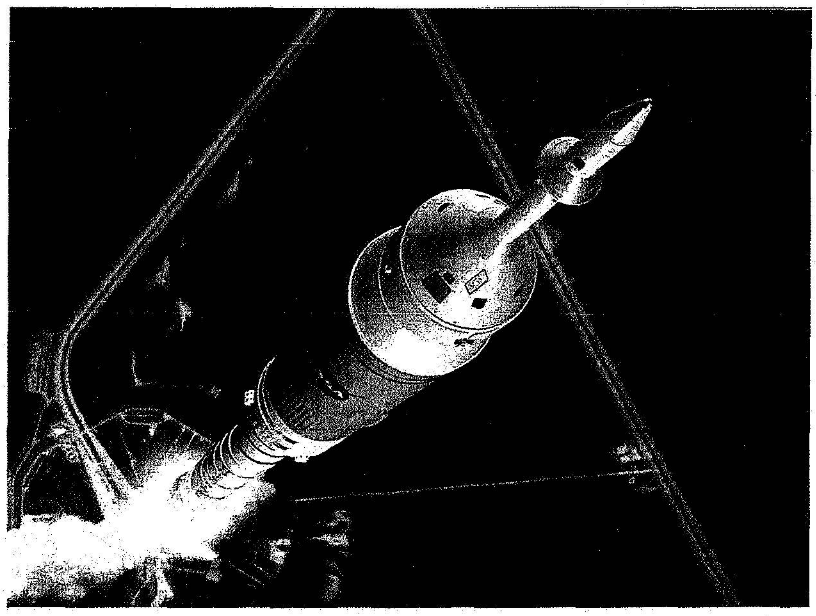


Figure 1. The Crew Launch Vehicle will deliver 25 metric tons to orbit (artist's concept).

In fiscal year 2005, NASA invested approximately $4.3 billion of its $16 billion budget on the Space Shuttle, and in fiscal year 2006, NASA invested $4.4 billion of a total $16.2 billion budget.[2,3] NASA's fiscal year 2007 budget of almost $17 billion allocates $4 billion for the Shuttle and $3.9 billion for Exploration Systems to begin the process of developing the vehicles and support infrastructure needed to fulfill the missions outlined in the U.S. Vision for Space Exploration.[4] NASA's Exploration Launch Projects office has been chartered to deliver safe, reliable space transportation systems designed to minimize life cycle costs so that NASA's budget can be more fully invested in missions of scientific discovery. NASA is applying aerospace best practices by leveraging existing technologies and resources and employing rigorous systems engineering and systems management standards to ensure that these new space transportation systems meet stringent standards and satisfy well-defined customer and stakeholder requirements.

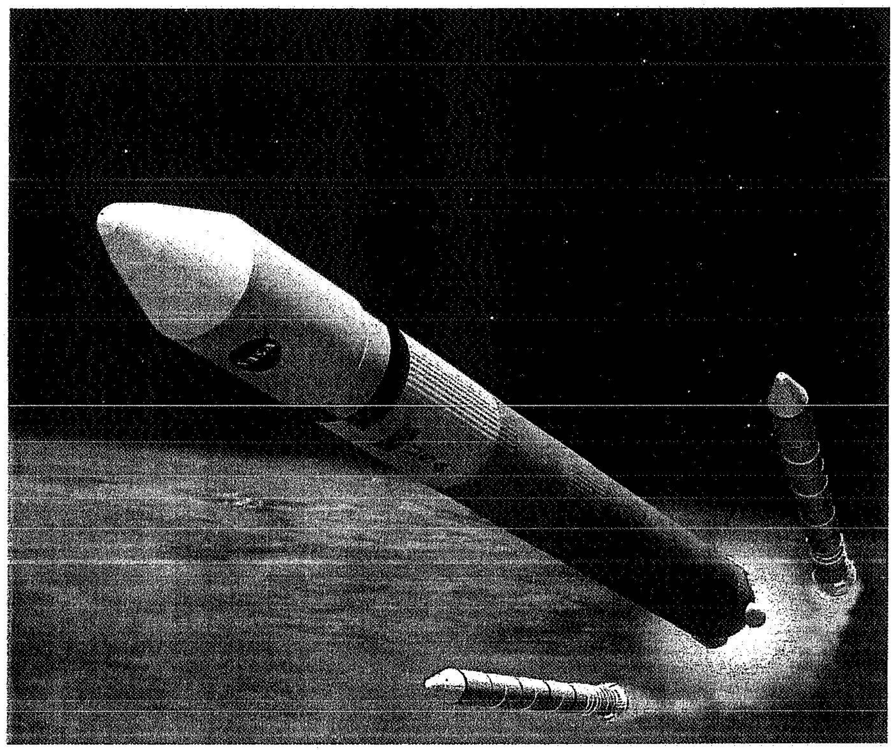


Figure 2. The Cargo Launch Vehicle will deliver 125 metric tons to orbit (artist's concept).

Over the past few decades, NASA, the U.S. Department of Defense (DoD), and private industry have invested in advanced propulsion technologies, some yielding a greater return on investment than others. Staying within the budget prescribed, and delivering within the timeframe needed, drives NASA's 21st century space transportation fleet to draw on evolutionary technologies to the maximum extent possible and to implement a number of innovative operations concepts that reduce operations costs through such things as common tooling, manufacturing, and processing of components, subsystems, and systems. With a "test as you fly, and fly as you test" philosophy, the Exploration Launch Projects office draws on analysis results from subscale wind tunnel models (Fig. 3) and from computer aided applications that test integrated avionics software and simulate vehicle dynamics in cyberspace, leading 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 decisions.

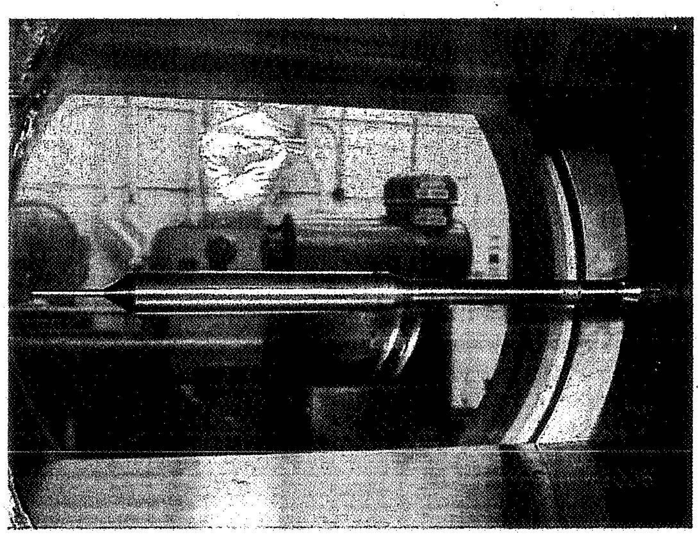


Figure 3. Crew Launch Vehicle scale model positioned in wind tunnel test facility.

Despite the impressive research and technology investments made by the aerospace community at large, the access to space remains elusive, its cost limiting the expansion of business potential into that fertile territory. Fielding a sustainable modern space transportation system is, therefore, a key decision driver in NASA's current transportation strategy. For example, in December 2005, NASA released the draft announcement for Commercial Orbital Transportation Services Demonstrations, effectively opening the ISS resupply market to competitive bid by the aerospace industry, with the goal of reducing the logistics costs associated with that orbital outpost, where crews are learning to live and work in space for long durations.[5] Commercial businesses may one day satisfy such emerging markets, allowing NASA to invest its budget more fully in the "why" of exploration rather than on the "how".

While market forces may lead to fresh space access capabilities, NASA's responsibility to deliver human-rated space systems and cargo designed for destinations beyond LEO is being fulfilled through its CLV and CaLV Projects. Most of the CLV and CaLV systems are being developed by industry teams, with Government insight, with a goal of reducing costs through a number of methods, ranging from validating requirements to conducting trades studies against potential designs. Operations concepts such as automated processing build on lessons learned from the Shuttle's labor-intensive hands-on processing. Flight tests of the Delta Clipper-Experimental Advanced (DC-XA) subscale vehicle in 1996 validated streamlined operations that utilized minimal touch labor, automated cryogenic propellant loading, and an 8-hour turnaround for a cryogenic propulsion system.[6] For the CLV, the results of hazard analyses are leading to requirements for an integrated vehicle health monitoring system that will troubleshoot anomalies and determine which ones can be solved without human intervention. These and other advances will help standardize and economize mission scenarios, reducing the operations bottom line.

The Exploration Launch Projects' Government and industry team is in the process of designing, developing, testing, and evaluating (DDT&E) vehicle configurations that can best meet or exceed customer and stakeholder requirements, technical performance, and safety standards, as well as be ready within the desired timeframe and budget guidelines. Analysis shows that evolutionary systems, though not without risk, offer the best likelihood of delivering the needed launch vehicles capabilities.[7] Therefore, the Exploration Launch Projects' approach to mission success includes:

- Leveraging existing technologies and applying lessons learned to work smarter.
- Building an accountable team that is dedicated to implementing aerospace best practices, including rigorous systems engineering and systems management, to mitigate the risks inherent in delivering complex prototype space transportation systems that fulfill stakeholder and customer requirements, including reduced operations costs from system inception to retirement.

II. Maximizing Mature Technologies and Informative Knowledge Bases

The value of applying lessons learned is undeniable. Countless review boards have been convened and libraries written to document the reasons for mission failures, with indictments of both technical and programmatic management. Perhaps the most important finding of the Columbia Accident Investigation Board (CAIB) Report was that the lack of an overarching vision to guide NASA's challenging missions diluted its efforts and skewed its agenda.[8] Now, the U.S. Vision for Space Exploration provides clear goals and objectives to guide technical and programmatic decisions, and the findings and recommendations provided by the CAIB give aerospace professionals sobering lessons that are being applied as legacy propulsion components are transformed into space transportation systems suitable for a new space age.

The ultimate goal of the Exploration Launch Projects office is to deliver safe, reliable crew and cargo systems designed to minimize life cycle costs so that NASA can concentrate on missions of scientific discovery. To that end, the Space Shuttle follow-on systems are being designed and developed within the safety, reliability, and cost figures of merit (FOM) provided in tandem with design reference missions (DRM) that clearly define the various exploration-related destinations ahead. Together, these aspects form a trade space that is bounded by top-level requirements that are decomposed to lower system levels. A brief background of how the CLV and CaLV vehicle configurations were selected provides a frame of reference for the magnitude of hardware development currently in progress and insight into associated systems engineering and systems management processes employed.

To provide in-depth data for selecting these follow-on launch vehicles, the Exploration Systems Architecture Study (ESAS) was conducted during the summer of 2005, following the confirmation of the new NASA Administrator in April 2005. A team of aerospace subject matter experts used technical, budget, and schedule objectives to analyze a number of potential launch systems, both reusable and expendable, with a focus on human rating for exploration missions. The results showed that a variant of the Space Shuttle, utilizing the RSRB as the first stage, along with a new upper stage that uses a derivative of the SSME RS-25 modified to start at altitude, was the quickest path to delivering the CLV, while also meeting safety and cost guidelines. In January 2006, as part of the engineering trade studies conducted during the formulation phase, NASA streamlined its CLV hardware development approach, so that the propulsion elements now under development are more fully extensible to the heavy lift CaLV and future EDS lunar systems (see Fig. 4).

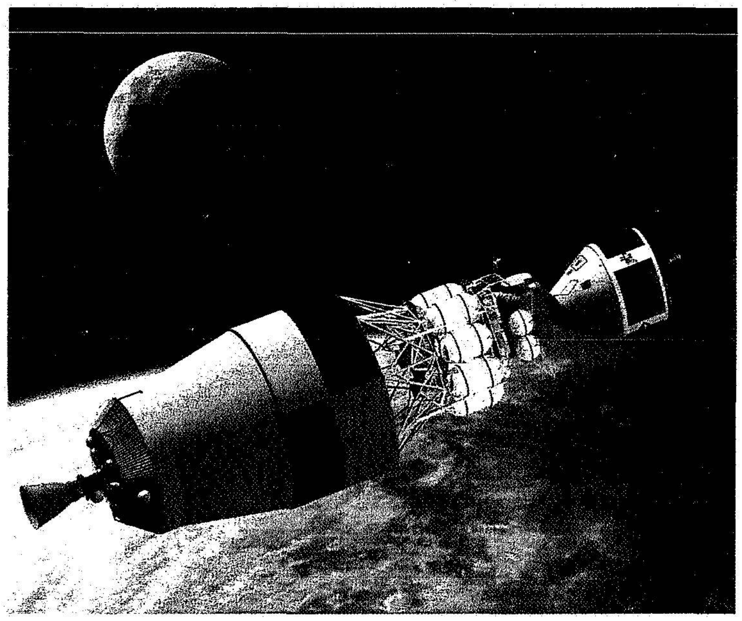


Figure 4. The Earth Departure Stage and Crew Exploration Vehicle will rendezvous in low-Earth orbit (artist's concept).

Specifically, with the current approach, the CLV will use a 5-segment RSRB first stage instead of the modified Space Shuttle 4-segment RSRB originally proposed in the ESAS. A 5-segment RSRB was tested in 2003, demonstrating that configuration and establishing that the propellant burn rate can be tailored for current CaLV mission parameters. The CLV upper stage will use the J-2X engine, a derivative of the Saturn V's S-II and S-IVB upper stage main propulsion, which also will serve as the CaLV EDS engine. A key element of the J-2X engine, the turbomachinery, was successfully restarted during the X-33 Program in 1996. In a move that delivers more performance and saves at least 50 percent per main engine unit cost, the CaLV configuration employs a cluster of 5 commercially available RS-68 engines upgraded to meet NASA's standards and a Saturn-class 33-foot diameter core stage tank.

This plan offers multiple benefits by developing one RSRB and one upper stage engine, reducing the total number of separate major hardware elements originally proposed in the ESAS. It also capitalizes on a low-cost expendable engine that can meet the high production rates that will be needed for CaLV missions. The resulting funding profile is more sustainable and the plan will reduce both recurring and nonrecurring operations costs through infrastructure (manufacturing and processing) commonality. In addition, the new safety and reliability projections are comparable to the ESAS recommended configuration. Although the first stage and upper stage engine selections have matured, the Moon mission "1.5 launch architecture" remains the same: the CLV will deliver the CEV to rendezvous in low-Earth orbit with the EDS and LSAM delivered by the CaLV (see Fig. 5).

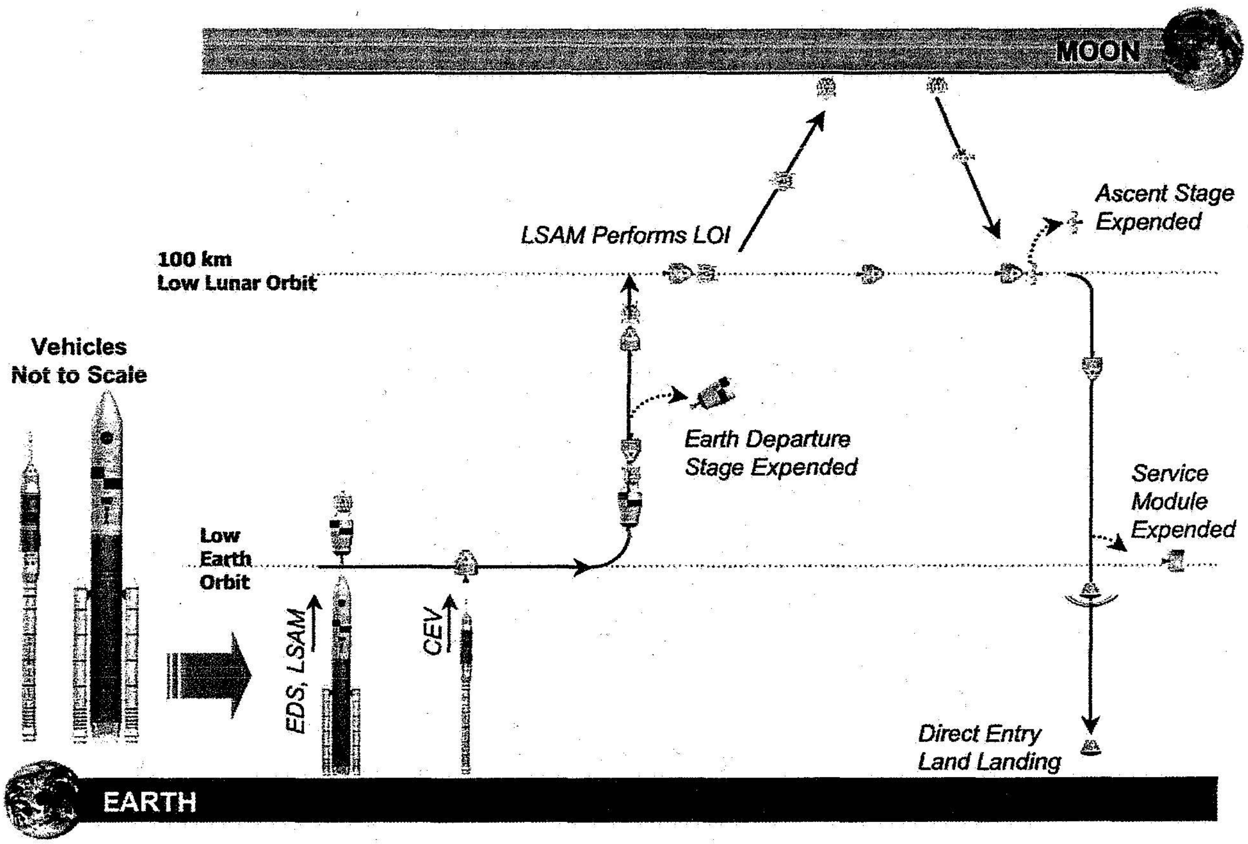


Figure 5. Return to the Moon mission architecture.

III. Applying Rigorous Systems Engineering and Systems Management Principles

It is against this backdrop of multiple, parallel hardware efforts that NASA is using extensive experience gained from past and ongoing launch vehicle programs to maximize vehicle integration, both from an engineering perspective and from a management standpoint. The CLV and CaLV are being designed to reduce costs through a number of methods, ranging from validating requirements (what the system must do, how often, and when), to conducting trades studies, such as the ones described above, against the vehicle concepts to ensure that the optimum design solutions are selected during the current formulation phase, prior to the implementation phase that begins in 2008.[9]

Each project phase is marked by a number of data deliverables that undergo systematic reviews performed by internal and independent experts who help guide decisions at critical junctures. Systems engineering is performed by the Exploration Launch Projects' Vehicle Integration Element, which brings to bear management systems that knit together geographically dispersed business units. The Vehicle Integration Element functions as a centralized communications conduit for wide-ranging activities within a framework of open, honest interactions among the hundreds of individuals engaged in this complex business.[10]

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 Vehicle Integration Element understands the pieces in relation to the integrated whole 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.

Requirement management is one aspect of systems engineering that captures the goals and objectives that the integrated space transportation systems must deliver. Associated trade studies add to the space transportation knowledge base, while building on information captured during decades of successful, and not so successful, programs and projects to verify and validate requirements in relation to the system options being considered. This flexible, durable design process allows a knowledge-based organization to effectively harness the volumes of information relative to the primarily existing propulsion technologies NASA has selected for its CLV and CaLV systems.

Propulsion systems development is an extremely risky business. Utilizing specific technical and programmatic lessons learned, and understanding their implications for reducing the risk of developing CLV and CaLV systems, is paramount in the Exploration Launch Projects' philosophy. For example, the J-2X upper stage engine is an evolution of a tried-and-true propulsion element that powered the Saturn V second and third stages during the 1960s and 1970. During the X-33 Program, the J-2X turbopumps were tested; recent analysis of that data and hardware helps inform the engine component design process. Interestingly, the J-2X engine prime contractor, Pratt & Whitney Rocketdyne, brought in over a dozen consultants who once were Apollo-era engineers on the first J-2 engine to share firsthand their experiences with the new J-2X team.

Add to these advantages NASA's continuous risk management process (Fig. 6), which involves proactive risk identification techniques, such as assessments against the work breakdown structure that defines various tasks to identify, assess, plan mitigation, track, and control risks. Quantitative risk management techniques, such as probabilistic risk assessment, gauge the risk environment and optimize the use of resources to mitigate risk. Risk management is validated using an industry-accepted risk management capability maturity model. Monthly assessments are conducted and opportunities for improvements are identified.

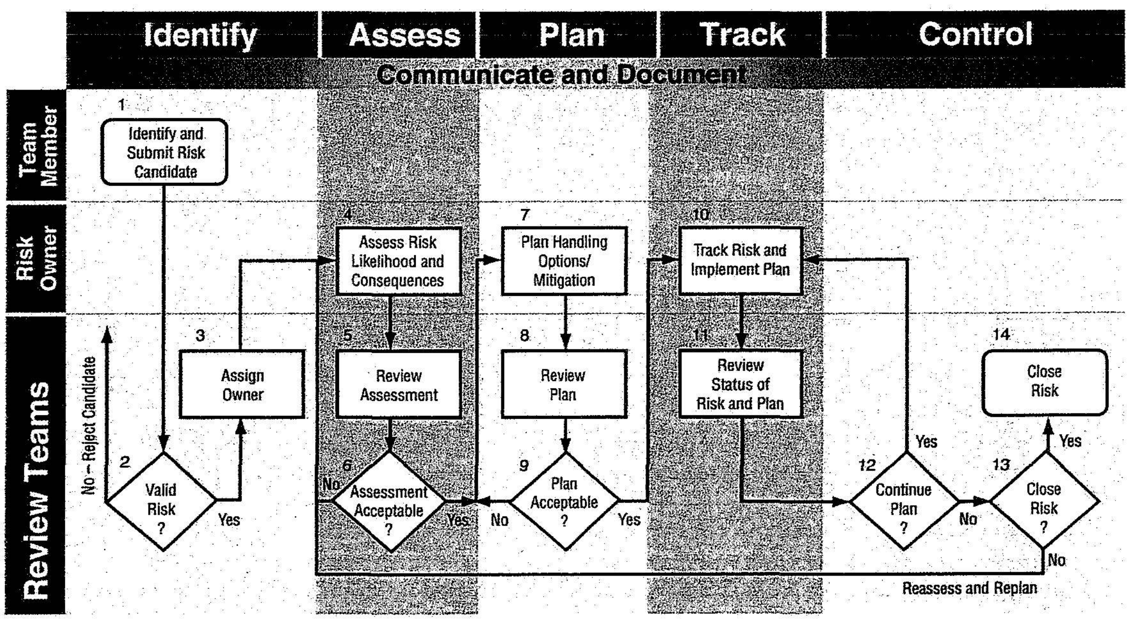


Figure 6. Continuous risk management process.

To promote a knowledge-based organization — one that is continually attuned to the opportunities for gathering, capturing, and applying technical and programmatic lessons — requires disciplined commitment to learning from the past and contributing to the future. Managers are provided reference materials such as books and reports and are encouraged to share corporate knowledge and mentor junior engineers. The Exploration Launch Projects organization fosters a common vocabulary for clear communication among the engineers, technicians, business professionals, support personnel, and others involved in this demanding work.[11] Team members are responsible for applying, and rewarded for sharing, applicable lessons learned as part of an overall learning culture, as outlined in the Knowledge Management Plan.[12,13] The tangible and intangible benefits that accrue from knowledge management, enacted through these and other means, pay dividends in terms of increasing the potential for mission success.

The cost of access to space limits the budget that can be invested in the missions that space transportation enables. The business of delivering new space transportation capabilities includes operations concepts that reduce both recurring costs, such as propulsion element production and sustaining engineering and processing the launch vehicle stack, and nonrecurring costs, such as modifying the existing launch infrastructure to accommodate these new systems (see Fig. 7). By studying the pros and cons of past and present launch vehicle processing, plans are for the various hardware elements to arrive at the launch facility in pre-configured sets (i.e., the engine will be mated with the upper stage element) for streamlined handling. The operations working group, as a subset of Vehicle Integration and part of the Constellation Ground and Mission Operations Systems Integration Group, ensures that logistics and other details are considered as part of the overall operations concept and requirements development.

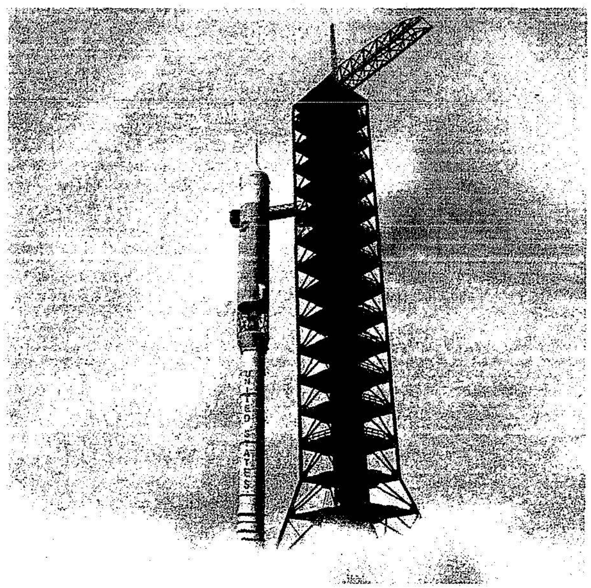


Figure 7. Crew Launch Vehicle on the launch pad (artist's concept).

More than 4 decades of experience have taught us that effective management, rather than technology alone, is the key ingredient for a high rate of mission success.[14] Therefore, the Exploration Launch Projects organizational foundation establishes the hierarchy for technical insight and control mechanisms designed to produce quality components, subsystems, and systems that work together within well-defined tolerances and interface correctly with other systems, such as a payload integrating with a launch vehicle that then is positioned on the launch pad. Whereas programmatic control of the budget and schedule can gauge resources (namely, time and money) in relation to technical progress, the systems engineering and integration function serves as a conduit through which communication flows among the hundreds of technical personnel involved in a massive effort such as the Exploration Launch Projects.

Learning from what worked during the Apollo era and applying modern business principles, NASA Headquarters has recently established a system of checks and balances that results in a healthy tension between technical and programmatic concerns.[15] Chief Engineers are matrixed to the Exploration Launch Projects through a dedicated engineering organization and, therefore, maintain an independent technical voice. Safety and Mission Assurance representatives, also matrixed from another organization, provide independent opinions in their field. Also, an Independent Project Review Team has been commissioned to give an outside perspective regarding technical progress and issues that arise during the course of developing complex hardware systems destined for use in the harsh space environment.

Engineering and business information technologies are employed to effectively manage change; to estimate, track, and forecast resource utilization; and to determine technical progress against milestones captured in an integrated master schedule (IMS) (Figs. 8 and 9). These and other systems engineering and systems management processes and procedures also build on a heritage foundation to give confidence that the launch vehicles fielded next decade can deliver the operational capability required more economically than current systems. From a management systems perspective, the Exploration Launch Projects team depends on tools such as a sound configuration management process, as well as on rigorous internal and independent reviews that serve as decision gates on the path to delivering new space transportation capabilities.

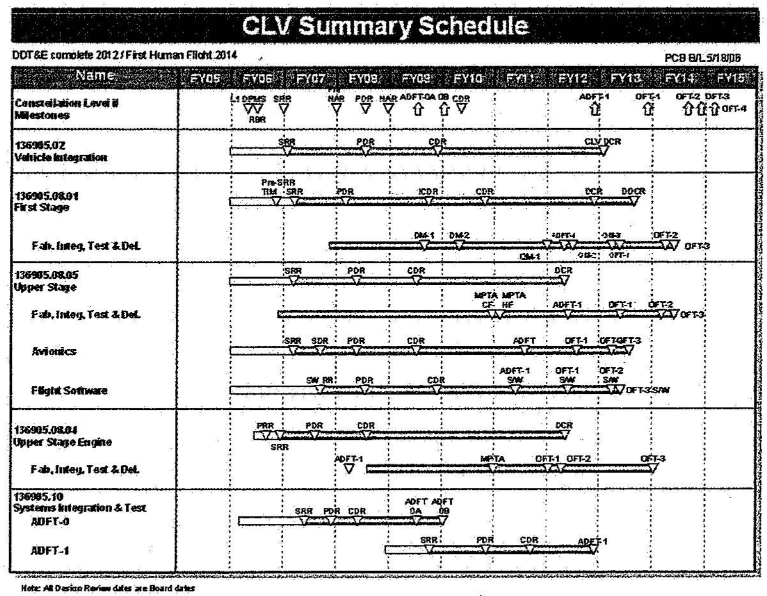


Figure 8. Preliminary Crew Launch Vehicle integrated master schedule.

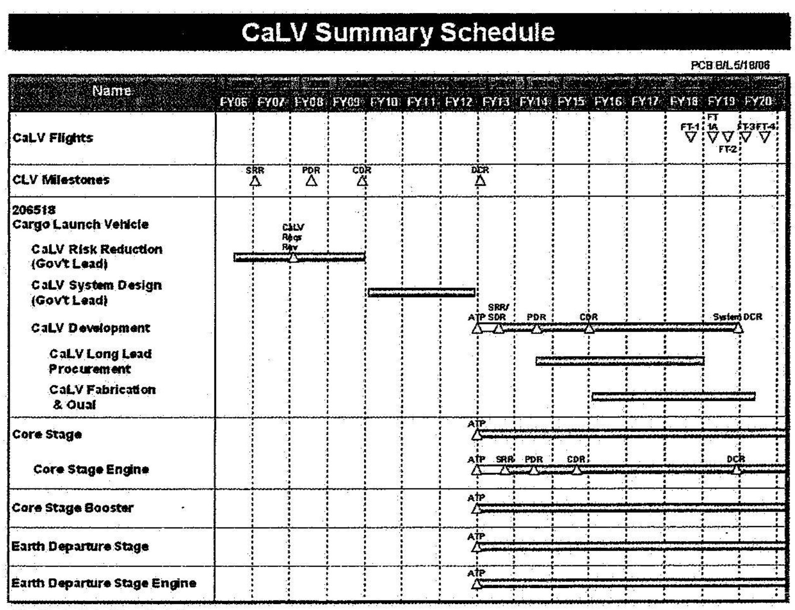
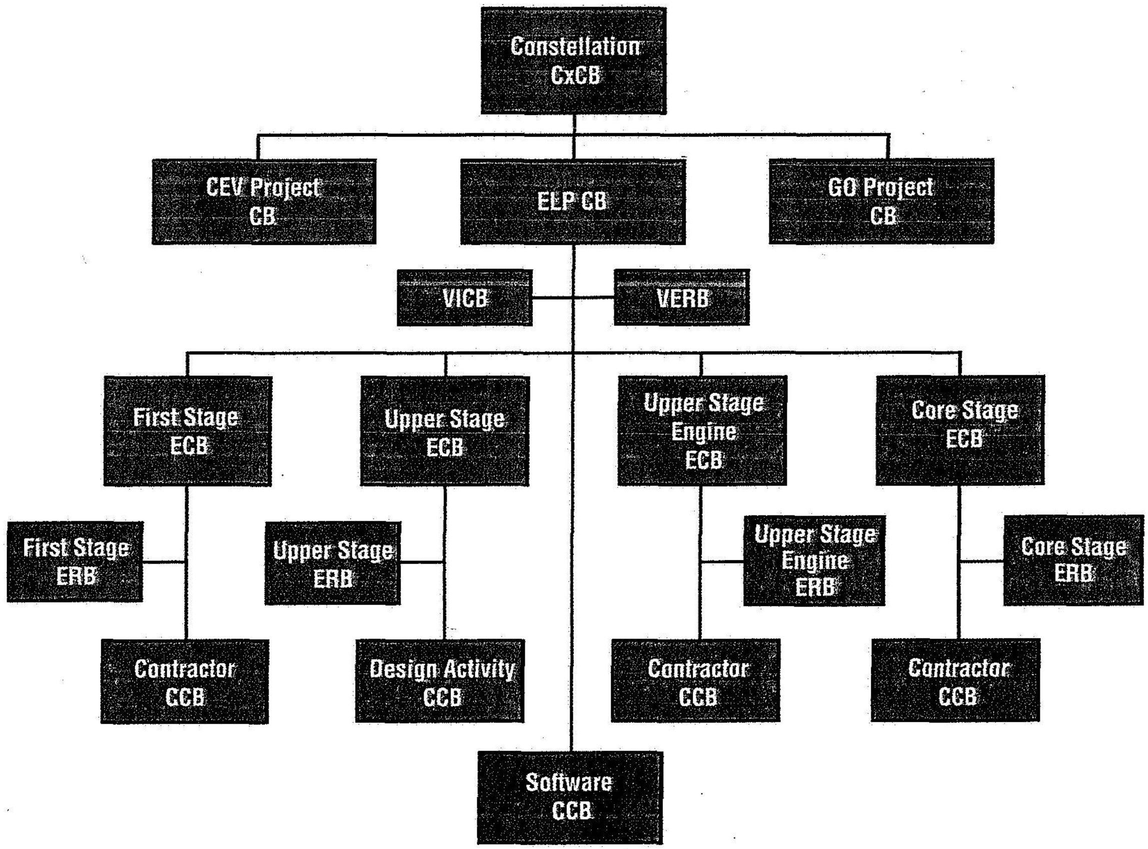


Figure 9. Preliminary Cargo Launch Vehicle integrated master schedule.

Within the systems engineering function, Integrated Product Teams report through a board structure to the Project- and Program-level Control Boards (CB) (Fig. 10). This hierarchy is documented in the Exploration Launch Projects Systems Engineering Management Plan (SEMP).[16] 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 reporting 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.[17]



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

Figure 10. Configuration control is achieved 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 progress against established funding guidelines and schedule milestones.[17] Non-advocate reviews survey technical and programmatic documentation and provide forums for interactive discussions relative to project progress. The series of reviews is listed in Table 1 below.

Table 1. NASA project internal technical reviews.

Review Title	Review Purpose/Outcome
System Requirements Review	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	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	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	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	After the system has been configured for launch, the Flight Readiness Review (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.

IV. Conclusion: The Journey Continues

NASA is accountable for delivering on the strategic goals set forth in the Vision for Space Exploration; therefore, it is investing its near-term resources in returning astronauts to the Moon as the logical first step toward the eventual human exploration of Mars — both events that will affect the future for generations to come. NASA's Exploration Launch Projects office is addressing the magnitude of work needed to deliver improved transportation systems tailored to empower a new age of space exploration.

NASA is committed to applying rigorous systems engineering and systems management processes and standards to ensure that technical performance is accurately reflected in, and inextricably connected to, budget allocations and schedule milestones. By building on a foundation of heritage hardware and applying lessons learned from past and current missions, the probability of success is greatly increased.

On the Moon, astronauts will gain the experience needed to travel to other worlds and learn to work productively while relatively close to home. These lunar missions will serve as test-beds for technologies and management practices that will enable the eventual first human trips to Mars, Earth's closest planetary neighbor. While robotic spacecraft and rovers provide mapping data, scout potential landing sites, and locate *in situ* resources that can be utilized by the first Moon settlers and the first explorers on Mars, NASA and its partners are engaged in the task of designing, developing, testing, fielding, and operating the space transportation systems that will carry those for whom the journey of discovery has begun anew.

Mission success demands a disciplined, innovative approach to developing CLV and CaLV systems that deliver greater safety and reliability, along with marked reductions in operations costs. Building on a foundation of heritage knowledge is a prime risk reduction strategy being applied by NASA's Exploration Launch Projects office, which is dedicated to delivering sustainable transportation solutions that result in more cost-effective access to space.

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