NASA Ares I Crew Launch Vehicle Upper Stage Configuration Selection Process

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Abstract

The Upper Stage Element of NASA's Ares I Crew Launch Vehicle (CLV) is a "clean-sheet" approach that is being designed and developed in-house, with Element management at MSFC. The USE concept is a self-supporting cylindrical structure, approximately 115' long and 216" in diameter. While the Reusable Solid Rocket Booster (RSRB) design has changed since the CLV inception, the Upper Stage Element design has remained essentially a clean-sheet approach. Although a clean-sheet upper stage design inherently carries more risk than a modified design, it does offer many advantages: a design for increased reliability; built-in extensibility to allow for commonality/growth without major redesign; and incorporation of state-of-the-art materials, hardware, and design, fabrication, and test techniques and processes to facilitate a potentially better, more reliable system.

Introduction

NASA's Crew Launch Vehicle (CLV), recently named "Ares I," is an integral part of the Constellation Program's transportation system. Exploration missions will include launch systems required to place crew and cargo in low-Earth orbit (LEO), crew and cargo transportation systems required for human space travel, and transportation systems and scientific equipment required for human exploration of the Moon and Mars. Early Ares I configurations will support International Space Station (ISS) re-supply missions.

- **Ares I**
  - **Single 5 segment RSRB/M 1st stage**
  - **Upper Stage**
    - **Powered by a single engine derived from the Saturn J-2**
- **Ares V**
  - **Twin 5 segment RSRB/M 1st stage**
  - **Core stage derived from the External Tank**
  - **Powered by 5 low cost RS-68s**
  - **Ares I-derived avionics**
- **Earth Departure Stage**
  - **Upper Stage derived from the External Tank**
    - **Powered by a single J-2 Upper Stage Engine - 2 burn capability**
  - **Ares I - derived main propulsion systems and avionics**

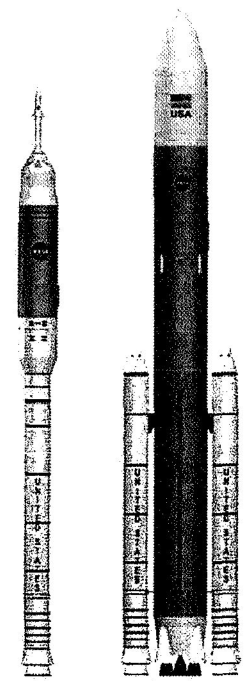

Figure 1. Ares I and V Vehicles

NASA will lead a substantial in-house effort to develop the requirements, design, and testing required to deliver the integrated Upper Stage elements to the Kennedy Space Center (KSC). The Ares I Upper Stage will be designed by NASA and fabricated by an industry partner selected via a competitive procurement planned for release early next year. The final integrated Upper Stage will be the product of numerous partnerships among industry participants and NASA for the delivery and operation of the integrated Upper Stage. Throughout the life of the Upper Stage Element, NASA will maintain data rights for the design and the resulting Upper Stage hardware.

The Exploration Systems Architecture Study (ESAS) originally recommended a CEV to be launched atop a four-segment Space Shuttle Main Engine (SSME) CLV, utilizing an RS-25 engine-powered upper stage. However, Agency decisions to utilize fewer CLV development steps to lunar missions, reduce the overall risk for the lunar program, and provide a more balanced engine production rate requirement prompted engineers to switch to a five-segment design with a single Saturn-derived J-2X engine. This approach provides for single upper stage engine development for the CLV and an Earth Departure Stage, single Reusable Solid Rocket Booster (RSRB) development for the CLV and a Cargo Launch Vehicle, and single core SSME development.

The Upper Stage Element, including the Upper Stage Engine (USE), will provide the navigation, guidance, control, and propulsive impulse required for the second phase of the Ares I ascent flight after the First Stage separates from the launch vehicle. This includes the Main Propulsion System (MPS) with active Thrust Vector Control (TVC), reaction control impulse for attitude roll and pitch control, and the separation systems required to perform First Stage separation. The self-supporting cylindrical structure measures approximately 115' long and 216" in diameter.

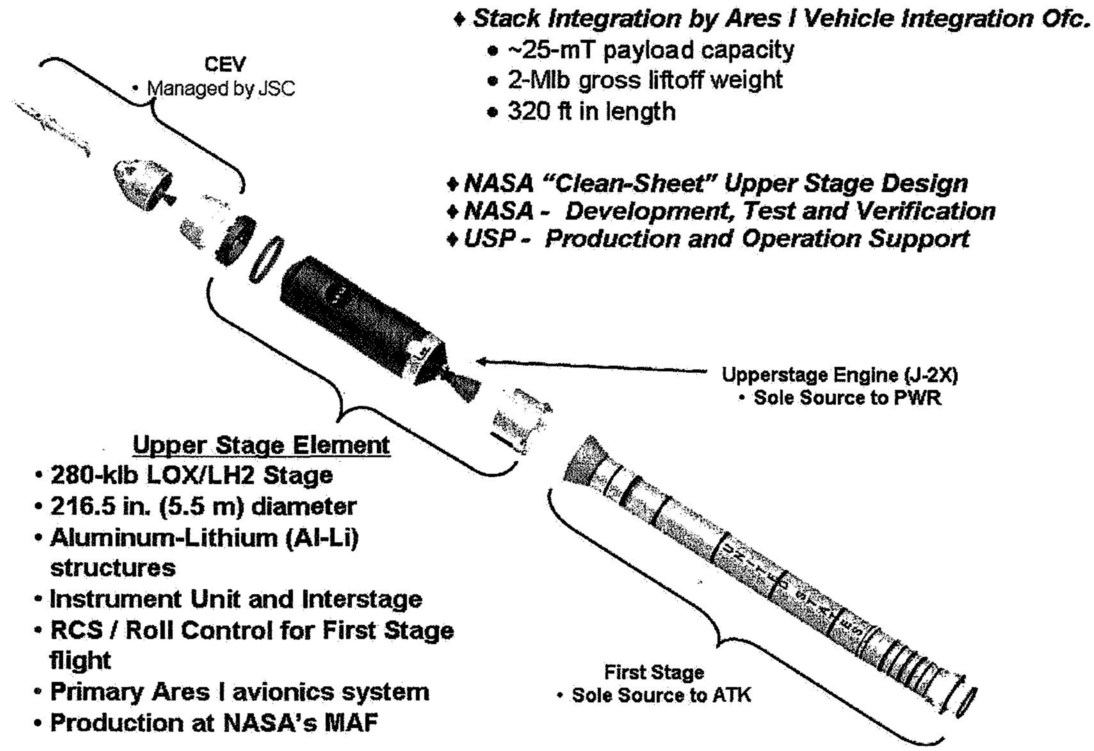

Figure 2. Upper Stage Overview

As illustrated in Figure 3, the baseline Design Reference Mission calls for the Upper Stage to provide active thrust via the USE for approximately 463 seconds after First Stage burnout and separation. Shortly after USE cut-off, the CEV separates from the Upper Stage and ignites for insertion into LEO. The Upper Stage is dormant after safe shut-down of the USE and re-enters for disposal in the Indian Ocean. The two Design Reference Mission trajectories envisioned for the Ares I launch vehicle are a 28.5° flight profile to support Lunar missions and a 51.6° flight profile to support ISS missions.

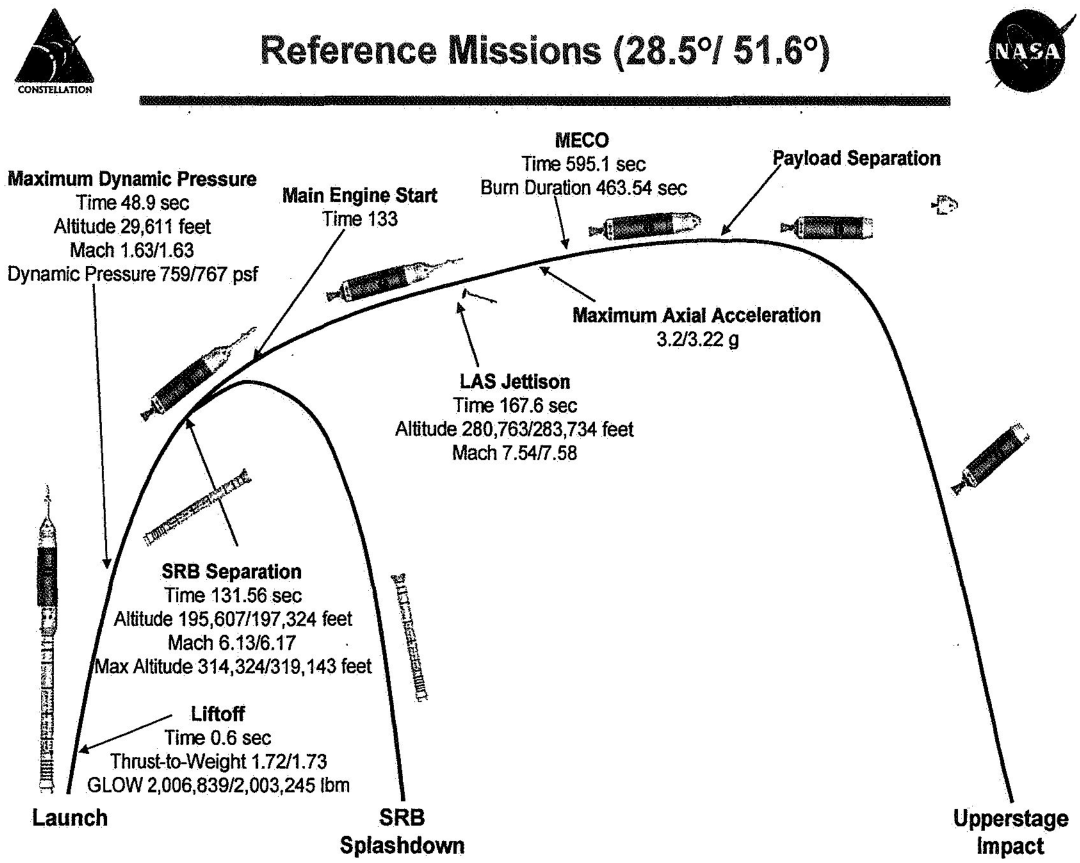

Figure 3. Reference Missions

Upper Stage Element Functional Overview

The Upper Stage Core, as illustrated in Figure 4, consists of the following primary elements and their respective subsystems: Forward Skirt, Liquid Hydrogen (LH2) Tank, Intertank, Liquid Oxygen (LOX) Tank, Aft Skirt, Thrust Structure, Main Propulsion System (MPS), Thrust Vector Control, Systems Tunnel, Purge and Vent System, and associated separation systems.

1. Instrument Unit
2. Forward Skirt
3. Liquid Hydrogen Tank
4. Intertank
5. Liquid Oxygen Tank
6. Thrust Structure / Aft Skirt
7. Interstage
8. System Tunnel
9. Upper Stage Engine
10. Hydrogen Vent System
11. Pressurization System
12. Oxygen Vent System
13. Liquid Hydrogen Fluid Systems
14. Liquid Oxygen Fluid Systems
15. Upper Stage RCS
16. First Stage RCS
17. Thrust Vector Control
18. Liquid Hydrogen Feedline Fairing

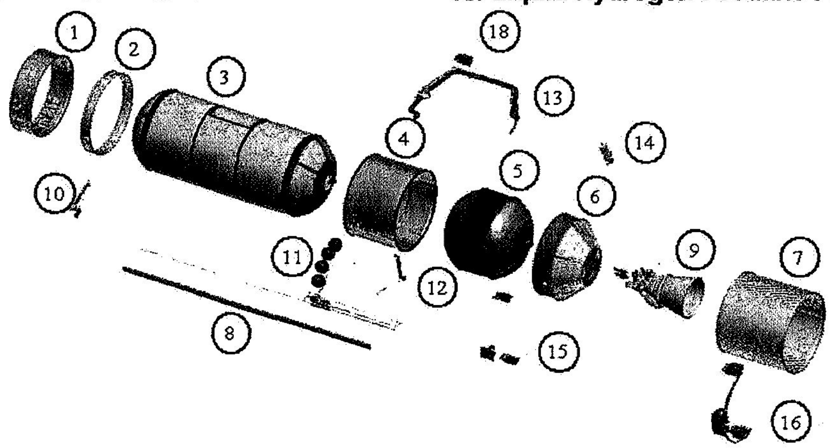

Figure 4. Upper Stage Core Primary Elements

The Upper Stage configuration and performance is based on the top-level driving requirements developed in the Upper Stage Element Requirements Document (ERD). The following paragraphs provide an overview of the current design based on the results of the Upper Stage Design Analysis Cycle 1-A.

The integrated Upper Stage Element extends from the First Stage frustum to the CEV spacecraft. The Instrument Unit (IU) will provide the structural interface between the Core Stage and the CEV spacecraft adapter assembly. It will house the majority of the avionics and provides the mechanical and electrical interfaces between the Ares I and the CEV.

The Forward Skirt provides the structural load path between the IU and the LH2 tank and will provide an interface for the LH2 vent line and ground-based purge umbilical connections.

The LH2 tank provides the insulated storage for the J-2X engine's fuel and is located between the Forward Skirt and the Intertank. It is approximately 410" in length and is fabricated from 2195 Aluminum-Lithium (Al-Li) alloy. The current tank design is sized to provide 10,710 cubic feet of total volume.

The LOX tank provides the insulated storage for the J-2X engine's oxidizer and is located aft of the Intertank. The tank, also fabricated from 2195 Al-Li alloy, is approximately 66 inches in length and will provide 3,566 cubic feet of total volume.

The Intertank serves as the link between the LH2 and LOX tanks. It is approximately 155 inches in length, is fabricated from 2195 Al-Li alloy, and will provide the umbilical carrier plate for the electrical and fluid interfaces.

The Thrust Structure that includes the Aft Skirt and the Thrust Cone assembly provides the interface between the Core Stage and the Interstage. The J-2X engine will be mounted to the cross-beam assembly located at the bottom of the Thrust Cone. The Thrust Vector Control (TVC) actuators will be mounted outside of the Thrust Cone.

A Systems Tunnel will be mounted on the side of the Core Stage, extending from the Forward Skirt to the Aft Skirt, and will provide a protective enclosure for the vehicle systems and cabling routed externally to the Core Stage tanks.

The Interstage will provide the primary interface between the First Stage and the Upper Stage. It contains the separation systems to separate the First Stage from the Upper Stage and will house the roll control systems for both elements. Additionally, the Interstage will provide the structure to mount the booster deceleration motors required to decelerate the First Stage at the conclusion of its active burn.

The Main Propulsion System (MPS) for the Upper Stage Element is comprised of the LOX, LH2, and the Pressurization and Pneumatic subsystems. The Oxygen and Hydrogen subsystems encompass all functions required to fill and drain their respective systems and to feed thermally conditioned propellants to the J-2X engine.

The Pressurization and Pneumatic subsystems provide the necessary functions to pressurize/vent the propellant tanks, store gaseous helium, control the MPS valves and to purge the MPS and J-2X engine.

The First Stage Roll Control system will provide one (1) degree-of-freedom (DOF) active roll control for the First Stage active mission phase. The system, mounted on the Interstage, will be a distributed pressure regulated hypergolic bi-propellant system. It contains two (2) RCS modules located 180° apart. Each system will contain sixteen (16) 800 lbf thrusters.

The Upper Stage Reaction Control System (RCS) will provide three (3) DOF active control during the active mission phase for the Upper Stage. The system, a distributed pressure regulated mono-propellant hydrazine system, will contain two (2) RCS thruster modules located 180 degrees apart on the Interstage. Each module will contain six (6) 100 lbf thrusters.

The Thrust Vector Control (TVC) for the Upper Stage contains two (2) actuators (pitch / yaw) that will provide the force and control to gimbal the J-2X for TVC and vehicle steering.

The Upper Stage Element will provide the avionics and supporting hardware and software necessary to control the Ares I during all phases of ground processing and flight. As stated earlier, the IU will be the primary location for the avionics systems; however, some hardware will be located at other key areas.

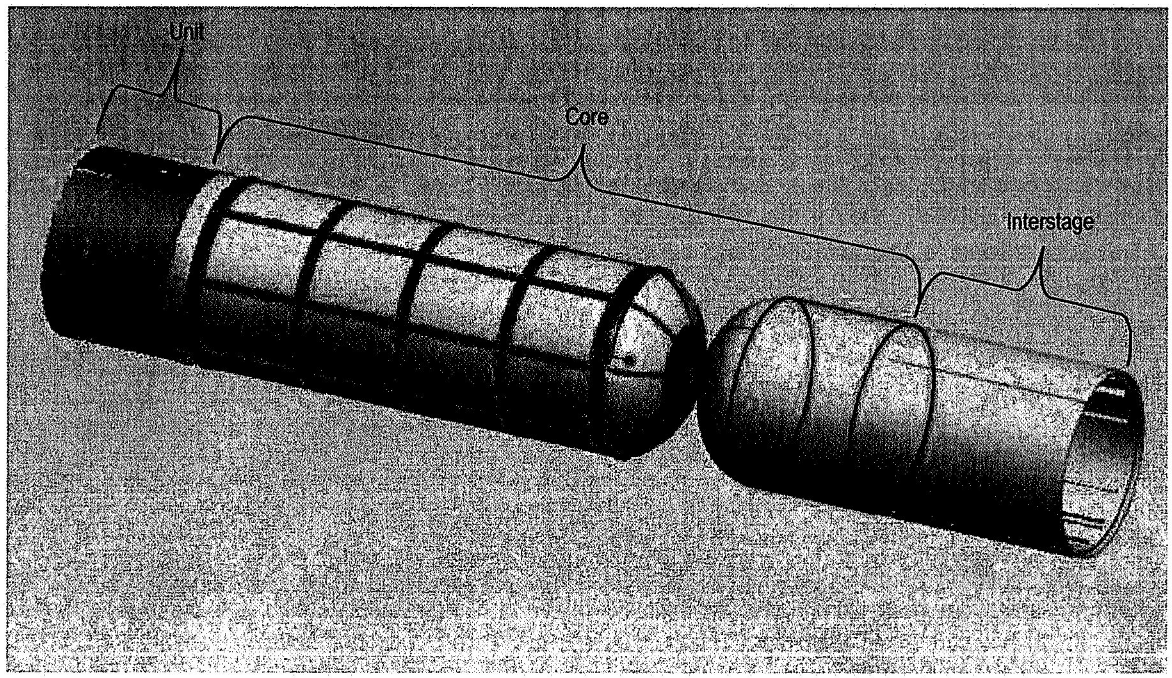

Figure 5. CLV Upper Stage (Intertank not shown)

Clean-Sheet Design

As mentioned in the Introduction section of this paper, the Exploration Systems Architecture Study (ESAS), completed in July 2005, recommended that the Agency launch the CEV utilizing a two-stage launch vehicle. The first stage would consist of a four-segment Space Shuttle Solid Rocket Booster and a clean-sheet design for an Upper Stage that utilized a modified Space Shuttle Engine (SSME)

Since the release of the ESAS report, the Agency has decided to proceed with a new Ares I configuration that will reduce the development steps and overall risk, and provide a balanced engine production rate requirement, thus prompting engineers to switch to a five-segment solid rocket motor design for the first stage and an upper stage powered by a single Saturn-era derived J-2X engine.

The "clean-sheet" Upper Stage design approach inherently carries more risk than modifying an existing proven design or qualified hardware. New systems, especially those that require human-rating, require extensive Design, Development, Test, and

Evaluation (DDT&E) prior to flight certification. Additionally, the existence of qualified hardware and vendors to produce human-rated hardware is limited. Most current flight hardware being produced today supports non-human-rated, expendable launch systems. While designs for human-rated components and subsystems exist, they primarily represent designs for reusable Shuttle systems and are not necessarily applicable for a clean-sheet expendable system. Many of the original hardware vendors utilized during the early development of the Space Shuttle have been displaced or retired, the designs and fabrication rights have been bought and sold, and the design drawings are not, in all cases, currently up-to-date. Reconstitution of the vendor base for the production of a new human-rated system is required.

While a clean-sheet approach will take longer to design, develop, and implement than modification of an existing system, this approach also has many advantages. Starting from a clean-sheet and developing a design around the primary requirements for the ISS and Lunar missions, the Upper Stage Element can be designed for increased supportability to help meet the goal of reducing the logistics footprint, and increased reliability, as would be necessary to meet human-rating requirements imposed by NASA standards. The extensibility of the Upper Stage to the Earth Departure Stage (EDS) is a prime risk mitigation strategy in the area of structures and interfaces. State-of-the-art materials, hardware, design, fabrication processes, test techniques, and integrated logistics planning are incorporated, facilitating a supportable, reliable, and operable system.

Development Approach

Unlike similar programs, NASA will lead the DDT&E for the CLV Ares I Upper Stage Element, and will be responsible for development of the Upper Stage Systems Requirements, the CLV external and internal Interface Requirements Documents, the Component End Item Specifications, and the definition of the CLV Avionics and Software Architectures. The NASA team includes participation from the following field centers:

- Marshall Space Flight Center – Lead – Overall management and design responsibility of the Upper Stage.
- MSFC Michoud Assembly Facility (MAF) – Facility services and planning support to Logistics and Manufacturing & Assembly Integrated Product Teams (IPTs).
- Glenn Research Center – Electrical Power Systems – component development support to Avionics & Software IPT; Developmental Flight Instrumentation – component development support to Avionics & Software IPT; Thrust Vector Control (TVC) – Subsystem development responsibility; and Hazardous Gas Detection – Component development support to the Structures & Thermal IPT.
- Kennedy Space Center – Ground Umbilicals development – component development support to the Upper Stage Design Integration Working Group (DIWG); and Development of propellant systems at the Main Propulsion Test Article (MPTA) test site.

- Langley Research Center – Structural design support to Structures & Thermal IPT (focus on composite design); and Manufacturing support for forgings.
- Stennis Space Center – Test planning and support per Rocket Propulsion Test Board directives – support to Integrated Test IPT.
- Johnson Space Center – Test support at the White Sands Test Facility.
- Ames Research Center – Health Management Analysis - supplemental support to the Avionics & Software IPT.

NASA will manage the Upper Stage MPS, RCS, and TVC advanced component development programs, including the potential for early procurement of long lead critical hardware for advanced development as required to support the design.

NASA will solicit for an Upper Stage Production (USP) contractor to provide fabrication, assembly, checkout, and delivery of the completed integrated Upper Stage(s). The Upper Stage Office will work closely with the USP contractor selected as soon as possible after contract award to facilitate an efficient integration and transition from a NASA-developed design to contractor production. This acquisition approach has been patterned after the successes of earlier NASA programs such as Apollo and Space Shuttle.

NASA also plans to solicit for an Upper Stage Avionics Production (AP) contractor to fabricate, assemble, and checkout the avionics hardware and systems into the Instrument Unit (IU). It is anticipated that a competitive USP Request for Proposal (RFP) will be released in early calendar year 2007 and a competitive Upper Stage AP RFP will be released in spring 2008.

All Upper Stage flight hardware will be manufactured and assembled at the Marshall Space Flight Center's Michoud Assembly Facility (MAF). This government-owned, contractor-operated facility houses the current Space Shuttle External Tank production team.

Requirements and Multiple Design Cycles

The Upper Stage development process begins with the definition of requirements and ends with flight systems certification. In addition to the classical design phases, the Upper Stage design efforts will comply with specific Design Analysis Cycles (DACs) established by the Constellation Program, whose intent is to establish and control interim milestones for defining design configurations and associated analysis baselines of the Constellation Program, including the Ares I and Upper Stage requirements and designs. A major benefit of the clean-sheet design is the Upper Stage Element's flexibility to adapt to changing requirements as the Element goes from its Systems Requirements Review (SRR) to Preliminary Design Review (PDR) to Critical Design Review (CDR), prior to initial development flight tests. Technical requirements and specifications for the systems, subsystems, and components will be developed during the initial "requirements phase," based on applicable Agency and Center requirements and the systems and performance requirements defined in the Program and Project requirements documents.

The requirements phase will be followed by the preliminary design phase, which will be completed with the PDRs for the Upper Stage system and each of the subsystems. Subsystem components will be fabricated and procured during this phase to support the development phase design and test activities.

Upon completion of the PDRs, the Element will enter the final flight design phase, culminating with the CDRs, at which point the Upper Stage flight configuration design will be baselined. After completion of the CDRs, flight configuration hardware fabrication to support component-level design qualification testing, systems-level design qualification, and flight systems fabrication and assembly will begin. All flight configuration hardware, including all qualification hardware, will be fabricated to released drawings.

Trade Studies Conducted

Several major Element-level trade studies have been conducted thus far related to the Ares I Upper Stage, with additional studies underway as the design team enters the next Design Analysis Cycle (DAC). The following paragraphs will provide a brief description of the trades listed below and their respective results.

- Upper Stage Intertank Bulkhead Design,
- Reaction Control System (RCS) Design,
- Acceptance Testing of Upper Stage Engines (Green Run), and
- Thrust Vector Control (TVC) Design.

Upper Stage Intertank Bulkhead Design

The baseline Upper Stage Point-of-Departure configuration consists of convex LH2 and LOX tanks separated by an Intertank section. In an effort to reduce the overall mass and length of the Upper Stage, it may be advantageous to have either a common bulkhead or nested tank bulkhead between the LH2 and LOX tanks.

The objective of this trade study was to identify and evaluate representative design options for separate, common, and nested tanks to potentially reduce the overall length and mass of the Upper Stage, and evaluate the impacts and feasibility of the various options. A comparative analysis of these options was performed, and a recommendation was made based on manufacturability, supportability, accessibility, verification, performance, length mass, risks, cost, and schedule to help determine preferred, or preferable, design configurations.

To perform this trade study, NASA engineers: (1) obtained all pertinent data and information available on the current Point-of-Departure for the Upper Stage; (2) identified an initial set of tank bulkhead design options and performed a preliminary assessment to drive out a representative set of potential options; (3) further defined the details of the selected set of options and identified and quantified the pros and cons, impacts, and major issues related to each; (4) performed a preliminary assessment of the options from structures, thermal, manufacturing, verification, test, supportability, performance, size, mass, risk, and cost perspectives; (5) defined the Figures-of-Merit (FOMs) and weighting for each; (6) ran the analysis and identified preferred options; and (7) prepared final products.

Design Options

Nineteen (19) trade study options were originally considered for analysis. The options were categorized by Common, Separate, and Nested dome configurations. During the study, the options were reduced to the three major configuration options referenced above and detailed analysis was performed on each option. Pros and cons defined for each design option were collected and guided trade members in their assessments and analysis.

This study concluded that the Point-of-Departure Separate Tanks design is the preferred option, considering all FOMs. The Nested Tank is still a viable option considering risks versus benefits if length and weight reduction becomes critical. A Common Bulkhead design had little performance advantage over Nested Tanks, and, in fact, rated the worst with the lowest safety/reliability assessment, greatest risk of cost and schedule impacts, and highest development cost.

Reaction Control System (RCS) Design

This study provided FOM comparisons between modular and distributed liquid hypergolic Roll Control and RCS systems using components that will require minimal testing to achieve human-rated qualification.

This study concluded that (1) a distributed mono-propellant hydrazine architecture for the RCS is baselined and supported by all FOMs; (2) a distributed bi-propellant architecture for First Stage Roll RCS is baselined primarily due to perceived technical risk associated with large First Stage roll class mono-propellant hydrazine thrusters (low heritage); (3) the FOMs favor a distributed mono-propellant hydrazine architecture; and (4) the RCS DAC 1-B will continue the trade study and further evaluate mono-propellant versus bi-propellant distributed architectures for First Stage Roll Control.

Acceptance Testing of Upper Stage Engines (Green Run)

The initial version of the CLV Concept of Operations document required that each flight upper stage be hot-fire acceptance tested (green run) with its Upper Stage Engine (USE) before each launch. The outcome of this trade study decision impacts the CLV logistics, costs, and test requirements. Green Run is an acceptance test only that verifies manufacturing and assembly of flight hardware and software on a production basis only. The study assumes all development and design qualification tests have been completed.

Eight trade study alternatives were initially identified, consisting of the following four basic options: (A) Hot-Fire (Green Run) Test every Upper Stage; (B) Hot-Fire (Green Run) Test the first TBD Upper Stages; (C) Only perform "cold" Testing of all Upper Stages; and (D) No special acceptance testing.

From the eight original options, the following options were selected for final analysis:

- A-1: Hot-Fire (Green Run) Test every Upper Stage with its flight engine until experience dictates otherwise.
- A-2: Hot-Fire (Green Run) Test every Upper Stage with a slave engine until experience dictates otherwise.
- C-2: Perform Cold (Wet Flight Readiness Test) Testing Only of Upper Stages at Pad (No flowing).
- D-1: No Green Run. Rely on standard manufacturing inspections, Non-Destructive Inspection, Proof Pressure Tests, etc.

Determining factors were FOMs, weighting, and decision-making processes. This trade study team also reviewed the history of past programs related to green run testing (Saturn, Shuttle, and Expendable Launch Vehicles).

This study concluded that Option A-1 was the overall winner, with the Mission Success deemed the most important FOM considered. However, the trade study team recommended that this position be re-evaluated after a minimum of five flights.

Thrust Vector Control (TVC) Design

The Thrust Vector Control (TVC) Design Trade Study was a NASA-led, multi-center trade study to identify and evaluate alternative design options for the Upper Stage TVC systems in order to support selection of an architecture for the TVC system, including actuators, power avionics, structure, propulsion, ground processing, schedule, and costs. The Multi-Center Trade Study Review Board considered contractor data as related to trends, but relied on the NASA team for numerical results. Three major trade study objectives were to (1) define the "Best Solution" for Ares I Upper Stage TVC, (2) provide information to the Ares I TVC Baseline Study Team, and (3) identify opportunities for technology development.

The Trade Study Team recommended the following three actuator system configurations, which were compared using Mass, Volume, Ground Safety, Operations Costs, and Production Costs:

- (A) Electric Actuator System Configuration (270 v Lithium Ion Battery EMA System),
- (B) Hydraulic Actuator System Configuration (PTO/270 VDC Battery Backup), and
- (C) Hydraulic Actuator System Configuration (PTO/56 VDC Battery Backup).

While the Trade Study Review Board perceived that all of the above architectures are viable alternatives, it voted to rank the architectures as follows: B, C, and A. The final discriminating factors for the Board were technical/performance, cost, and schedule risk.

Conclusion

By designing, developing, and implementing the CLV Ares I Upper Stage and identifying and mitigating risks to safety, reliability, and costs, the Upper Stage Element is enabling NASA exploration missions by providing high quality engineering and management support to the development of the exploration transportation systems. Through a thorough configuration selection process, an evolutionary approach of multiple design cycles, rigorous trade studies, and the flexibility to adapt to changing requirements through programmatic reviews, the Upper Stage Element is an integral part of the Crew Launch Vehicle (CLV) Ares I as NASA implements the President's Vision for Space Exploration.