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Human-Rated Delta IV Heavy Study
Constellation Architecture Impacts

1 June 2009

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Prepared for:

NASA Headquarters
Exploration Systems Mission Directorate
Washington, DC 20546-0001

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Executive Summary

This study assesses the technical, cost, and schedule feasibility of replacing the Ares I with a human-rated evolved expendable launch vehicle (HR EELV), and its first-order effects on the overall Constellation architecture. The study consists of several objectives:

1. Examine if an EELV, specifically the Delta IV Heavy (Delta IV H), could serve the crew-launch function, and if so, determine the impacts to the launch vehicle, production, and launch-base processing and fabrication.
2. Assess the effects on the Constellation architecture elements of replacing Ares I with a human-rated version of Delta IV H (HR Delta IV H).
3. Estimate the costs and timeline of replacing Ares I with an HR Delta IV H. Estimate the impacts to Ares V cost and development time and other Constellation elements to the extent possible.
4. Identify the impacts on national security space (NSS) if NASA utilizes an HR Delta IV H for low Earth orbit (LEO) human missions.

History

The Aerospace Corporation (Aerospace) was asked by NASA to assess human-rating an EELV in 2005, 2008, and 2009. The 2005 Aerospace study looked at the technical feasibility and cost of human-rating an EELV. The second (2008) and third (2009) studies addressed refinements of the technical feasibility, and focused on the implications of replacing the Ares I launch system with a human-rated version of Delta IV H in the Ares I/Ares V architecture.

In 2005, NASA performed the Exploration Systems Architecture Study (ESAS), which examined, among other things, human-launch options in two broad categories: human-rated, shuttle-derived vehicles and human-rated, EELV-derived (Delta IV H, Atlas V) vehicles. Both systems would require a new human-rated second stage and crew exploration vehicle (CEV) to safely deliver crew. At that time, Aerospace was asked to examine EELV reliability and safety drivers (and potential improvements), lift and abort performance, failure environments, vehicle health monitoring/management, and human-rating requirements. This information was used to assess potential costs associated with modifications to EELV for human-rating, including hardware and software changes to improve safety and reliability; support crew interaction with launch vehicle systems, facilities improvements, and system flight tests; and enhanced quality assurance and process control during fabrication. The study concluded that EELV was “human-ratable.” However, the cost was found to be highly dependent on program requirements, specifically interpretation of and compliance with NASA’s human-rating requirements document, NPR 8705.2A.

In 2008, NASA again asked Aerospace to examine EELV to assess the affordability of replacing Ares I with an HR EELV as a means of human spaceflight to the International Space Station (ISS) target. The motivation was to re-examine EELV in light of Air Force investments that had made reliability and performance improvements to EELV since 2005, and the successful EELV launch record to date. In addition, the agency’s human-rating requirements changed from dual-fault to single-fault tolerance between 2005 and 2008, as codified in NPR 8705.2B, changing the Ares I technical baseline established by the ESAS. Delta IV H was the focus of this study since it had flown two operational missions with eight planned launches before the first projected operational flight of Ares I in the third quarter, FY 2014. Findings of the 2008 HR EELV study were that the HR Delta IV H can meet ISS and lunar target performance requirements, and that Ares I and HR EELV architecture options were roughly equivalent from an affordability standpoint when uncertainties in the cost estimates were considered.

In early 2009, Aerospace was asked to refine and update the analysis with assessments of HR Delta IV H production and ground-processing infrastructure; payload performance to ISS and lunar target orbits with Orion abort constraints; hardware changes to human-rate the Delta IV H booster and second-stage engine; and updated cost and schedule estimates. Additionally, Aerospace was asked to develop a plan for a more comprehensive and equitable comparison of implementing human-rating on Ares I and on a Delta IV H EELV.

Emphasis was placed on scenarios that preserved, to the extent possible, the existing infrastructure and workforce utilized for Ares I and needed for Ares V. The technical feasibility of human-rating the Delta IV H EELV was assessed, with an appraisal of the Delta IV H first- and second-stage engines and requirements on the first and second stages. Payload performance to the ISS and lunar target orbits was found to provide significant positive mass margin with respect to Orion requirements for most design options studied. HR EELV costs to provide human lift to LEO were estimated to be equal to or lower than Ares I costs. However, carrying costs would be incurred for capabilities needed for Ares V that are developed under Ares I but not required for HR Delta IV H EELV.

This report provides a summary of these assessments. It documents the results and findings of analyses to date, including a more recent examination of potential impacts to the Constellation program and NSS, should NASA decide to move to a HR EELV for the crew-launch function.

Scope and Limitations

The study examines the technical and programmatic feasibility of replacing the Ares I with a human-rated Delta IV H, and the associated impacts on the existing Constellation architecture. This study is not intended to revisit the current Constellation architecture or propose alternative heavy lift approaches. The study is also not intended to assess either the cost confidence of the Ares I development or the uncertainty and viability of the current Constellation program initial operational capability (IOC) date.

EELV consists of two launch vehicle families, the Atlas V and the Delta IV. This study limited its focus to the Delta IV H launch vehicle. The Delta IV family of launch vehicles includes a Delta IV H configuration that is in the weight class of the Ares I vehicle, and has flown two operational missions to date. An Atlas V Heavy configuration was also planned, but development on this configuration was halted at critical design review (CDR). The estimated performance of the Atlas V Heavy was roughly comparable to the performance of the Delta IV H. United Launch Alliance (ULA) has estimated that the Atlas V Heavy would require approximately 30 months from authority to proceed (ATP) to first flight. Due to the fact that the Atlas V Heavy doesn't presently exist, and since the vehicle performance is planned to be similar to Delta IV H, the decision was made to focus on the Delta IV H configuration.

Aerospace did not perform estimates of loss of mission (LOM) and loss of crew (LOC) probabilities for the HR Delta IV H options studied. Estimates of safety made prior to or outside of this study, for example during the ESAS timeframe, were not independently verified by Aerospace and likely do not apply. To allow an equitable comparison of HR Delta IV H to Ares I LOM/LOC, a new study of safety estimates informed by Delta IV H actual flight experience (using the current approach being applied to human-rating Ares I and based on specific HR Delta IV H vehicle modifications, margins, and potential failure modes) would be needed.

This study assumes a specific cargo launch vehicle (CaLV), namely Ares V, and specific crew launch vehicle (CLV), namely Ares I, in the current program of record.

Although this study by The Aerospace Corporation includes vendor-supplied data, the opinions and conclusions presented herein do not imply vendor concurrence with or endorsement of those opinions and conclusions.

Options Studied

Aerospace's recommended option utilizes a new second stage with four RL-10 derivative engines to meet human-rating requirements with the added benefit of "engine out" capability. Other viable options include an HR Delta IV H first stage with a J-2X-based second stage and a configuration with only one RL-10 derivative engine. The single-engine RL-10 second-stage option requires further analysis to identify the specific balance between thrust level, payload performance, and human-rated margins. Another feasible configuration does not require a second stage and relies instead on a fully loaded service module to achieve orbit. This option would perform the ISS mission only and defers development of the HR Delta IV H second stage until needed for lunar missions.

Key Findings

Technical Feasibility. It is technically feasible to human-rate the Delta IV H, following a human-rating design implementation approach equivalent to that used for Ares I. The addition of human-rating requirements results in changes to the Delta IV H hardware, software, fabrication, and processing flow, and most likely the development of a new, human-rated second stage. These changes address improvements in fault tolerance, structural factor of safety margins, trajectory shaping for full performance envelope abort, a delayed destruct abort separation sequence, and functional enhancements including the use of Ares I-derived avionics to support crew function and interfaces between Orion and the new second stage. Delta IV H first- and second-stage engines can be human-rated. For most HR Delta IV design options studied, the payload performance to the ISS and lunar target orbits provides significant positive margin with respect to Ares I ISS and lunar gross performance. HR Delta IV H can manage abort re-entry g-loading via constraints on ascent trajectory optimization in order to achieve abort capability over the full performance envelope. With regard to production capacity, the Decatur, Alabama facility can accommodate NSS and civil EELV missions plus Constellation through 2019, to support launches through 2020. Moreover, a significant fraction of the elements, workforce, and facilities existing or planned for Ares I can be used for HR Delta IV H.

Constellation Impacts. A top-level, qualitative review of the Orion modifications indicated that the technical impacts to Orion are manageable, since most impacts can be absorbed in development of the new HR Delta IV H second stage. The processing time for Ares I was found to be longer than for HR Delta IV H due to increased pre-launch processing and post-launch pad refurbish times associated with the use of the solid rocket motors (SRMs). The most effective launch processing infrastructure concept is at the Orbiter processing facility (OPF) at Space Launch Complex-39 (SLC-39) for first-stage processing, and launch from a modified SLC-39B complex. If the Ares I is replaced by the HR Delta IV H, SRM and J-2X engine development would need to be carried by the Ares V program. In order to determine the financial viability of the SRM industrial base in the absence of Ares I, there needs to be a joint civil and military assessment. Significant HR Delta IV H performance margins to

ISS and lunar target orbits may make delivery of additional mass to ISS or lunar rendezvous targets possible.

National Security Space Impacts. There are significant risks and opportunities inherent to NSS from a NASA HR Delta IV H program. The increased production rates from the human-rated launch program should have positive effects on ULA hardware cost and reliability, as well as the ULA vendor industrial base. This should result in improved support to the Department of Defense (DOD). However, the focused demands from a human-rated launch program could draw attention from critical NSS needs. The greatest risk comes from a proliferation of multiple and diverse requirements and conflicting U.S. Government demands, which may impact DOD (and potentially NASA) programs in terms of priorities or staff support. It is strongly recommended that any actions be cooperatively managed by all stakeholders via a formal risk and opportunity management program. Pad and range issues are a manageable risk. Range impacts from the implementation of HR Delta IV are not a unique risk. Though shared operations within the SLC-37 Complex could encounter operational, security, or safety conflicts, the implementation of the SLC-39 option mitigates this risk.

Cost Impacts. The design, development, test, and evaluation (DDT&E) and lifecycle costs (DDT&E plus 14 flights to ISS through 2020) for HR Delta IV H are equal to or lower than Ares I costs. There is no change in lifecycle cost for HR Delta IV H configurations that utilize the Ares I J-2X-based second stage. There is a $3B to $6B FY 2009 reduction in lifecycle cost for HR Delta IV H, depending on whether a new four-engine RL10-derivative second stage, a modified single-engine RL10-derivative second stage, or no second stage is used, with implications for performance as noted above. Total DDT&E cost of Ares V is estimated to increase by $1.1B to $3.5B FY 2009 depending on the HR Delta IV H configuration. These costs are for completion of elements that would have been developed under Ares I, including the solid rocket booster (SRB) DDT&E, the J-2X engine DDT&E, and the portion of SLC-39 processing infrastructure not used by HR Delta IV H. Carrying costs for design, production, and processing infrastructure and industrial base capabilities needed for Ares V but not required for HR Delta IV H have the potential to further increase cost. Sustaining the large, segmented SRM industrial base is the largest contributor to carrying costs. Carrying costs associated with delaying J-2X production may be offset by additional RL10 and RS-68 production for HR Delta IV H, but this requires further industry study. Cost impacts to Orion depend in large part on design maturity at the point in time the decision is made to switch to HR Delta IV H, and on the extent to which physical and functional interfaces, mission design, and environmental analyses need to be revisited. NASA estimates an additional increase of $14.1B to $16.6B FY 2009 in carrying costs and impacts to Orion. Aerospace has not independently verified these figures or the underlying assumptions.

Schedule Impacts. The nominal HR Delta IV H development time is estimated to be on the order of 5.5 to 7 years. There was no comparative or feasibility analysis performed for the Ares I planned IOC date. The impact to the Ares V overall schedule is expected to be minimal since the J-2X and SRM need-date is not driven by the 2015 ISS requirement but by the lunar mission requirement in the 2020 timeframe. The impact to the Orion schedule is also expected to be enveloped by an assumed design period following Ares I cancellation. Since the delay due to Orion impacts is less than the overall HR Delta IV H development, Orion would not be on the critical path.

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1. Introduction

1.1 Study Objectives

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1.3 Scope and Limitations

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2. Human-Rating Delta IV H

NASA's human-rating requirements document, NPR 8705.2B, establishes broad functional, safety, reliability, and mission-success requirements for a crewed launch vehicle. The requirements are flowed down to lower levels for allocation to individual vehicle subsystem elements, then into the hardware and software implementation approach. In order to assess what "human-rating" means for the Delta IV H, it is first important to understand what human-rating means for Ares I in terms of requirements interpretation, flow-down to lower levels, and implementation into the hardware and software.

2.1 Human-Rating Requirements Assessment Approach

Aerospace reviewed NASA documentation relating to human-rating the Ares I design implementation. The document review was supplemented by discussions with NASA subject matter experts in order to understand NASA's current approach to implementation of human-rating requirements on the Ares I vehicle. The design implementation for human-rating the Ares I first- and second-stage systems and interfaces to Orion was determined at a top level, along with the flow-down of the human-rating requirements to Ares I specifications at level 2 and 3. The Ares I approach to human-rating implementation was then applied to the existing Delta IV H to achieve an equivalent flow-down of the human-rating requirements for first- and second-stage systems and interfaces.

2.1.1 Approach to Human-Rating Ares I

Ares I is designed for a minimum of single-fault tolerance, with an abort initiated in response to a second critical fault. Zero-fault tolerance is allowable in some areas through design for minimum risk (DFMR) techniques. Items assessed as DFMR are generally structural and pressure-vessel components, which are designed for higher structural margins (typically 1.4 vs. 1.25 for expendable systems). In cases where DFMR is to be implemented, the component or subsystem will be approved via waiver to the single-fault-tolerance requirement.

Vehicle health monitoring, fault isolation, and response rely on monitoring effects rather than determining causes. Although there may be many potential causes of a failure that lead either to a failure response or an abort, there are generally a smaller number of critical hardware performance parameters that are monitored in determining vehicle health status and fault responses. Ares I makes minimal use of advanced integrated vehicle health management (IVHM) techniques and complex predictive algorithms. Instead, the focus is on IVHM simplicity to maintain direct traceability to fault isolation and abort responses, and to support comprehensive testing. This approach employs sensors that directly measure known phenomenology for fault detection and response, rather than using derived parameters that require on-board processing or modeling for fault detection. Where possible, Ares I will isolate faults after detection to recover functionality to the extent possible. Ares I design includes an abort capability over the full launch vehicle performance envelope, in response to a second critical fault.

Ares I LOC, loss of vehicle (LOV), and LOM requirements are approximately 10 times higher than previously achieved in crewed space flight systems. Estimates for LOC, LOV, and LOM are calculated based on known potential failure modes identified in the design of the vehicle through a comprehensive failure modes, effects, and criticality analysis (FMECA). The plan for Ares I is to meet these requirements for failure modes identified using only the FMECA process. Achieving these levels of safety, reliability, and mission success in a generic sense for all possible failures would require an unprecedented level of mission assurance rigor and sophistication in vehicle health monitoring, fault detection, and response processing. It should be noted that LOC, LOV, and LOM probabilistic calculations have not yet been performed, and thus it is not clear that the current approach to fault detection will meet requirements. If not, more sensor development, testing, and flight calibration may be needed than is currently planned for Ares I.

The same numerical requirement, 10^{-4} (1 in 10,000) or better against known phenomenology, is levied for both false-negative and false-positive fault detections. Traditionally, when abort options are available, the decision is biased toward false positives. False positives lead to aborts that have a high probability of success, whereas false negatives lead to more catastrophic outcomes. In the event that the LOC, LOV, and LOM requirements are not met for Ares I, consideration might be given to biasing toward false positives through the use of additional sensor data, which would minimize LOC at the expense of increased LOV and LOM.

2.1.2 Application of Ares I Human-Rating Philosophy to Delta IV H

Applying the Ares I human-rating approach to Delta IV H results in several changes to Delta IV H hardware, software, and processing flow:

Fault Tolerance. Delta IV H is generally single-fault tolerant; however, some effectors, actuators, and valves must be modified to meet the requirement for system-wide single-fault tolerance. Any exceptions must be defensible using an analytic approach similar to DFMR.

Structural Factor of Safety and Redundancy. The Delta IV H structural factor of safety must be at least 1.4 for all structural components of the first and second stages, including all pressure vessels. Modification through design changes or additional redundancy to some effectors, actuators, and valves is needed to improve reliability.

Abort Requirements. To address unique human-rating requirements, including initiation of an abort, the Delta IV H avionics architecture will require modification. There are two options for updating the Delta IV H avionics: the Delta IV H redundant inertial flight control assembly (RIFCA) can be replaced with the Ares I second-stage avionics, or the RIFCA can be upgraded to interface with Orion, first stage, and external interfaces. This trade includes an investigation of the commonality with Orion’s launch abort system (LAS), robustness of the avionics package, and degree of leveraging RIFCA boards, software, and/or algorithms. More analysis is required to ensure the feasibility of either option, and to identify the lowest cost and lowest risk path. In order to identify a vehicle configuration and determine its performance, the study baselined the use of the Ares I avionics system for the HR Delta IV H. Additional functional requirements such as manual override of autonomous systems and manual flight path control must be addressed, either through use of Ares I avionics or through design of new launch and ground elements.

Separation Sequence. The Delta IV H separation sequence must be modified to include delaying the destruct command until after crew and vehicle separation. In addition, launch site modifications, including a crew access tower and escape system, will be required.

Abort Entry. Delta IV H needs to manage re-entry g-loading (the deceleration experienced by the crew) via constraints on ascent trajectory optimization in order to achieve abort capability over the full performance envelope. The Delta IV H lift estimates must include the performance impact of trajectory shaping to meet the abort constraints.

When the modifications described above are implemented, the baseline Delta IV H becomes a human-rated version of the launch vehicle, HR Delta IV H. Mission-support requirements that enable successful execution of the mission must be addressed as part of the HR Delta IV H system development. This includes requirements for availability, maintainability, production, launch rates, and logistics support. This analysis must be performed for both HR Delta IV H and Ares I.

2.1.3 What's Needed for a Comprehensive and Equitable Comparison

A more comprehensive assessment of the Ares I requirements flow-down to the specification level is required to make the final determination of an equivalent human-rating design implementation approach for HR Delta IV H. This assessment requires deeper insight into the Ares I human-rating implementation, the current Delta IV H design, and fabrication process assurance and quality assurance. Specific functional, safety, or reliability shortfalls associated with human-rating Delta IV H will require review with respect to potential compensation at the system level through use of performance margin, actual flight history, and robust postflight characterization. An analysis of design equivalency would be useful in identifying in detail the key hardware, software, fabrication, and process improvements needed to human-rate Delta IV H. This detailed analysis will require increased insight into NASA analytical and test processes, coordination with ULA, and the following inputs:

- Detailed subsystem designs, including requirement compliance matrices
- Sensor and effector redundancies
- Sensor testing and calibration plans, including voting algorithms/logic and timing considerations
- Detailed FMECA/critical items list (CIL) analysis
- Structural margins and DFMR approach
- Identification and justification of any required deviations and waivers
- The Ares I Probabilistic Risk Analysis (PRA) methodology to be used as a basis for the PRA of the HR Delta IV H system
- Mission-support data: system availability, including weather, launch window, component reliabilities (mean time between failures, or MTBF), supportable production rates, etc.

In addition, a comparative assessment of crew survivability for liquid vs. solid stages should be performed in order to make better-informed decisions about crew safety and mission success for Ares I and HR Delta IV H. This assessment should consider the impact of fault propagation and warning time, abort initiation and LAS performance, and the effects of launch vehicle thrust durations on crew survivability.

2.2 Human-Rated Delta IV H Defined

A number of configurations were considered along a continuum between the existing Delta IV H and the planned Ares I. The goal was to examine configurations that represented the trade space from maximizing use of existing Delta IV H flight systems to minimizing changes to the Constellation architecture by utilizing subsystems in development for Ares I.

In keeping with this objective, it was decided to baseline the use of the Ares I avionics system for the HR Delta IV H. This design assumption was based on commonality with Orion interfaces, probable limitations of expanding the current RIFCA avionics system on the Delta IV H to meet HR and Orion requirements, and maximizing applicable investments by the Constellation program. It is assumed that some modifications would need to be made to the command and control functions to accommodate the particular sensors and controllable elements of the HR Delta IV H launch system.

As a further foundation to focus on options that were both feasible and cost-effective, the various first- and second-stage engine alternatives and implications for human-rating these engines are discussed below.

2.2.1 Approach to Human-Rating Engines

The Delta IV H launch vehicle uses three RS-68 liquid engines for booster propulsion, one at the base of each common booster core(s) (CBC) and a single RL10B-2 liquid engine at the base of the second stage. Both engine variants employ liquid hydrogen as the fuel and liquid oxygen as the oxidizer. At their current state of development, neither of these engines could be considered human-rated.

For a human-rated Delta IV H that is capable of performing an Ares I-equivalent mission, a variant of the current RS-68 is required. The only other alternative is to develop a new engine as a replacement, and that has been ruled out due to schedule and cost considerations. Several spiral development programs are ongoing and planned for the RS-68. DOD-funded Assured Access to Space is a program implementing design modifications intended to improve reliability for the engine. Similarly, RS-68A development is an active NSS-funded program intended to improve performance and increase the thrust of the RS-68 to 108 percent, resulting in increased lift capability to LEO and geosynchronous Earth orbit (GEO). RS-68B is a NASA-sponsored program, currently in the planning stages, whose primary intent is reducing prelaunch helium consumption and demonstrating extended firing duration for a six-engine cluster mounted at the base of the Ares V.

Given the synergy of the development schedule of the RS-68B for Ares V and the potential development of a human-rated Delta IV H, the lowest-cost option is to human-rate the RS-68B rather than the RS-68A. Further, this would provide a common engine for use on both the HR Delta IV H and Ares V. It should be noted that for the current Ares V design, a human-rated RS-68B is not required, since the Ares V vehicle is intended to deliver cargo. NASA has made a point, however, of requiring that Ares V elements be "human-ratable." Hence, human-rating the RS-68B would be feasible for an HR Delta IV H, and actually provides some schedule advantages. Both would cost nearly the same to qualify in the short term. However, over the years, it will likely be desirable to phase out the RS-68A in favor of the RS-68B given the higher production rate for Ares V and the extensive use of helium prior to flight. In this scenario, human-rated qualification of the RS-68B will be necessary at an additional cost. One disadvantage to human-rating the RS-68B for use on an HR Delta IV H is the need to alter the start date or compress the schedule of RS-68B development by approximately one year to put the CDR for the human-rated engine in FY 2015, and incorporate the required human-rating development activities into the program.

Human-rating the RS-68B adds requirements not necessary for a cargo-rated RS-68B. A representative list includes: 1) improving the reliability of the engine controller; 2) further evaluating and mitigating any structural margin issues that do not comply with "Strength and Life Assessment Requirements for Liquid Fueled Space Propulsion System Engines," NASA-STD-5012, 13 June 2006; 3) developing redundant actuators and valves, and installing triple-redundant sensors for more robust fault detection; 4) improving quality control to meet human-rating requirements; 5) implementing a cross-strapped pressurization system; and 6) additional qualification testing to demonstrate reliability.

For an HR Delta IV H that is capable of performing an Ares I-equivalent mission, several second-stage engines have the potential to be utilized. These engines include the current Delta IV second-stage engine RL10B-2, the Ares I and V second-stage engine J-2X, and the current Atlas V second-stage engine RL10A-4-2. Other engines that have not completed development, such as the RL60 which completed development through CDR, were considered as well. However, the significant additional cost to complete development, and the use of foreign designed and manufactured hardware, made these engines less favorable than the RL10 and J-2X.

The RL10B-2 and RL10A-4-2 have substantial component commonality, with the primary exceptions being the ignition system, chamber design, and nozzle extension. Given that the second-stage engine must meet human-rated reliability requirements, the RL10B-2 was eliminated from consideration based on its requirement to extend a large nozzle extension following stage separation using a single-string belt drive system. It may be possible to develop redundancy for this hardware, but such a system would likely be difficult and expensive to develop and also to verify that it meets reliability requirements under flight-like conditions.

Both RL10 variants currently do not meet the structural requirements outlined in NASA-STD-5012. It is possible that design modifications could achieve these requirements, but substantial modifications to the engine appear likely. One concept developed to achieve these requirements is to perform the first hot-fire at current thrust levels to cold work the engine components in question, followed by trimming the engine to a lower thrust level that would meet the standard. The drawback to this approach is the loss of available thrust to the second stage. In order to mitigate this problem, a cluster of four thrust-derated RL10s could be considered.

For simplicity, the derated RL10 thrust has been set to 16,800 pounds force (lbf), identical to the thrust level produced by the RL10A-3-3A used for an extensive period of time on Atlas and Titan missions. Ideally, the structural margin would be determined for the derated engine and the thrust altered slightly to meet NASA-STD-5012. However, this analysis was not performed given the schedule and modeling limitations for this study. Rough estimates indicate this thrust level will meet the requirement.

The RL10A-4-2 has a fixed nozzle extension (to improve performance) that can be clustered into a group of four engines and mounted on the base of the Delta IV H second stage. This design provides adequate clearance from the interstage, and can be mounted in the NASA Stennis A-3 test facility for main propulsion test article (MPTA) testing, if deemed necessary. A smaller-diameter nozzle extension can also be employed to improve fit margins, at the expense of engine performance, if for some unforeseen reason these margins degrade.

Based on Aerospace's assessments it appears that the A-3 test stand can be used to qualify and acceptance test both the variants of the RS-68 and all of the RL10 derivatives. This means that the high-altitude, near-vacuum test facility at Stennis Space Flight Center would be utilized for either the Ares I or HR Delta IV H options and, at the level of detail of this assessment, is not a discriminator between launch vehicle options.

Similar challenges with respect to the other engines considered exist for human-rating the RL10A-4-2, including the development and integration of upgraded electronics (e.g., igniter, wiring, health monitoring system, and redundant electromechanical or electropneumatic actuators). Reliability improvements are also deemed necessary for the idler bearing design, inlet valves, and cool-down valves. In addition, enhanced systems engineering/safety, reliability, quality assurance (SE/SRQA) and extensive engine qualification are needed.

Aside from the advantage of meeting NASA-STD-5012, the derated RL10 cluster design substantially reduces the in-flight engine burn time from 1150 to 450 seconds. This helps mitigate unforeseen part wear-out modes that might otherwise compromise mission success. Further, the design also permits for “engine out” capability in the event health monitoring indicates imminent engine failure. If desired, the thrust of the remaining engines could be increased to maintain stage thrust, or the opposing engine can be shut down to mitigate thrust vector asymmetry. It is important to note that this cluster design is not a novelty. The second stage of the Saturn I vehicle employed a six-engine RL10 cluster, with slightly less thrust per engine (~15,000 lbf).

The final contender for second-stage propulsion is the J-2X. This engine provides synergy with the existing Ares V program, which uses this engine for second-stage propulsion. Given that this engine is currently under development (funded by Ares I), and is planned to meet all human-rating and NASA standards, it trades well as an HR Delta IV H second-stage engine. However, development cost and schedule to qualify as human-rated will likely be substantially greater than the derated RL10 cluster.

2.2.2 Human-Rated Delta IV Heavy Configuration Options

Since the Delta IV H vehicle is not human-rated, it cannot presently be used for the Constellation program. Therefore, design changes must be made to the vehicle. These changes produce a number of options for an HR Delta IV H. The options are presented in Figure 1.

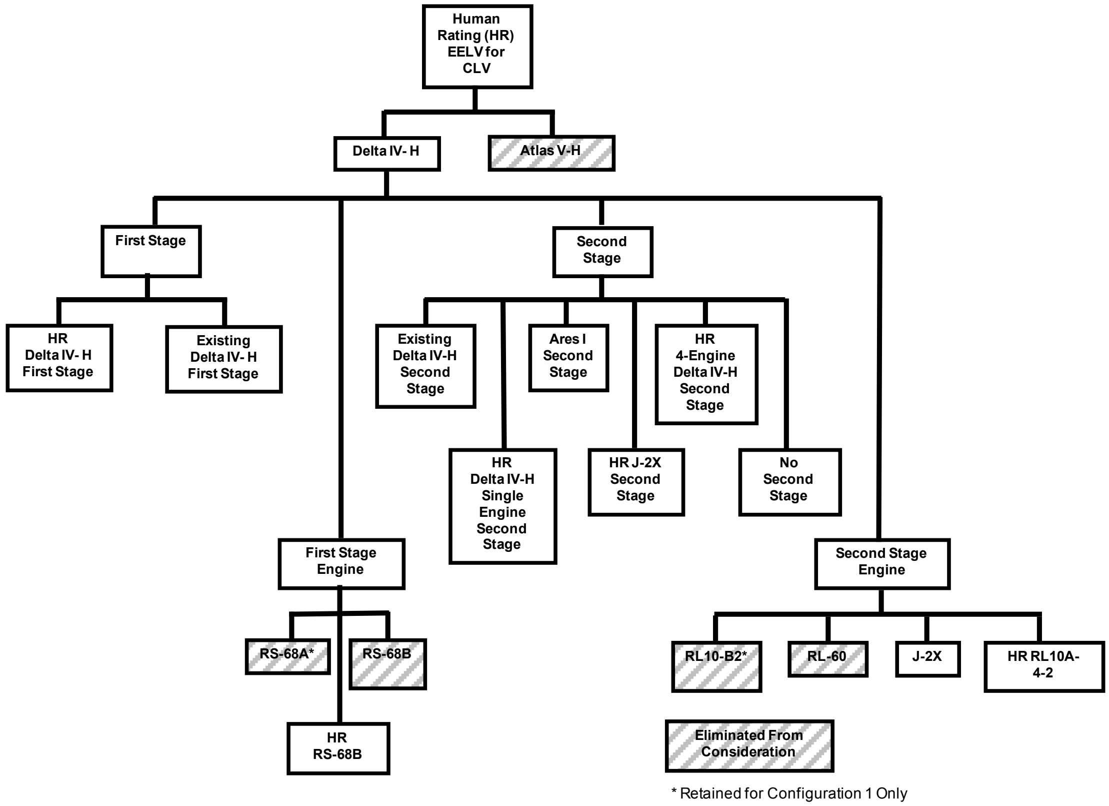

Figure 1. Human-rated Delta IV H option tree.

Based on the various stage and engine options presented in Figure 1, six Delta IV H configurations were evaluated. These six configurations are presented in Table 1.

Table 1. Delta IV H Options

Configuration No.	First Stage	First-Stage Engine	Second Stage	Second-Stage Engine	Engine-Out
1	Existing	RS-68A	Existing	1 RL10-B2	no
2	Human-rated	RS-68B HR	Ares I US	1 J-2X	no
3	Human-rated	RS-68B HR	Resized Ares I US	1 J-2X	no
4	Human-rated	RS-68B HR	New, human-rated	4 RL10-A-4-2	yes
5	Human-rated	RS-68B HR	No US	--	--
6	Human-rated	RS-68B HR	Existing	1 RL10-A-4-2	no

Configuration 1 represents the existing Delta IV H vehicle, which is not human-rated and cannot perform the Constellation mission. It is included in the option list as a reference point to an existing launch vehicle.

Configurations 2 through 6 all utilize three HR Delta IV H CBCs for the first stage, each with a human-rated RS-68B engine.

Configuration 2 utilizes the present design of the Ares I second stage with no modifications. Though this concept will have weight and height issues due to the large size of the planned Ares I second stage, it was included to evaluate the potential cost savings of not requiring a redesign of the second stage or re-competition of the second-stage contract.

Configuration 3 utilizes a new second stage with a single J-2X engine. This configuration is similar to configuration 2, except that the second stage is resized to optimize the performance of the vehicle.

Configuration 4 (highlighted) utilizes a new second stage with four RL10-A-4-2 engines. This configuration is Aerospace's recommended baseline to meet HR requirements with engine out capability.

Configuration 5 presents a novel look at using the Delta IV H without a second stage. This configuration has a number of advantages, as will be discussed later.

Configuration 6 is similar to configuration 4, but utilizes a single RL10-A-4-2 engine.

Figure 2 presents a size comparison of the Delta IV H options to the Space Transportation System (STS) and Ares I. Ares I is intended to replace the space shuttle for crew transport to ISS and the lunar departure target. The Ares I first stage is a 5-segment reusable solid rocket motor (SRM), based on the 4-segment STS reusable solid rocket motor (RSRM). The second stage is a liquid hydrogen, liquid oxygen (LH2/LOX) propulsion stage, using a J-2X engine, which is a derivative of the J-2 engine used on the second and third stage of the Saturn V. The Ares I payload is the Orion service module and crew module, which transports crew to LEO. Delta IV H is the U.S. Air Force's heavy lift EELV.

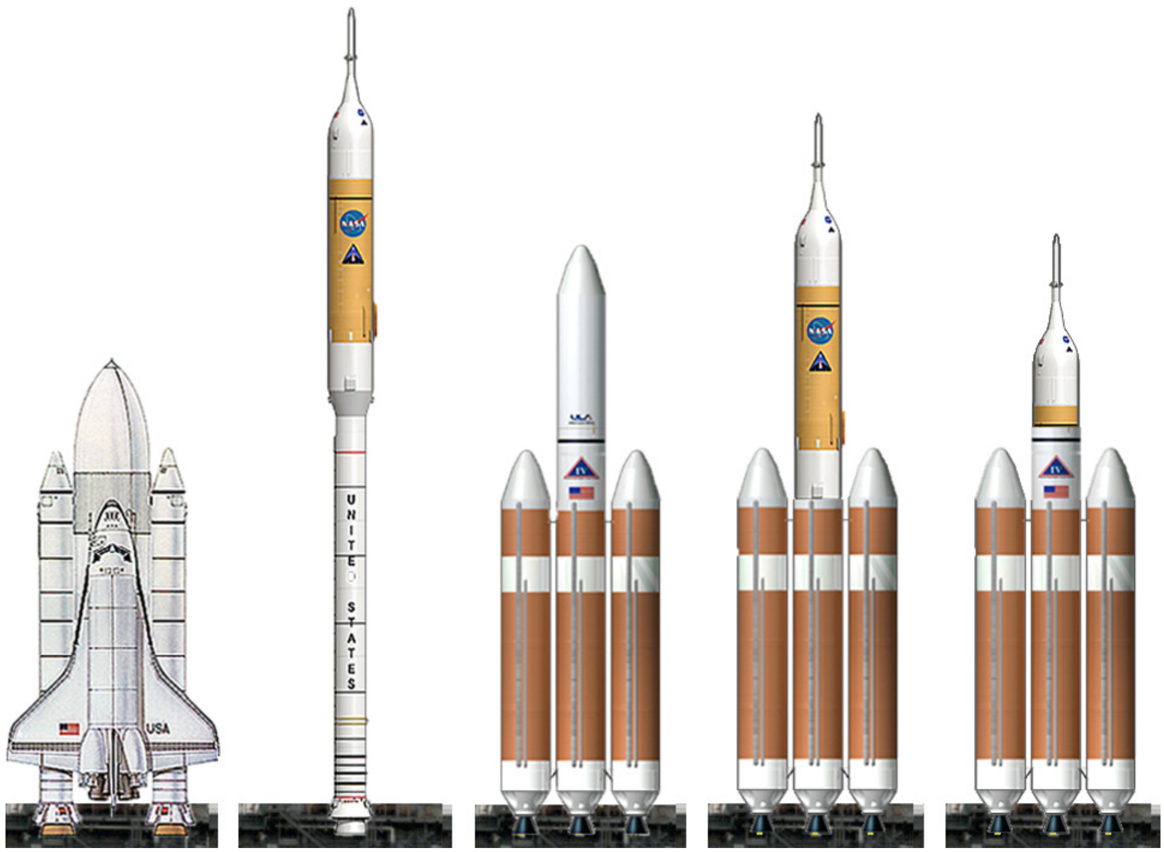

Figure 2. Vehicle size comparison.

2.2.3 Weight Impact of Human-Rating the Delta IV H

The process for human-rating the Delta IV H focused on the structural factor of safety requirement of 1.4, and the redundancy requirements for the rocket engine. In order to evaluate the impact of the structural factor of safety requirement of 1.4, a loads analysis was performed on an actual mission of the Delta IV H. Based on extrapolation from this assessment, it was determined that the propellant tanks of the CBCs would not require structural changes, but the composite components of the CBCs would require structural changes. These composite components include the interstage, the LOX skirt, and the centerbody, as well as the nose cones for the strap-on CBCs. This leads to an increase in weight to the core CBC of approximately 340 lbs., and an increase in weight to each of the strap-on CBCs of approximately 200 lbs.

In order to evaluate the impact of the redundancy requirements for the RS-68 engine, the details of various subsystems of the engine were evaluated. To meet the redundancy requirements, it was determined that the engine would require dual hydraulics, redundant actuators, and additional engine valves. The additional weight from these modifications produced an added weight of approximately 570 lbs. for the core CBC and for each strap-on CBC.

Adding the weight increases from both the structural factor of safety requirement and the engine redundancy requirements to produce the weight impact due to human-rating leads to a core CBC weight increase of 910 lbs. and a strap-on CBC weight increase of 770 lbs. each. Table 2 presents a summary of the weight impacts due to human-rating.

Table 2. Delta IV H Stage Weight Impact due to Human-Rating

Structures Weight Increase due to Factor of Safety of 1.4	
Core CBC weight increase	340 lbs.
Strap-on CBC weight increase	200 lbs. per strap-on
Engine Weight Increase for Human-Rating	
Weight increase for dual hydraulics	220 lbs.
Weight increase for redundant actuators	170 lbs.
Weight increase for engine valves	180 lbs.
Total engine weight increase	570 lbs. for core and strap-ons
Stage Weight Increase	
Core CBC weight increase	910 lbs.
Strap-on CBC weight increase	770 lbs. per strap-on

2.2.4 New Human-Rated Second-Stage Options

The new second stages for configurations 1 and 2 were sized using Aerospace's launch vehicle sizing models. In order to improve the fidelity of the sizing models for this analysis, Aerospace acquired the detailed mass properties statement for the Ares I second stage from NASA, and also acquired the detailed mass properties statement for the Delta IV H second stage from ULA. This allowed both an improvement in the fidelity of the models, and a calibration to the second stages of the two vehicles. The second stage for configuration 3 was sized around a single J-2X engine, while the second stage for configuration 4 was sized around four RL10-A-4-2 engines.

The weight information for the propulsion system of the four RL10-A-4-2 second stages for configuration 4 was based on an Aerospace analysis of the engine options. The amount of propellant for each of these stages was varied until an optimized payload performance of the vehicle was achieved. In addition, an assumption was made that the new second stages would utilize the existing Ares I second-stage avionics, since these stages will be performing the same mission and would require the same avionics systems.

2.2.5 No Second Stage Option

Use of an HR Delta IV H first stage mated directly to Orion is also technically feasible for crew transportation to ISS. The HR Delta IV H first stage has sufficient performance when combined with a fully propellant-loaded service module to meet the Orion delivery mass to ISS, with performance reserve for re-entry. This unique option does not support crew transportation to the lunar target. However, it does eliminate the need for a second stage for ISS missions, thus taking it off the critical path for crew launch. The human-rated second stage for HR Delta IV H would still be required in the Ares V time-frame to support crew transportation for the lunar mission LEO target.

2.2.6 Lift and Abort Performance

Aerospace performed a trajectory optimization for each launch vehicle configuration shown in Table 1, in order to assess vehicle lift performance relative to the Ares I ISS and lunar target requirements. Aerospace employs these same simulation tools to validate Air Force EELV launch trajectories. With the exception of configuration 5 (no second stage), the optimization maximized payload to the baseline Ares I/Orion delivery orbits and separation altitude. The baseline Ares I delivery orbit is -11 nautical miles (nmi) x 100 nmi orbit; 28.5 degree inclination for lunar, 51.6 degree inclination for ISS; and separation altitude is 70 nmi. The LAS and encapsulated service module (ESM) panels are jettisoned 30 seconds after second stage ignition, or at the equivalent altitude, for configuration 5.

Delta IV H is designed primarily for placing payloads into geosynchronous Earth orbit (GEO), whereas Ares I is designed for a sub-orbital trajectory, with the final LEO achieved using service module propulsion. For a typical GEO mission, the Delta IV H flies a highly lofted first stage trajectory which, from the perspective of human-rating, results in unacceptably high abort re-entry g-loads. For human-rating, HR Delta IV H trajectory was shaped to constrain the abort re-entry g-loads within required levels at all points along the trajectory. Maximum abort re-entry g-loads were computed at 10-second intervals during launch vehicle ascent. A peak acceleration constraint of 18 g's was applied to the trajectory optimization which allowed for some margin over the maximum loading (g forces over time) referenced in human-rating guidelines. Ares I abort scenarios assume the crew module orients to a nominal attitude after LAS separation. This assumption was also applied to the HR Delta IV H abort scenarios. A nominal crew module entry attitude (lifting) results in an aerodynamic lift force on the vehicle, which helps reduce the re-entry g-loading. Orion command module aerodynamics were modeled based upon Apollo maximum lift to drag hypersonic aerodynamic characteristics (drag coefficient of 1.29, lift coefficient of 0.39). Non-nominal crew module attitudes (ballistic) result in unacceptably high abort g-loading for both Ares I and HR Delta IV H.

Figure 3 shows the human abort re-entry g-loading requirement as a function of time (blue dashed line), compared to the maximum loads experienced on the Orion crew module during a lifting abort re-entry (red solid line). The hash-marked area represents the allowable g-loading envelope for human-rating. The red dashed line is the 18 g abort re-entry constraint placed on the ascent trajectory by the optimizer. The Delta IV H abort re-entry g-loading meets and exceeds the requirement in all configurations, at all points along the optimized ascent trajectory. Configuration 6, using the human-rated, single-engine second stage, is the only configuration with an ascent trajectory subject to the abort re-entry constraint, and therefore represents the HR Delta IV H maximum abort re-entry load envelope. Abort re-entry loads for the remaining configurations lie within the allowable envelope, as shown in the figure.

Figures 4 and 5 show lift performance to ISS and the lunar requirement, respectively, for each of the HR Delta IV H configurations. All configurations meet the abort constraint requirements described above. Configurations 1 through 4 exceed the Ares I gross performance requirements to ISS (23.1 metric tons, or mT) and the lunar target (25.5 mT). Configuration 1 is not human-rated. Configuration 2 may not be technically feasible, due to the mass properties of the vehicle at lift-off. Configurations 3 and 4 have significant margin against the Ares I requirements, even with significant mass growth in the launch vehicle or Orion. Figure 6 shows ascent g-loading for configuration 3, at two thrust levels and the minimum Orion weight specification, and Orion maximum performance specification, which corresponds to a fully loaded service module at the maximum Orion mass specification. Configuration 3 may result in high ascent loads (> 4 g) in the last 10 seconds of powered flight at the minimum Orion weight estimate, as shown in Figure 3. Increasing second stage mass or reducing J-2X thrust would decrease ascent loading. Configuration 5, with no second stage, meets the Ares I/Orion dry mass delivery requirement to ISS (19.5 mT). The Orion service module performs the ISS orbit insertion using the full lunar mission propellant load, with a 500-meters-per-second (m/s) hold-back for re-entry. Configuration 6, which uses a human-rated version of the existing Delta IV H 5m Delta cryogenic second stage (DCSS), does not meet the ISS or lunar performance requirement at the fully de-rated thrust level of 16,800 lbf due to the poor thrust to weight ratio and large gravity losses. Configurations 5 and 6 represent minimum bounding cases in terms of cost and performance. Neither point design, as defined in this study, meets both Ares I gross performance requirements for ISS and lunar missions. These cases suggest that matching Ares I gross performance may be achievable through a more detailed trade on engine structural margins, thrust levels, propellant off-loading, and second-stage configurations. Using both the second stage and Orion to achieve the requirements, operating the second-stage engine at thrust levels above 16,800 lbf, or adding a second RL10A-4-2 engine to the second stage are options for further investigation.

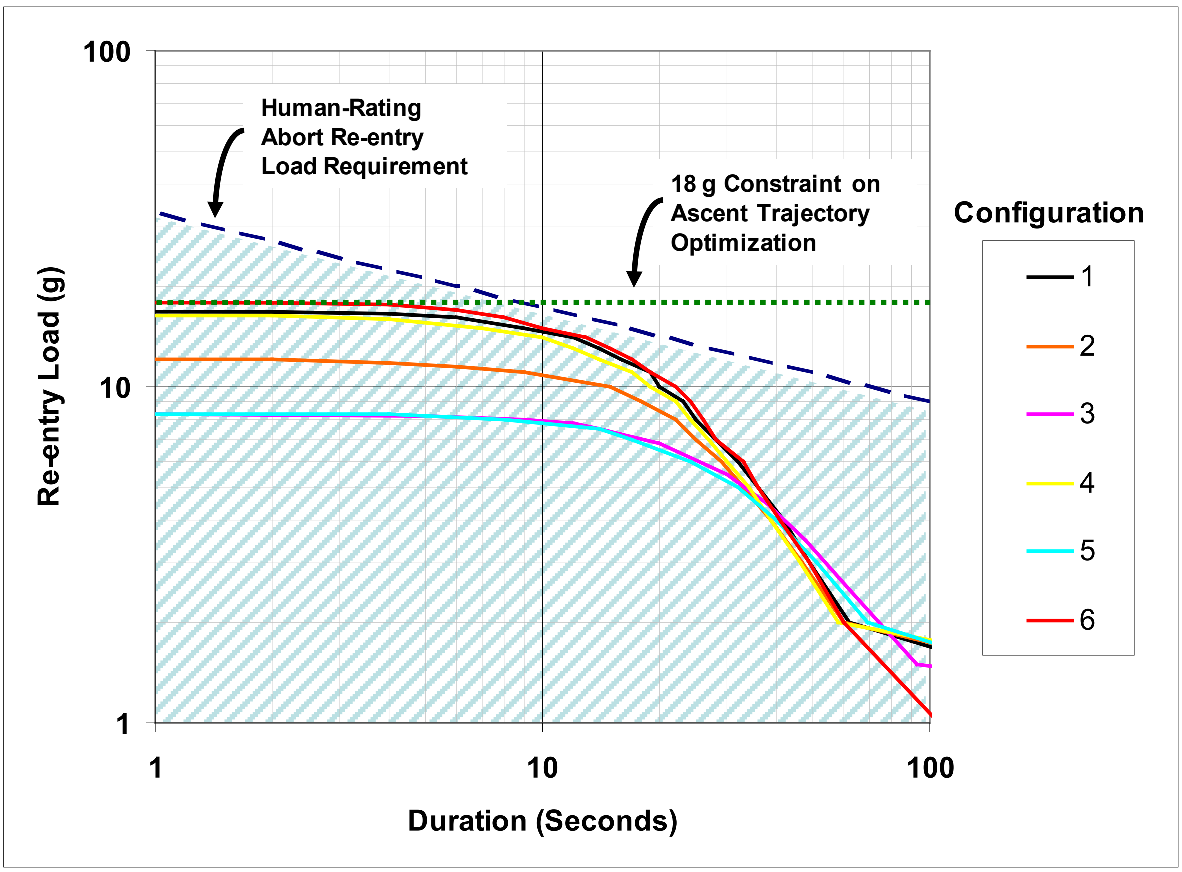

Figure 3. Abort re-entry g-load requirement compared to HR Delta IV H maximum re-entry loading.

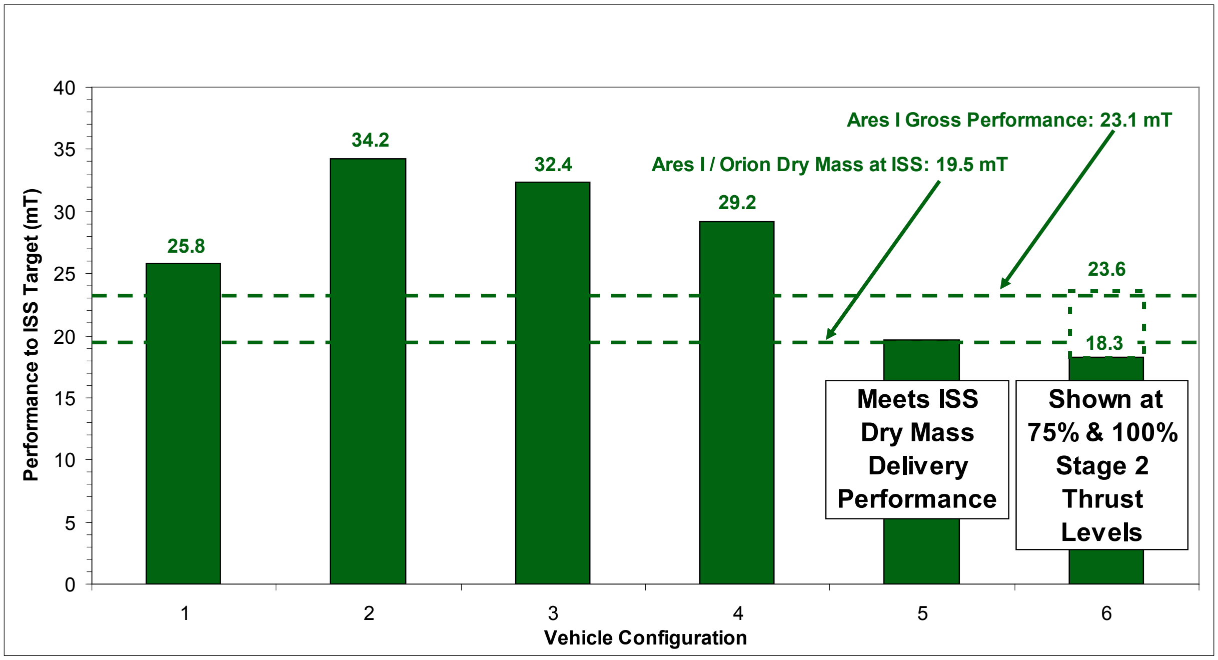

Figure 4. HR Delta IV H lift performance to ISS requirement.

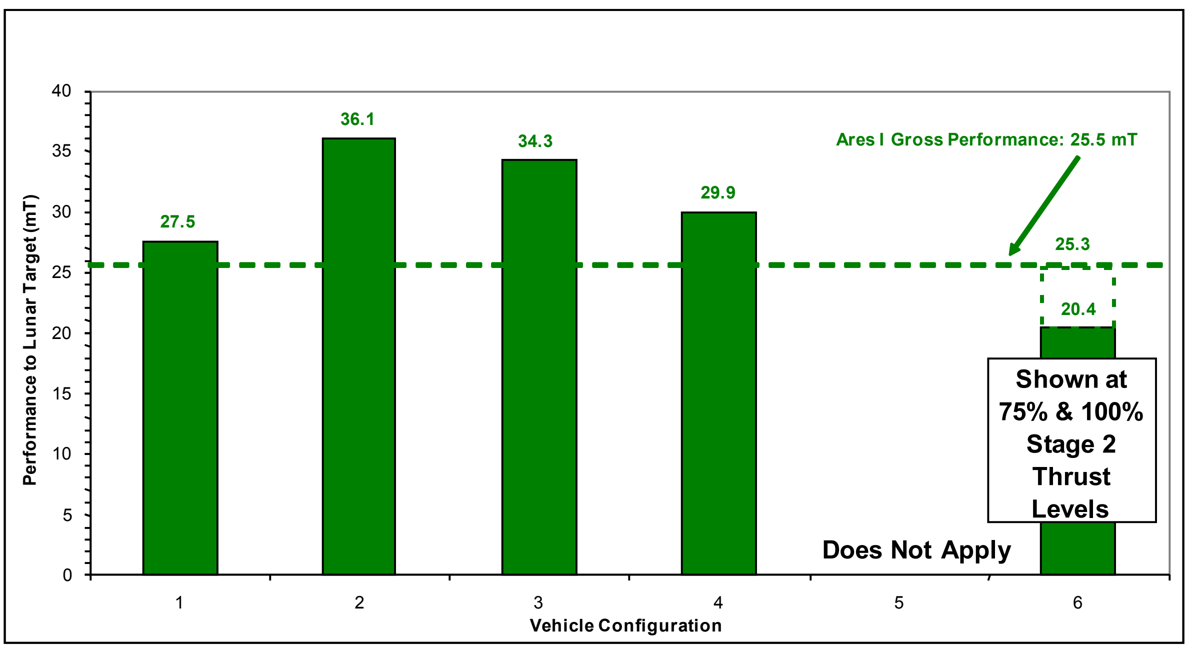

Figure 5. HR Delta IV H lift performance to lunar requirement.

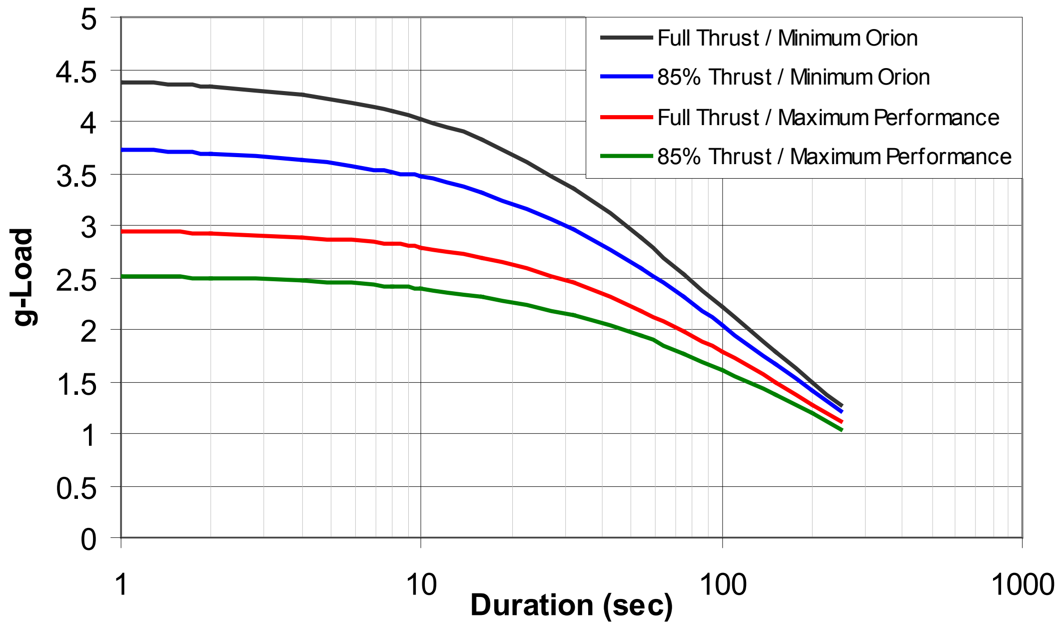

Figure 6. Orion ascent g-loading for configuration 3.

3. HR Delta IV H Technical Impacts to Constellation Architecture

Key to a decision on whether to switch to HR Delta IV H for NASA's crew-launch function is an understanding of production, ground, and launch processing scenarios and their potential impacts to or utilization of existing infrastructure. Collateral impacts to Orion and the implications for Ares V of removing Ares I as the program that would maintain the SRM industrial base and production capability are likewise important factors to consider.

3.1 Ground Infrastructure

The ground infrastructure portion of this study evaluated two separate elements of the ground system:

- HR Delta IV H production infrastructure
- HR Delta IV H/Orion launch-processing infrastructure

The objective was to adequately define the ground infrastructure concept(s) to allow comparison to the Ares I/Orion baseline.

The ground infrastructure concept evaluation for each element included the following:

- Facility construction and modifications
- Production/processing timelines and throughput
- Transportation and processing flow
- Ground support equipment (GSE) modifications/additions
- Labor resources required for development, production, and operations
- Environmental impact assessments resulting from change to an HR Delta IV H
- Inputs to cost estimates and timeline estimates for both development and operations
- Impacts to current Delta IV H operations

Figure 7 describes the ground infrastructure concepts examined during this study.

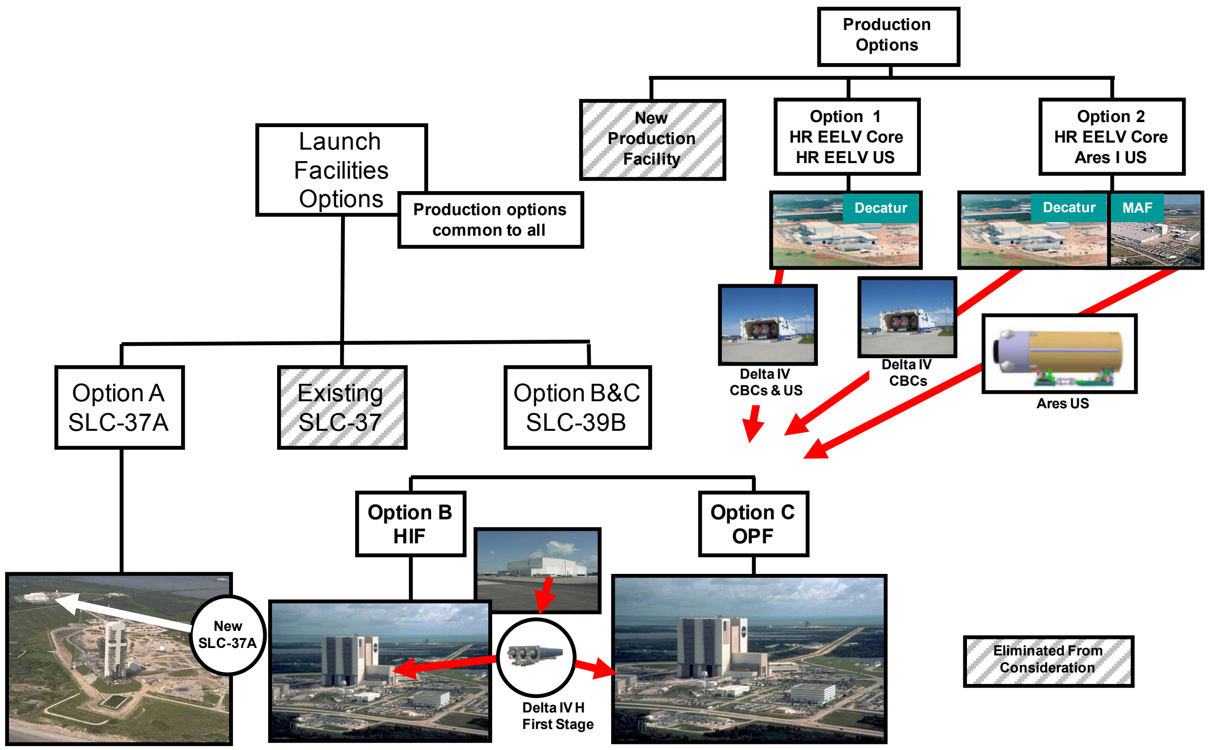

Figure 7. Ground infrastructure options examined.

3.2 Production Infrastructure

For the production infrastructure, two options were considered:

- Option 1: Based on the HR Delta IV H first stage and RL10-based second stage. This option assumes that all flight hardware elements would be produced at Decatur, AL using the same production concept currently employed for Delta IV H.
- Option 2: Based on the HR Delta IV H first stage and J-2X (Ares I)-based second stage. This option assumes that the HR Delta IV H first stage hardware would be produced at Decatur, AL, while the J-2X second stage would be produced at Michoud, LA in accordance with the current manufacturing plan.

The Decatur facility is currently well underutilized based on the original production throughput planned. As a result, ULA is in the process of consolidating production of all Delta IV and Atlas V stages at Decatur. Currently, all Delta II and IV vehicle manufacturing is based in Decatur, while Atlas V manufacturing is based in Denver, CO and San Diego, CA. To assess the future impact of adding an HR Delta IV H production capability at Decatur, Aerospace evaluated the Delta IV Medium and Heavy launch manifest through 2020, and overlaid the baseline Constellation program launch schedule to determine the total annual production rate of CBCs and DCSSs that would be required to satisfy the increased demand. Using data that was both independently derived and obtained from ULA, Aerospace found that the added hardware production required for either vehicle option can be supported at Decatur without additional facility expansion. Some build-ahead of rocket stages and engines is required early in the production program in order to have the inventory needed to sustain the higher flight rates in the later years. However, this can be accommodated within the existing and planned facility foot-print.

The current consolidation plan includes adding storage space as a buffer for hardware manufacturing. Aerospace's assessment is that the added HR Delta IV H production will require the addition of a full second shift and limited third-shift staffing. Although adequate floor space may exist for the additional CBC production, a new dedicated test cell may be needed in Decatur for the HR Delta IV H second stage for option 1. Development and staffing ramp-up could be accomplished in two to three years. This may impact the planned relocation of the Atlas V/Centaur manufacturing from San Diego, CA, and should be studied further. In the worst case, the delay in relocation, or the decision not to relocate, may result in cancellation costs that were not included in this assessment. Otherwise, all identified production-implementation costs were included for each option.

This assessment also assumes Delta II production in Decatur will be discontinued per the current plan. In the case of option B, NASA's Ares I production estimates were used as the baseline, and the Decatur production estimates were adjusted to remove the second-stage labor and test cell.

3.3 Launch Processing Infrastructure

For launch processing, three infrastructure concepts were considered:

- Option A: Based on an HR Delta IV H/Orion launch from a new SLC-37A complex.
- Option B: Uses the SLC-37 horizontal integration facility (HIF) for Delta IV H first-stage processing from a modified SLC-39B complex.
- Option C: Uses a modified OPF at SLC-39 for Delta IV H first-stage processing from a modified SLC-39B complex.

Figure 8 describes the option A concept that uses a new SLC-37A launch complex to be constructed at the currently sited second pad located approximately 1,750 feet from the current SLC-37B. Although the basic site work for the new pad is similar to the original SLC-37B design, most of the system installations need to be upgraded to human-launch requirements. Additional major configuration changes to the original launch pad design include a larger mobile service tower (MST) compatible with Orion, and a larger fixed umbilical tower (FUT) with crew access, emergency egress, and Orion interfaces. A new launch control center (LCC) with a new ground control system to support dual operations and human requirements, and additional GSE for handling and checkout of the HR Delta IV H elements, are included. Option A was assessed based on the prior SLC-37B development and determined to be feasible, with a development time estimated at 56-60 months. A potential issue identified for option A is that SLC-37 is currently a contractor-owned, contractor-operated (COCO) facility, while NASA conventionally operates government-owned, contractor-operated (GOCO) facilities such as those at SLC-39. In addition, this concept is limited to a maximum of five launches per year, and may encounter conflicts from other operations within the SLC-37 complex.

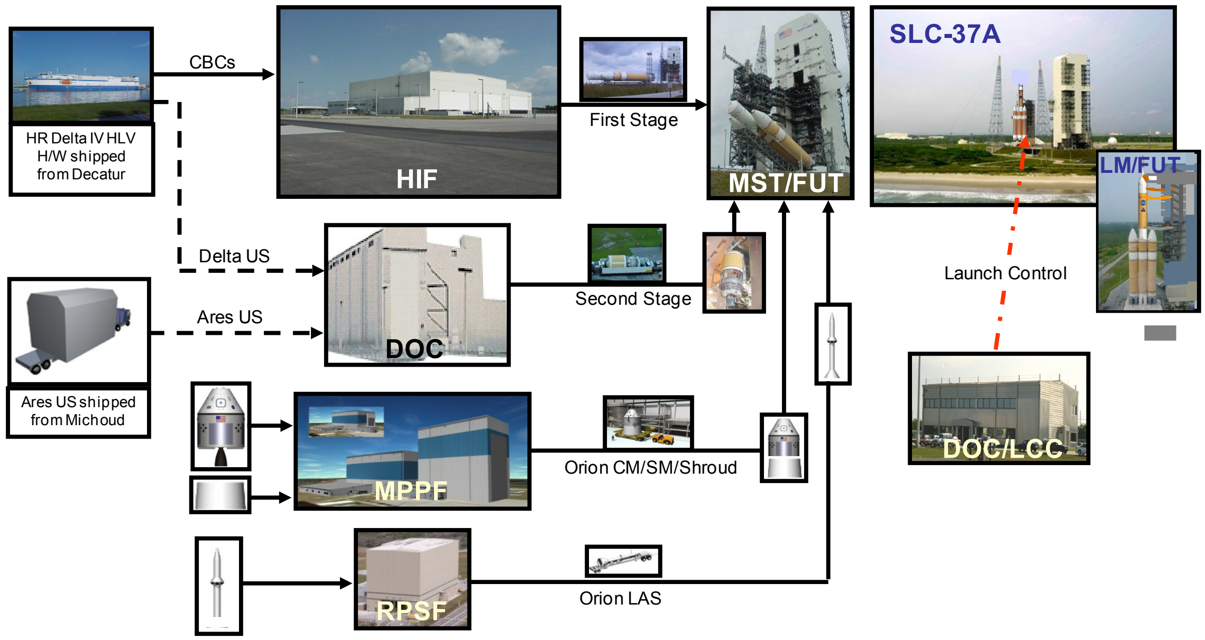

Figure 8. Option A: HR Delta IV H/Orion launch from a new SLC-37A complex.

Figure 9 describes the options B and C concepts. Options B and C use a modified SLC-39B launch complex similar to the planned Ares I modifications. Both concepts also use modified vehicle assembly building (VAB) and LCC facilities, and a new mobile launcher platform (MLP) similar to the planned Ares I concept. Option B uses the horizontal integration facility (HIF) at SLC-37 for HR Delta IV H first-stage processing prior to transportation and erection in the VAB, whereas option C uses a modified OPF near the VAB at SLC-39. Necessary transportation equipment and infrastructure upgrades are included for each option. The NASA estimates for the Ares I concept were determined to be applicable to the HR Delta IV H concept since all modifications are of a similar scale to Ares I. Additions were made for the HR Delta IV H-unique GSE, umbilicals, and servicing requirements. No incompatibilities could be found. A delta cost was included for the lost effort on the MLP currently under construction.

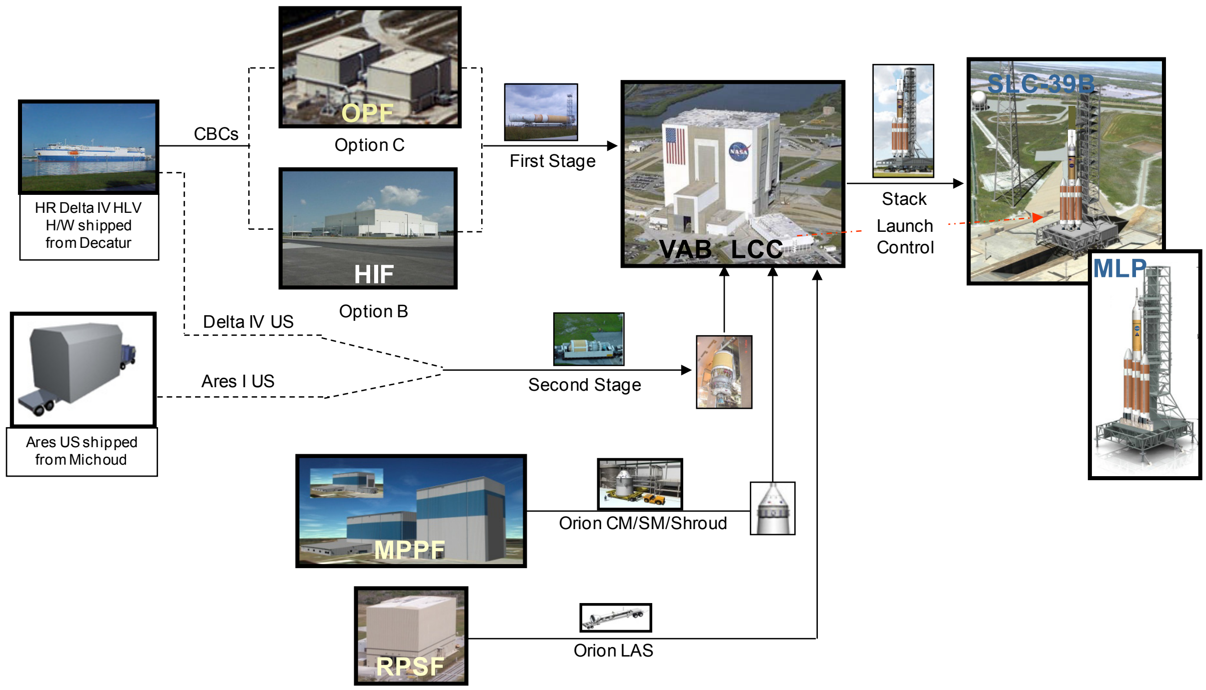

Figure 9. Options B and C for HR Delta IV H launch processing infrastructure.

Option C appears to be the most attractive of all three options based on current NASA launch operations, isolation from DOD Delta IV H operations, integration with Ares V operations, and marginal cost and schedule differences. Option B is recommended as an interim concept if the OPFs are not readily available. There will be no lost investment since all GSE can be relocated. Development time was estimated at 60-66 months for both options B and C. The potential issues identified for these options include: operations and GSE design for hoisting and mating of the assembled HR Delta IV H first stage in the VAB along with potential vehicle structural issues; HR Delta IV H vertical transportation limits and new wind damper design; and design to incorporate HR Delta IV H umbilical tower/swing arm arrangement on the MLP. Implementation will require a design concept study to pursue the SLC-39 options with up to an additional 12-month impact for redesign. This was included in the development estimates. Requirements for real-time launch support from Denver, CO as currently performed for Delta IV H launches could not be assessed for either launch concept. These requirements should also be included in the design concept study.

Table 3 summarizes the different launch vehicle configurations, production, processing, and launch options studied. Configurations 2, 3, and 4 show options A, B, and C, which correspond to the processing and launch options discussed above. Option A is processing and launch from a new SLC-37A. In option B, the first stage is processed in the SLC-37 HIF and launched from SLC-39B. In option C, the first stage is processed in the OPF and launched from SLC-39B. Configurations 1, 5, and 6 assume option A for processing and launch.

Table 3. Launch Vehicle Configurations, Production, Processing, and Launch Option Summary

Launch Vehicle Elements

		First Stage Engine		Second Stage Engine			First Stage		Second Stage				
Configuration	Name	RS-68A	HR RS-68B	RL10-B2	HR RL10A-4-2	J-2X	Existing Delta IV H First Stage	HR Delta IV H First Stage	Existing Delta IV H Second Stage	HR Single Engine Delta IV H Second Stage	HR 4 RL10A-4-2 Delta IV H Second Stage	Ares I Second Stage	HR J-2X Second Stage
1	Existing (Baseline)	X		X			X		X				
2A	Ares I Second Stage		X			X		X				X	
2B	Ares I Second Stage		X			X		X				X	
2C	Ares I Second Stage		X			X		X				X	
3A	Re-sized J-2X Second Stage		X			X		X					X
3B	Re-sized J-2X Second Stage		X			X		X					X
3C	Re-sized J-2X Second Stage		X			X		X					X
4A	New HR 4 RL10 Second Stage*		X		X			X			X		
4B	New HR 4 RL10 Second Stage*		X		X			X			X		
4C	New HR 4 RL10 Second Stage*		X		X			X			X		
5	No Second Stage		X					X					
6	HR Existing Second Stage		X		X			X		X			

Production, Processing and Launch Elements

		Production			Ground Processing and Launch			
Configuration	Name	Decatur Production Facility - First Stage	Decatur Production Facility - Second Stage	Michoud Production Facility - Second Stage	Existing SLC-37	New SLC-37A (Existing HIF)	SLC-39 and HIF (SLC-37)	SLC-39 and OPF
1	Existing (Baseline)	X	X		X			
2A	Ares I Second Stage	X		X		X		
2B	Ares I Second Stage	X		X			X	
2C	Ares I Second Stage	X		X				X
3A	Re-sized J-2X Second Stage	X		X		X		
3B	Re-sized J-2X Second Stage	X		X			X	
3C	Re-sized J-2X Second Stage	X		X				X
4A	New HR 4 RL10 Second Stage*	X	X			X		
4B	New HR 4 RL10 Second Stage*	X	X				X	
4C	New HR 4 RL10 Second Stage*	X	X					X
5	No Second Stage	X				X		
6	HR Existing Second Stage	X	X			X		

* Engine-out capability with 4 RL10A-4-2 engine cluster

3.4 Orion

The transition from Ares I to an HR Delta IV H launch vehicle requires a revisit of the timeline and content of the technical and programmatic work-to-go for the Orion crew module, service module, and launch abort system. Aerospace performed a top-level, qualitative review of the Orion modifications. Technical considerations include revisiting physical and functional interfaces, ground facilities interfaces, as well as the nominal mission design, abort mission design, and environmental analysis (including aero-thermal, aero-acoustic, and integrated dynamic loads analysis). Programmatic considerations to return the Orion program to the current level of design maturity include the time and resources needed to revisit and re-assess each technical topic, and then complete a detailed assessment to include any re-analysis and redesign work that results.

Technical Considerations. The Orion preliminary design review (PDR) is currently scheduled for August 2009. The primary technical effort in transitioning Orion to HR Delta IV H is characterizing the Orion launch vehicle interface and integration work that will be completed before this date. Table 4 lists the topic areas that would require re-evaluation as part of the transition. Aerospace reviewed these topic areas to provide a top-level assessment of the potential changes relative to Ares I, in terms of no change, change with a potential technical benefit to Orion, and change with no benefit.

Much of the mechanical, electrical, and data interface considerations focus on changes to the planned Ares I second-stage/Orion interfaces caused by introduction of a new HR Delta IV H second stage. The HR Delta IV H development program assumed the development of a new, human-rated second stage to replace the existing 5-m DCSS, incorporating the planned Ares I second-stage avionics suite. This assumption allows the HR Delta IV H development program to minimize potential impacts to Orion. Under this development approach, there would be no changes to Orion electrical, avionics, or mechanical interfaces. The Orion outer moldline (OML) would be maintained as-is across the Orion-second stage interface, and a new first stage-second stage adapter would be developed to transition from the HR Delta IV H core to the new second stage.

Physical Interfaces. Ares I first-stage thrust oscillation during the first-stage burn results in high-g, high-frequency dynamics induced on the Ares I second-stage/Orion stack. These dynamics are currently mitigated through mechanical isolation at the first stage-second stage and second stage-Orion adapters, and by other means. The HR Delta IV H liquid-core stage does not have this feature, and both the first stage-second stage and the second stage-Orion adapter could potentially be simplified in design, and reduced in mass.

Functional Interfaces. Crew data, signals, and command interfaces would require redesign to accommodate the HR Delta IV H first stage, and second stage differences from Ares I. These redesigns would include changes in system health monitoring signals and data interfaces, command shutdown, and command abort interfaces for the all-liquid first-stage propulsion system, four-engine second stage, and second-stage manual control. Software functionality would also require review in light of the hardware configuration changes associated with the first stage and the new second stage.

Table 4. Top-Level Aerospace Assessment of Technical Considerations Relative to Orion Transition from Ares I to HR Delta IV H Launch Vehicle

Orion - HR Delta IV H Integration and Interface Considerations	Assessment	Orion - HR Delta IV H Integration and Interface Considerations	Assessment
Physical Interfaces		***Nominal Mission***	
Spacecraft adapter/mechanism	↑	**Mass to orbit & delta V to LEO**	↑
Avionics integration	→	**Ascent trajectory profile**	→
Mechanical envelope and clearances	→	**Separation conditions**	→
Electrical interfaces	→	**Separation dynamics**	→
OML compatibility	→		
Functional Interfaces		***Abort Mission***	
Data signals commands	↓	**Changes to abort modes**	↑
Crew performance	↑	**System triggers/fault detection**	→
Crew interaction - manual control	→	**Trajectory**	↑
Software (abort, guidance, navigation, and control, etc.)	↓	**Abort initiation**	↑
		LV shutdown assumptions	↑
		Abort black-out zones	→
Ground Facilities Interfaces		***Environments***	
Crew access	→	**Integrated loads**	↑
Emergency egress	→	**Aero-thermal**	↑
Purge/vent/drain	→	**Acoustics (T-0 and in-flight)**	↑
Stacking operations	↓	**Shock and vibration**	↑
		Maximum dynamic pressure	↑

Key	
→	No change relative to Ares I
↓	Change relative to Ares I
↑	Change, with potential benefits, relative to Ares I

Ground Facility Interfaces. Orion vehicle interfaces for ground processing would remain the same, with the exception of stacking operations. Two scenarios have been considered for integrating Orion to the HR Delta IV H: 1) integration at the launch pad, and 2) integration in the VAB. Integration at the launch pad consists of transport and erection of the first stage and second stage on the launch pad, followed by vertical integration of the Orion stack. This is facilitated through the use of a modified vertical integration facility at the launch pad, designed specifically for Orion integration and processing. Under this scenario, Orion processing from the start of launch vehicle integration through launch would require replanning. Integration in the VAB consists of integrating the HR Delta IV H first stage horizontally, erecting the first stage and stacking the second stage and Orion vertically. The full stack is then transported vertically to the launch pad. This scenario would have little impact on Orion itself. However, the lateral loads on the HR Delta IV H stack during transport would require further assessment, and may result in structural change to the launch vehicle or modifications to the mobile launch tower.

Nominal and Abort Mission. HR Delta IV H offers performance benefits over Ares I relative to Orion's nominal and abort missions. HR Delta IV H can match Ares I separation orbit (position and velocity) resulting in near-identical Orion separation conditions. It has been analytically demonstrated that the HR Delta IV H trajectory profile can be adjusted to match Ares I constraints yielding equal-to or more favorable flight environments, separation dynamics, mass to orbit, and ΔV to LEO. Under full abort coverage, HR Delta IV H carries an additional ~6 mT of performance above the Ares I baseline performance of 23.1 mT to the ISS, and an additional 4.5 mT to the lunar departure orbit target. This additional performance may be applied to relax design constraints on the Orion crew module launch mass (if any), to improve service module capabilities such as mission life or ΔV, or enable other logistics capabilities for LEO such as cargo transportation or the addition of a robotic arm for on-orbit repair.

HR Delta IV H enables additional flexibility in abort response and abort mission design, due to the ability to shut down first-stage engines in the event of a problem, and the ability to achieve the nominal mission with a second-stage, single-engine out. These inherent features allow for a more graceful degradation in performance than is possible with Ares I, and provide more abort-mission design options than are currently available. The flexibility of increased numbers of first stage and second stage abort modes, options for abort initiation and command vehicle shutdown, and trajectory options need to be weighed against the added complexity to mission planning. This is an area requiring further assessment to fully understand the risks and benefits.

Environments. Orion flight environments will also need to be reassessed for the new launch vehicle. These environments include loads, aero-thermal and aero-acoustics, shock and vibration, and maximum dynamic pressure. In general, the HR Delta IV H launch and flight environment is expected to be more benign than that of Ares I, due to both the lack of first-stage thrust oscillation and the lower-thrust, lower-mass second stage.

Programmatic Considerations. The cost impacts to Orion associated with redesign, re-analysis, and reverification of interfaces and environments depends, in large part, on design maturity at the point in time when the decision is made to switch from Ares I to HR Delta IV H. Orion physical and functional interfaces, ground facilities interfaces, mission design, and environmental analyses need to be revisited. Additional time and cost would be incurred to support these new analyses. The impact to the Orion schedule is expected to be commensurate with the time required to resynchronize the Constellation architecture following the Ares I cancellation. Since the delay due to Orion impacts is less than the overall schedule for HR Delta IV H development, Orion would not be on the critical path.

3.5 Ares V SRM and Second Stage

The CaLV function is currently represented by the specific design assumptions embedded within Ares V. The technical impacts to the CaLV caused by the replacement of Ares I with a human-rated Delta IV H are highly dependent on the programmatic and design assumptions made for that vehicle. Ares V, as CaLV is currently envisioned, is predicated on Ares I for critical vehicle elements, such as the J-2X engine used for the Ares I second stage; the large, segmented RSRM; and ground processing infrastructure developed for Ares I and available for use by Ares V. Ares V, with Ares I replaced with HR Delta IV H, shifts costs for the development of these elements to the Ares V project, and incurs additional costs for maintaining the SRM industrial base until needed for the development of the Ares V SRB.

In a human-exploration architecture that includes HR Delta IV H, decisions on design and heritage that led to the current Ares V baseline design should be reexamined. The trade space for CaLV is complex; it is useful to examine several alternatives to the Ares V design solution, in terms of impacts and benefits to the Constellation architecture and SRM industrial base. Within the time and resource constraints of this study, Aerospace performed only a top-level assessment of the Ares V.

Figure 9 describes a limited set of CaLV architecture options that offer similar lift performance. This set ranges from the current Ares V baseline to alternative options that rely on different degrees of STS and EELV heritage. The current Ares V baseline consists of an LH2/LOX core propulsive stage powered by six RS-68B engines and two STS-derived 5.5-segment strap-on RSRMs. The Ares V RSRMs are based on the 5-segment Ares I first-stage booster, which in turn is based on the 4-segment STS RSRM. As with STS, these motors are designed to be retrieved from the ocean after each use, after which the steel segments are disassembled, cleaned, and reloaded. The Ares V second stage, or EDS, is also an LH2/LOX stage powered by a single J-2X engine. The EDS is designed to carry cargo to lunar destinations and beyond. Ares V can lift approximately 170 mT to LEO, and 74.1 mT to translunar injection (TLI). As with STS, these motors are designed to be retrieved from the ocean after each use, after which the steel segments are disassembled, cleaned, and reloaded. As with STS, Ares I and Ares V use polybutadiene acrylonitrile (PBAN) binder in the solid propellant mixture. The absence of Ares I reopens the opportunity to consider an alternative expendable, composite-wrapped hydroxyl terminated polybutadiene (HTPB) advanced solid rocket motor (ASRM) for Ares V, which may offer performance improvements and reductions in the size of the liquid core. Industrial base impacts associated with this option are discussed in section 3.6.

Alternative CaLV options shown in Figure 10 include the use of existing STS RSRMs and existing Delta IV H CBCs. These options benefit through a reduced degree of new development for the SRMs, and the use of existing Delta IV H CBCs to augment a 5-engine-core stage. They maintain the use of STS-heritage hardware, maintain the STS-based RSRM industrial base capability, and leverage the nation's investment in EELV and the HR Delta IV H as a replacement for Ares V.

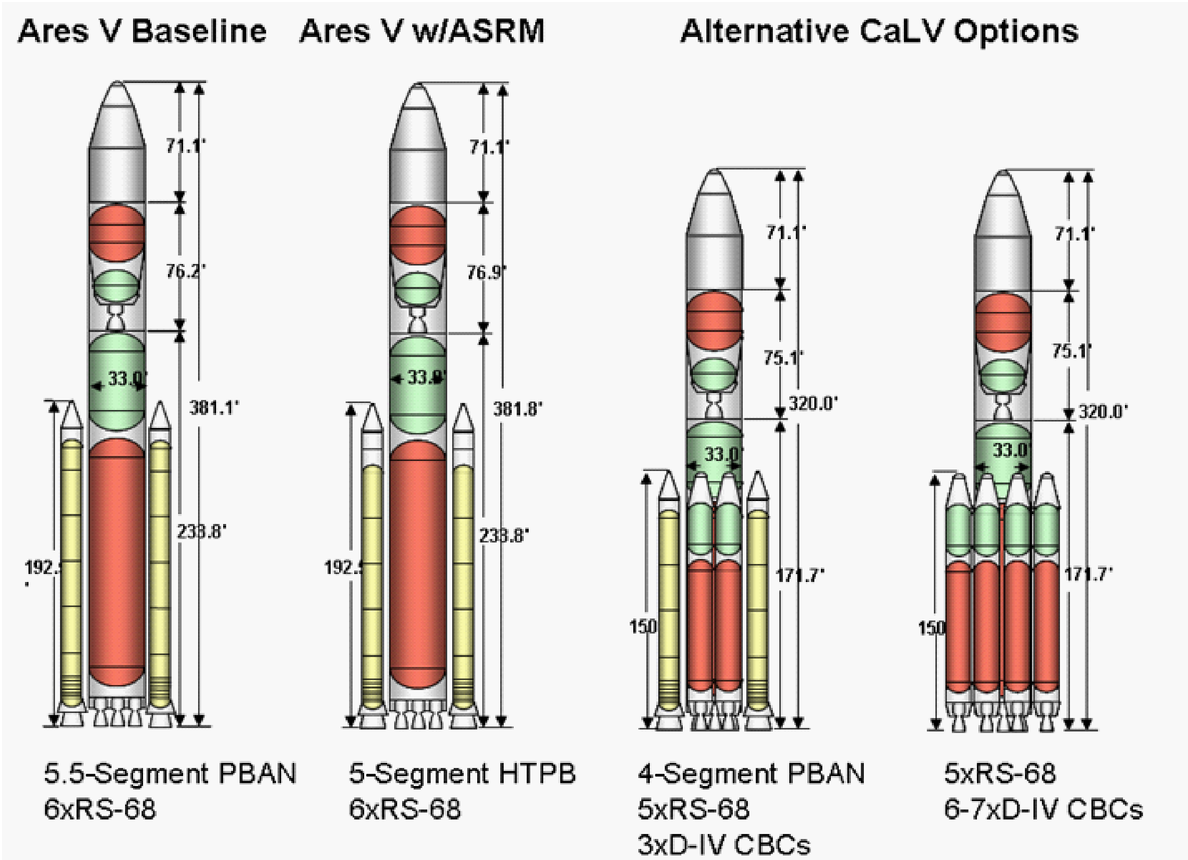

Figure 10. Ares V options and alternative CaLV options.

3.6 SRM Industrial Base

Consideration of an all-liquid propellant HR Delta IV H as an Orion launch system will have an impact on the only large, segmented SRM producer in the U.S. and its supply chain. The scale of this impact raises several questions concerning launch system decisions and the viability of the U.S. SRM industrial base. There are three primary questions that need to be addressed for the possible SRM scenarios:

Assuming that an HR Delta IV H replaces the Ares I and that the heavy lift cargo launch system requires large, segmented SRMs:

1. What will be required to sustain the industry until the onset of the design, development, test, and manufacture of the SRMs for the heavy lift cargo launch system?

Assuming that an HR Delta IV H replaces the Ares I and that the heavy lift cargo launch system *does not* require large, segmented SRMs:

2. What will be required to sustain the viability of the U.S. SRM industrial base?

And, under either of the first two assumptions:

3. Will these situations increase costs to the civil or military users of other SRMs, and if so, by how much?

While there have been many studies conducted in the last five years looking at the viability of the national SRM industrial base, a clear, succinct, and independently derived answer to these three questions does not exist today. From these past studies and current work, Aerospace can identify what is known, what is unknown, and provide recommendations to quantify the answers to these three questions.

3.6.1 What Is Known

It is convenient to separate the market for large SRMs into three classes: 1) strategic strike, which includes land- and sea-based intercontinental ballistic missiles (ICBMs); 2) missile defense applications; and 3) launch. A March 2008 study by The Aerospace Corporation on the SRM industry performed from the perspective of military applications cited four relevant studies that were finished over the past three years. These studies were conducted by the Office of the Undersecretary of Defense (March 2006), a Congressional Report (January 2008), a Booz Allen Hamilton Study (October 2006), and a January 2008 study by the 526 ICBM Systems Group. A common theme in all these studies is that the national SRM industrial base is going to experience significant reductions. Upon reviewing these studies, it is clear that these reductions will occur even if the Ares I and Ares V systems are developed as envisioned today. Another common theme was that the DOD, in recognition of this reduction in demand, has created funded programs that maintain the necessary infrastructure and skill sets to continue manufacturing, refurbishment, and new design capabilities for military applications within the SRM industrial base. A third common theme is that the SRM industrial base is very fragile, and reductions in SRM demand may have significant impact on the nation's SRM capability as a whole — not just in the large, segmented SRM portion of the industry, but potentially in other SRM application areas as well. There are many single-source and foreign suppliers that could potentially exit the business on very short notice due to a decrease in demand. Lastly, the industry has an aging workforce and is having problems attracting new talent. A protracted downturn in large, segmented SRM production could result in a significant loss of skills that would take many years to reconstitute. A recent Deputy UnderSecretary of Defense (Industrial Policy) report to Congress (March 2009) also supports these findings.

There are only two primary U.S. suppliers of large SRMs today, as compared to the five individual companies that existed 10 years ago. Of those two current suppliers (ATK and Aerojet), only ATK produces large, segmented SRMs that are used as shuttle boosters. Total FY 2009 sales for ATK were $4.6B, with $1.6B related to space systems. ATK sales to NASA were approximately $920M for FY 2009. By comparison, total FY 2008 sales for Aerojet were $726M, which included solid, liquid, air-breathing, and electric propulsion systems. Based on this publically available data, even if all sales to NASA were removed from ATK's FY 2009 sales, the remainder of its space systems sales would approximate Aerojet's sales for FY 2008 for all of its propulsion systems.

For the sake of understanding the nature of the SRM sustainment issue, important factors include the infrastructure necessary for eventual production (plants, special machinery, and other associated hardware), availability of skilled second- and third-tier suppliers, and skill-set retention for the prime contractor. Skill retention to some degree depends on the projected use of the manpower that would be sustained. If eventual production of systems already designed is the focus, the desired skill set is different than if the anticipated use also involves design and development of new systems.

During the course of Aerospace's current study, NASA Marshall Space Flight Center (MSFC) has provided the annual sustainment costs for ATK during the hiatus that would occur if an HR Delta IV H were to replace Ares I, and also the time at which the SRBs would begin undergoing design and development for the Ares V heavy lift cargo system. Aerospace understands these cost projections to be on the order of half a billion to a billion dollars annually, with a production hiatus starting in 2011 at the presumed switch to HR Delta IV H, and ending with the start of Ares V SRM production in 2017. This figure seems to be consistent with the funding to ATK during the standdown that occurred after each of the shuttle accidents and may be related to maintaining a state of full readiness for the RSRM production capability. The duration of the accident-related standdowns were unknown a-priori, but presumed to be less than a few years. Budgeting for full production operations, these unplanned shutdowns ensured that the SRM production capability could restart rapidly when the shuttle returned to flight readiness. Unlike the prior SRM production standdowns, substitution of the HR Delta IV H for Ares I results in a planned SRM design and production hiatus until needed for Ares V. A planned mothballing, or sustainment of a warm production line, plus minimum costs for skill retention, should be less than the annual cost to maintain production readiness over a period of unknown but relatively short standdowns.

SRM industrial base sustainment costs must be counted when examining the switch from Ares I to HR Delta IV H if the Ares V, as currently defined, represents the CaLV, as they are a major component of the total carrying costs. In December 2008, NASA estimated industrial base sustainment costs of $6.5B FY 2009 from 2011 to 2020. Currently all SRM production costs are book-kept under Ares I, whether they are for Ares I or Ares V. Considering only the production hiatus between 2011 and the start of Ares V, production in 2017 results in a $4.6B FY 2009 cost for an industrial base sustainment. Aerospace has not verified these NASA estimates.

Another factor in the Orion launch system decision and the magnitude and use of sustainment funds is the type of solid rocket propellant that could be used in the development of the heavy lift cargo system. The current shuttle boosters, and the planned Ares I and Ares V SRBs, use PBAN as the propellant binder. An alternative binder, HTPB, enables more energetic propellant because it allows a higher solids loading. Combined with a carbon-fiber composite case, this could be a useful alternative to the Ares V current design. NASA has studied this issue, and one of the reasons for retaining PBAN for the heavy lift cargo system would be its inheritance from the first-stage solid rocket for Ares I. If Ares I was replaced by the all-liquid-propellant HR Delta IV H, it may provide the heavy lift cargo system the opportunity to sustain ATK through the design, development, and test of a composite-case, expendable, HTPB SRB. Despite the wide usage of HTPB, in 1996 over 560M lbs of PBAN was used, while HTPB accounted for only about 260M lbs.

3.6.2 What Is Unknown

Despite several SRM industrial base studies with generally consistent results, Aerospace believes a new study is needed that would be conducted by a team of civil and military representatives to jointly produce an independent financial viability assessment of ATK and Aerojet under various future civil and military SRM demand scenarios. This task would determine, among other things, the skill base and infrastructure correlation between large, monolithic SRMs and large, segmented SRMs; the realistic level of continuing large SRM and/or large, segmented SRM national work force; the cost of preserving such a work force; and the equitable share of supporting the necessary infrastructure and capability for various projected civil and military needs. The primary unknown stems from the lack of an independent and thorough assessment of the projected financial health of the two domestic SRM suppliers. The reduction in the market appears to be well-recognized, and sharp decreases are already taking place stemming from the completion of certain strategic strike contracts. The question to be resolved is how downsized, yet fiscally sound, can either of the current suppliers become and still provide the capability required by the government sometime in the future? The DOD has already taken steps to preserve the domestic strategic strike capability; however, it is not clear whether this level of support is sufficient to support the industrial base without Ares production. It is reasonable to speculate that the government will fund the incumbent on the civil launch side to do the same thing if there is a decision to sustain large SRMs into the future. Because both civil and military demands constitute the market for large SRMs, it is clear that the resolution of this issue must be defined through a joint military and civil effort.

In the process of defining the minimum infrastructure, supplier base, and skill-retention costs to maintain a future domestic SRM capability, it is not known who is "paying" their fair share of fixed and variable costs. This becomes critical from the perspective of the cost impact resulting from a significant reduction in sales by one customer, and the degree to which that reduction generates increased costs for the other customer. Again, it is critical that a joint civil and military independent assessment be undertaken in recognition of the fundamental responsibilities both SRM companies have to their workforce and shareholders.

From the perspective of the launch vehicle decisions facing the Constellation program, it appears that one level of joint sustainment needs to be evaluated if the HR Delta IV H replaces Ares I, and the SRBs for the heavy lift cargo system remain as a requirement. A second level of joint sustainment would occur if Ares I is replaced, negating the need for the SRB first stage, and the heavy lift cargo system also turns out to not require SRBs. In the latter case, the question that has not been answered is: Do the civil or military sectors have a future requirement for large, segmented boosters? If not, then sustainment costs would solely focus on the strategic strike, missile defense, and much-reduced launch markets.

3.6.3 Recommendations

Two studies and resulting decisions are recommended. If NASA were to decide to use an HR Delta IV H as an Orion launcher, this approach would have to be accompanied by a study and resulting decisions on both the need for and the type of booster required for the heavy lift cargo system. The decisions from this study would then inform an independent, joint military and civil government study on the projected financial viability of the domestic large SRB providers and their associated supply chains, given various levels of reductions in future contracts. This joint study would also define a reasonable value for the amount of civil and military sustainment funding for the SRM industrial base if the government decided that the ability to design, develop, test, and manufacture large, segmented SRM boosters is a capability that is desirable to sustain into the future.

4. HR Delta IV H Impacts to National Security Space

Implementation of an HR Delta IV H for NASA's Constellation program can have both positive and negative impacts on the current DOD EELV program, and vice versa. Since these impacts cannot be assured of occurring, they should be viewed as opportunities (potential positive impacts) or risks (potential negative impacts). Either of these can be addressed using a standard risk management process, where the 5x5 matrices are focused on identifying and mitigating the greatest risks and pursuing the greatest opportunities. As a preliminary assessment, the most significant opportunities and risks are listed below.

4.1 Opportunities

Figure 11 identifies the opportunities available to the DOD from a NASA HR Delta IV H program. Aerospace believes the opportunities that can be realized are:

1. Improved CBC and engine production rates, which should improve unit costs.
2. Potential for transition to common heavy launch vehicle (HLV) configuration, which could streamline production and improve reliability for DOD launches.
3. Cooperative initiatives between NASA and DOD on Delta IV, which could benefit both programs.
4. Improved industrial base, which should enhance productivity of Delta IV suppliers.
5. Potential to accelerate transition to a common second stage between Delta IV and Atlas V, which would improve production rates and unit costs on all programs.

Although the Air Force Launch and Range Systems Wing (LRSW) launch programs do not have an opportunity management plan, the LRSW risk management plan was used to generate Figure 11 using the inverse risk values. Figure 11 shows the relative importance of the initially identified opportunities, while Table 5 lists the order of opportunities and recommended actions.

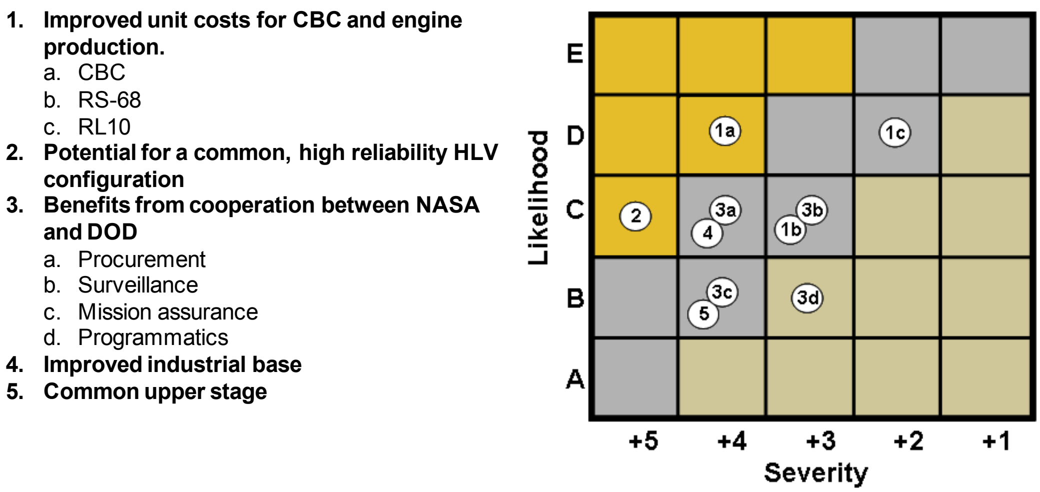

Figure 11. Preliminary HR Delta IV H NSS opportunity assessment matrix.

Table 5. Preliminary HR Delta IV H NSS Opportunity List

HR Delta IV NSS Opportunity Assessment				
Level	S	L	Opportunity Description	Recommended Action
HIGH	+4	D	Improved unit costs for CBC production	Assure through contract provisions
HIGH	+5	C	Common HLV	Perform trade study
MED	+4	C	Joint procurement between NASA and DOD	Cooperative agreement program
MED	+4	C	Improved industrial base	Assure through contract provisions
MED	+2	D	Improved unit costs for RL 10 production	Assure through contract provisions
MED	+4	B	Joint mission assurance between NASA and DOD	Cooperative agreement program
MED	+4	B	Common second stage	Perform trade study
MED	+3	C	Improved unit costs for RS-68 production	Assure through contract provisions
MED	+3	C	Joint surveillance between NASA and DOD	Cooperative agreement program
LOW	+3	B	Joint program between NASA and DOD	Cooperative agreement program

4.2 Risks

The LRSW risk management plan was used to generate Figure 12, which identifies the potential risks to the DOD from a NASA HR Delta IV program and shows the relative importance of the initially identified risks. Table 6 lists the order of risks and recommended actions. Aerospace believes that the potential risks are:

1. Potential interference at joint operating facilities at Cape Canaveral Air Force Station (CCAFS) due to personnel, development, operations, or safety conflicts.
2. Potential interference at joint production facilities at Decatur, AL due to personnel, development, operations, or safety conflicts.
3. Standdown due to anomaly/failure on HR Delta IV H program.
4. Reduced responsiveness to Air Force requirements; conflicts due to multiple contract types and requirements between Air Force and NASA.
5. Staffing/workload impacts due to proliferation of multiple review and control boards.
6. Potential interference with support infrastructure at Denver.

1. **Potential interference at joint operating facilities at CCAFS**
   a. SLC-37
   b. SLC-39
2. **Potential interference at joint production facilities at Decatur**
3. **Standdown due to HR Delta IV H anomaly/failure**
4. **Conflicts due to differing contract types and requirements**
   a. Supplier errors
   b. Responsiveness
   c. Problem reporting
5. **Reduced timeliness due to proliferation of multiple reviews and boards**
6. **Potential interference with support infrastructure at Denver**

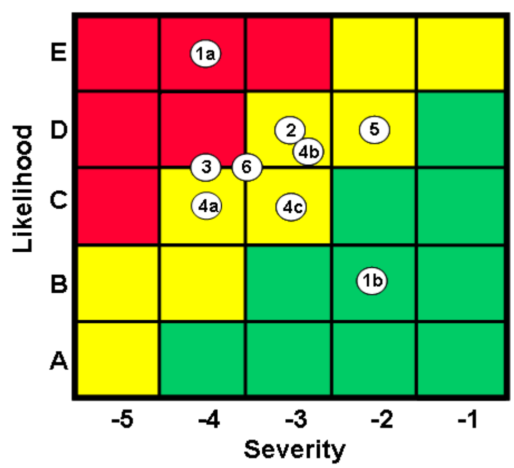

Figure 12. Preliminary HR Delta IV H NSS risk assessment matrix.

Table 6. Preliminary HR Delta IV H NSS Risk List

HR Delta IV NSS Risk Assessment				
Level	S	L	Risk Description	Recommended Action
HIGH	-4	E	Interference at joint SLC-37 operations	Select SLC-39 option
MED/HIGH	-4	C/D	Standdown due to HR Delta IV H anomaly/failure	Cooperative agreement program
MED	-4	C	Supplier errors due to requirements conflicts	Cooperative agreement program
MED	-3.5	C/D	Interference at joint Denver facilities	Perform trade study
MED	-3	D	Interference at joint production facilities	Cooperative agreement program
MED	-3	D	Responsiveness impacts due to HR program	Cooperative agreement program
MED	-2	D	Timeliness due to multiple reviews and boards	Cooperative agreement program
MED	-3	C	Problem reporting conflict errors	Assure through contract provisions
LOW	-2	B	Interference at joint SLC-39 operations	Select SLC-39 option

4.3 Single HR Delta IV H Configuration vs. Multiple Configurations

The hardware production impacts of an HR Delta IV H configuration will be highly dependent on the implementation strategy. Multiple HR Delta IV H configurations have the potential to create a significant impact to the NSS manufacturing and supplier base. For example, inconsistent requirements may cause confusion, whereas completely common systems may be unaffordable. To achieve the greatest benefit, a trade study that examines options of HLV CBC and second-stage commonality between DOD and NASA vehicles (e.g., structures, engines, avionics, controls, etc.) is needed as an opportunity pursuit. An optimum solution should be pursued that maximizes commonality as an overall cost-benefit solution from supplier manufacturing through launch operations. The trade study needs to consider whether implementation of the HR Delta IV H solutions on Air Force vehicles will result in an increased reliability for DOD missions. However, the improved reliability will increase launch vehicle weight and thus reduce mass-to-orbit for the DOD.

Improved production costs should be anticipated due to increased CBC, RL10, and RS-68 production rates. However, the maximum benefit can be expected only if a cooperative, joint Air Force/ NASA/ULA process is pursued that maximizes the returns to all stakeholders. Most of the opportunities identified rely on a comprehensive cooperative agreement coupled with contract provisions to realize the benefits.

A common 5-m second stage between non-HR and HR Delta IV H and Atlas V is another opportunity for cost savings due to production and performance commonality. The common-second-stage concept should be included as an option in the common Delta IV H trade study. Variables include various 4-m configurations vs. cost-benefits, when compared to the 5-m missions.

4.4 ULA, Second-, and Third-Tier Vendors

The majority of vendor suppliers of Delta IV H hardware are space hardware veterans with significant experience in NASA and Air Force programs. The launch-rate increases from Constellation are not considered onerous in terms of industrial capacity for these suppliers, and in fact, increased investment from a human-rated launch program should be a boon. New funding should have a ripple effect on supplier infrastructure and resources, resulting in improved support to DOD. However, the opposite could also occur. The focused demands from a human-rated launch program could draw attention from critical NSS needs. The greatest risk comes from a proliferation of multiple and diverse requirements and conflicting U.S. Government demands, which may impact DOD (and potentially NASA) programs in terms of priorities or staff support. A cooperative program between the Air Force and NASA that maximizes, to the extent possible, common supplier procurement requirements, joint contractor/supplier vigilance and production surveillance, and cooperative mission assurance processes with data and personnel sharing represents an opportunity for both agencies.

A significant risk identified for NSS missions is the potential standdown that would result from an anomaly/failure of HR Delta IV H hardware or software, whether it occurs prelaunch or during flight. Although the HR Delta IV H is expected to have an increased overall reliability, anomalies and failures are a fact of life in space launch operations, particularly during the developmental period. This risk would likewise apply to NASA missions. Therefore, a cooperative data-sharing program is paramount to minimize residual impacts. This should be viewed as a significant benefit of the cooperative action between the Air Force and NASA identified in the opportunity matrix provided in Figure 10.

4.5 Pad and Range Considerations

Impacts to the launch infrastructure by the addition of the Constellation program are to be expected. The use of Delta IV H with flight heritage will help mitigate range implementation impacts. However, the flight range-safety system will not be heritage. The launch rates remain the same for either system (Ares I or HR Delta IV H), and are not significantly different from today's situation with the shuttle. Range impacts are not considered a unique risk from implementation of an HR Delta IV H, and do not represent risks or opportunities that need to be specifically addressed at this time.

The launch infrastructure assessment identified potential operational impacts when sharing current Delta IV H infrastructure at SLC-37. Shared operations within SLC-37 could encounter operational, security, or safety conflicts, depending on the location and launch manifest requirements. Implementation of the SLC-39 launch option mitigates this risk since the likelihood of interference is considered low and should be isolatable between programs, except for range-driven requirements. These risks should be no more significant than current risks. Operating the HR Delta IV H/Orion operations out of SLC-39 also enhances the integrated operations with Ares V, but is not considered an influence in this NSS impact assessment.

4.6 NSS Impacts Summary

This preliminary assessment identified NSS opportunities and risks associated with the implementation of HR Delta IV H. Although the identification of these opportunities and risks may not be complete and are at a high level, Aerospace believes they capture the basic impacts that should be addressed. Although the risks may be realized, without intervention and management involvement, the opportunities will not be. Just as risk burn-down plans are appropriate to ensure they are appropriately managed, opportunity pursuit plans are appropriate to maximize the potential benefits. Based on this preliminary assessment, opportunities and risks appear to be inexorably linked for this program. Therefore, it is strongly recommended that any actions initiated to implement the HR Delta IV H concept be cooperatively managed by all primary stakeholders, and a formal opportunity management plan as well as a risk management program be implemented.

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5. HR Delta IV H Cost and Schedule

Estimates of the costs and development timeline, for both vehicles and facilities, of replacing Ares I with an HR Delta IV H were developed. Since Ares V is dependent in an architectural sense on certain system elements that were to be developed under Ares I, estimates of the impacts to Ares V cost and other Constellation elements, to the extent possible, were also developed.

5.1 HR Delta IV H Costs

Aerospace developed DDT&E costs and lifecycle cost estimates for the HR Delta IV H launch vehicle configurations. Cost estimates are reported at the 21-percent confidence level, which is consistent with the Ares I cost-confidence level documented in the Constellation program's program management review (PMR) 2008 Rev. 1 Confidence Level Analysis, October 2008.

Model-based estimates were developed using concept-level information from the engine, first stage, second stage, production, ground processing, and launch facilities assessments. These models were calibrated using historical costs for the principal launch vehicle assemblies and recent ground processing infrastructure developments. NASA estimates to complete (ETC), based on PMR 2008 Rev. 1B data, were used when considering NASA-designed and fabricated hardware, such as cost-to-go on development of the Ares I SRB, J-2X engine, and NASA-owned and -operated facilities. It was assumed that the work done to-date on elements was not lost. ULA cost data also informed the cost modeling.

NASA civil service workforce costs were addressed by defining a launch system project integration (LSPI) cost factor. This LSPI cost factor was used to estimate NASA costs for program management, systems engineering and integration, mission assurance, and provisioning at various levels within the program. LSPI costs were based on historical program wraps (ULA, KSC, MSFC, and Johnson Space Center (JSC)), which ranged from 27 percent to 32 percent of the program acquisition and operations costs. NASA-provided costs assumed full cost accounting, which includes a civil service workforce. LSPI costs of 27 percent were used in these cases to avoid double-booking costs. Aerospace estimates for non-NASA hardware include the 32 percent LSPI cost factor to reflect the possible application of additional NASA workforce not included in the estimating process.

DDT&E costs include the development of the launch vehicle, fabrication, ground processing and launch facilities, systems engineering and integration, contract termination or transition, and fee. The two system flight tests used two sets of full flight hardware. Lifecycle cost includes the development cost, along with the fixed and recurring costs of production and operations for 14 LEO flights, as well as sustaining program management, systems engineering, and mission assurance workforce.

NASA's Ares I ground processing and launch facilities development costs-to-go include Ares I and non-Ares I infrastructure costs, such as Ares V- and Orion-specific facilities costs, Ares I RSRM processing facilities costs, and KSC distributed workforce costs that benefit Ares I and other programs. These non-Ares-I-related costs, totaling $956M FY 2009, were removed for the purposes of comparing costs to HR Delta IV H.

HR Delta IV H lifecycle costs, including DDT&E, production, and operations costs for 14 ISS flights through the end of FY 2020, compared to Ares I costs-to-go, are shown in Figure 13. Possible crewed lunar flights in the 2019-2020 timeframe are not included in this number. Configurations 2, 3, and 4 show options A, B, and C, which correspond to the processing and launch options shown in Table 3. Option A is processing and launch from a new SLC-37A. In option B, the first stage is processed in the SLC-37 HIF and launched from SLC-39B. In option C, the first stage is processed in the OPF and launched from SLC-39B. Configurations 1, 5, and 6 assume option A for processing and launch.

DDT&E costs range from approximately $8B FY 2009 for configurations 2 and 3, to approximately $6B FY 2009 or less for configurations 4, 5, and 6. Configuration 1 is the existing non-human-rated Delta IV H vehicle as a reference point. It does not meet NASA's definition of human-rating. The major contribution to DDT&E in this case is the development of a new launch pad and the associated systems engineering and integration costs. Configurations 2 through 6 all utilize three HR Delta IV H CBCs for the first stage with a human-rated RS-68B engine. Configuration 2 utilizes the present design of the Ares I second stage with no modifications to highlight potential cost savings without redesign of the second stage or re-competition of the second-stage contract. Configuration 3 utilizes a new resized second stage with a single J-2X engine. Second-stage fabrication for both configurations 2 and 3 is done at the MAF. These configurations take maximum advantage of work on the Ares I second-stage development and J-2X engine development. Configuration 4 utilizes a new second stage with four RL10A-4-2 engines. It is developed by ULA and assumed to be fabricated in the Decatur, AL production facility using existing tooling. DDT&E cost reductions are due to the lower cost of modifying the existing RL10A-4-2 engine vs. the costs-to-go on the J-2X development, and savings associated with the MAF production line DDT&E for the second-stage fabrication. Configuration 5 does not use a second stage, and therefore results in additional DDT&E cost savings. Configuration 6 is similar to configuration 4, but utilizes a single RL10A-4-2 engine second stage.

The addition of production and operations costs bring the total to $19B FY 2009 for configurations 2 and 3, to approximately $16B FY 2009 or less for configurations 4, 5, and 6. As can be seen from Figure 13, there are no savings in lifecycle cost for HR Delta IV H configurations that utilizes a J-2X-based second stage. There is an approximate $3B FY 2009 savings in lifecycle cost for HR Delta IV H configurations that use a new human-rated RL10A-4-2-based second stage. There is $6B FY 2009 savings for configurations that use a modified single-engine RL10-derivative second stage, or no second stage, with lower performance margin than the four engine RL10-derivative second stage option. Matching Ares I gross performance may be achievable for these types of configurations, through a more detailed examination of the trade space. Production costs for configurations 2 and 3 are similar to Ares I production costs due to the fixed costs of production at the MAF. The fixed and variable cost of HR Delta IV H first-stage hardware production, using enhanced levels of fabrication process control and quality assurance to support human-rating, is approximately the same as the costs of refurbishing the reusable Ares I solid first stage. Configuration 4 shifts the fixed and variable cost of second-stage production in the MAF to Decatur, and may save approximately $1B FY 2009 over the 14 flights due to the sharing of fixed costs between NASA and DOD customers. The elimination of the second stage in configuration 5, or the use of a modified single-engine 5-m DCSS, reduces production and operations costs further.

The costs reported in Figure 13 do not include any additional carrying costs to fund hardware elements developed under Ares I but also needed for Ares V. These would include the J-2X engine, and forward work on the Ares I SRB that would benefit Ares V. A discussion of the cost impacts of HR Delta IV H on Ares V is provided in section 5.3.

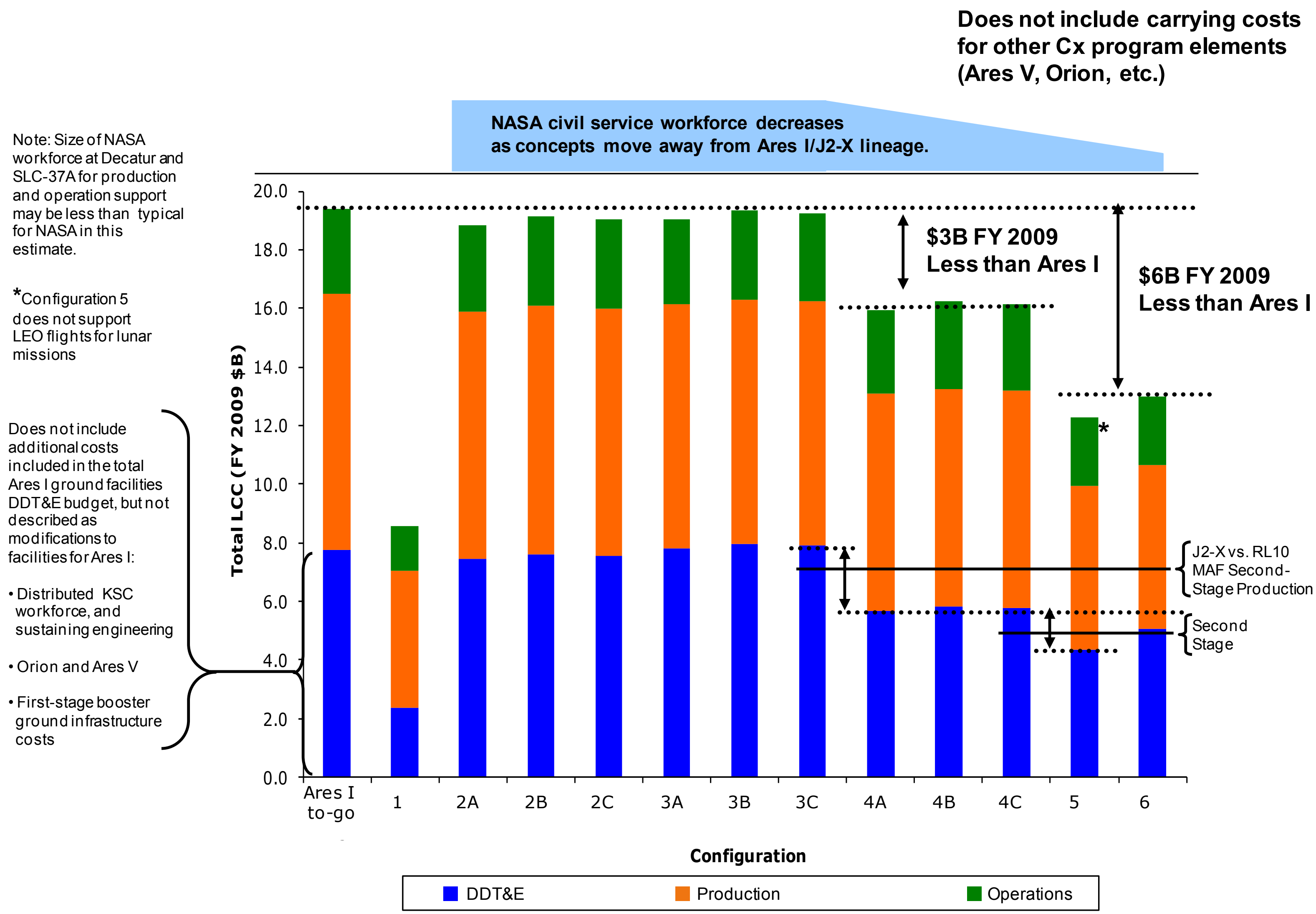

Figure 13. Lifecycle costs for HR Delta IV H compared
to Ares I (at 21 percent confidence level without carrying costs).

5.2 HR Delta IV H Development Time

Development time estimates for the HR Delta IV H configurations were based on expert assessment and comparison to recent historical launch vehicle element and ground infrastructure element developments. First, the scope and complexity of tasks associated with human-rating the existing Delta IV H first stage, modification or development of new second stages, and ground processing and launch pad modifications were estimated. Next, expert judgment, informed with historical data, was used as the basis of estimate for the time required to accomplish each task. Finally, the task-duration estimate was assembled into schedule elements, and assigned precedence and linkages to establish a full HR Delta IV H-program development duration estimate.

Estimated work scope included human-rating modifications to engines, first stage, and second stage, based on current understanding of Ares I human-rating strategy. Primary drivers included: 1) a 1.4 structural factor of safety on first stage; 2) engine combustion chamber structure; 3) mechanical, electrical, and data interfaces between first stage, second stage, and Orion; 4) additional sensors; and 5) implementation of autonomous or commanded abort and destruct with override. Also included were estimates for the qualification program and hardware fabrication time.

Modifications were assessed against the scope of work in recent historical developments, including the Delta IV H upgrade program (~ 42 months), the Delta IV H CBC design and development (~76 months), and the DCSS design and development (~60 months). It was assumed that the RS-68B engine development program start is shifted forward to begin in December 2009, and human-rating tasks are incorporated within that program such that this engine would be available in a timeframe consistent with the HR Delta IV H.

The only examples of the use of existing U.S. launch vehicles to carry crew were the Atlas booster for Project Mercury (IOC in 1961), and the Titan II rocket for Project Gemini (IOC in 1965). Development times for these projects were relatively short (~39 months). The work scope to accommodate the Mercury and Gemini spacecraft and support crew safety pre-dates current safety standards and human-rating requirements, and is therefore incomplete relative to the human-rating implementation proposed for Ares I and HR Delta IV H. Political imperatives of that era also contributed to an accelerated development timeline for these programs.

Aerospace did not assess uncertainty or viability of the current Constellation program IOC date. The current Constellation program IOC commitment data and IOC cost-level estimate do not consider schedule uncertainty. NASA is currently performing a schedule risk analysis at level 2 for each of the Constellation program elements, including Ares I. This analysis was not available for inclusion in this study.

Two bounding development times were estimated: 1) a nominal schedule, which is an estimate of the average time needed to complete the HR Delta IV H DDT&E; and 2) a conservative upper-bound estimate, which included more pessimistic estimates of the time needed to complete development and testing. The nominal and upper-bound development-time estimates included an initial 12-month preliminary architecture design period to resynchronize the element designs (e.g., Orion, ground infrastructure) with the change in launch vehicle. Launch system elements (such as stages, engines, and ground facilities) start six months into this architecture design phase. In cases where contract re-competition or transition was needed, such as with a new second stage, the start was delayed an additional six months, to the end of the architecture design phase. System flight-test preparations start eight months before the ground facilities and launch pad IOC, with the first launch at ground facilities IOC. The first or second system flight tests were not required to use or operate full flight hardware (even though costs were estimated that way), depending on the configuration and where the flight hardware readiness fell relative to the facilities IOC.

Figure 14 shows the total program development time for the various HR Delta IV H configurations. Nominal HR Delta IV H system development times range from 5.5 to 7 years. The lower end of the nominal range is from configuration 1, where the majority of the development effort is associated with the design and construction of the new SLC-37A launch facility. There are no launch vehicle modifications associated with configuration 1. Other contributors to the lower-end estimate, that are required for all configurations, include an architecture design re-synchronization period before the start of development, and a system flight test period starting once the new launch facility is ready. The upper end of the range corresponds to configurations 2, 3, and 4, and the use of SLC-39B. In these cases, the development of the human-rated RS-68B engine, or the new second stage, is the driver. Configurations 3 and 4 also require time, prior to the start of development, for re-competition and selection of the new second stage contractor. SLC-39B development is estimated to take longer to complete than that for SLC-37A.

Figure 15 shows the development time estimates for each of the major launch system elements as they would be generally phased relative to the start of the project. As can be seen, the ground facilities development and test program is the longest duration item. The new second stage development is the pacing item due to its later start. However, the other launch vehicle element developments are the same or only slightly shorter. This suggests that the critical path for an HR Delta IV H program development may include multiple launch system and ground infrastructure elements.

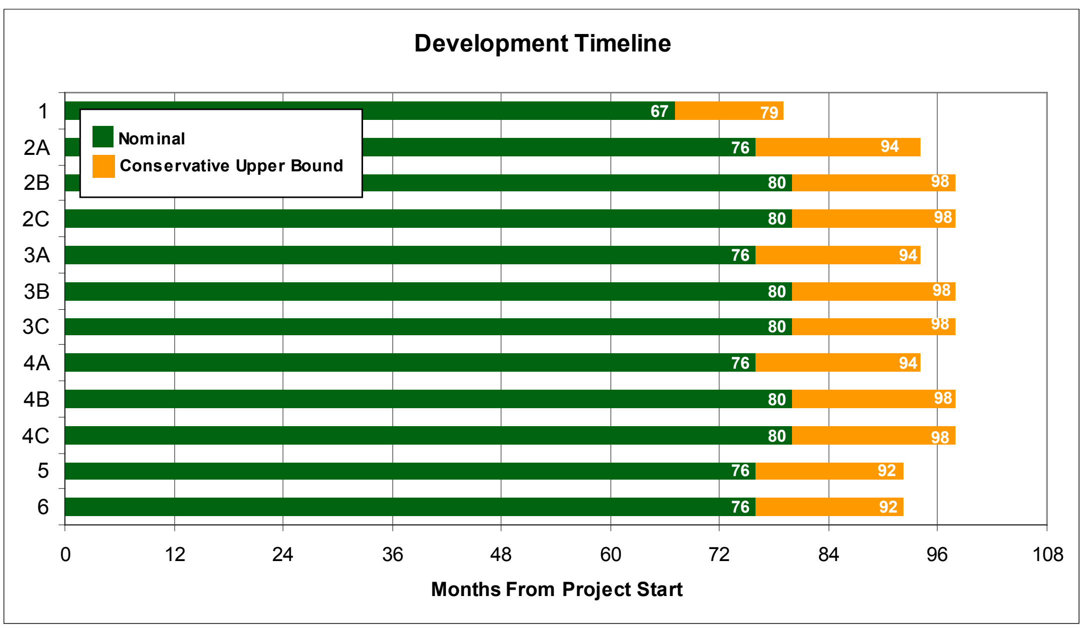

Figure 14. HR Delta IV H development time estimates.

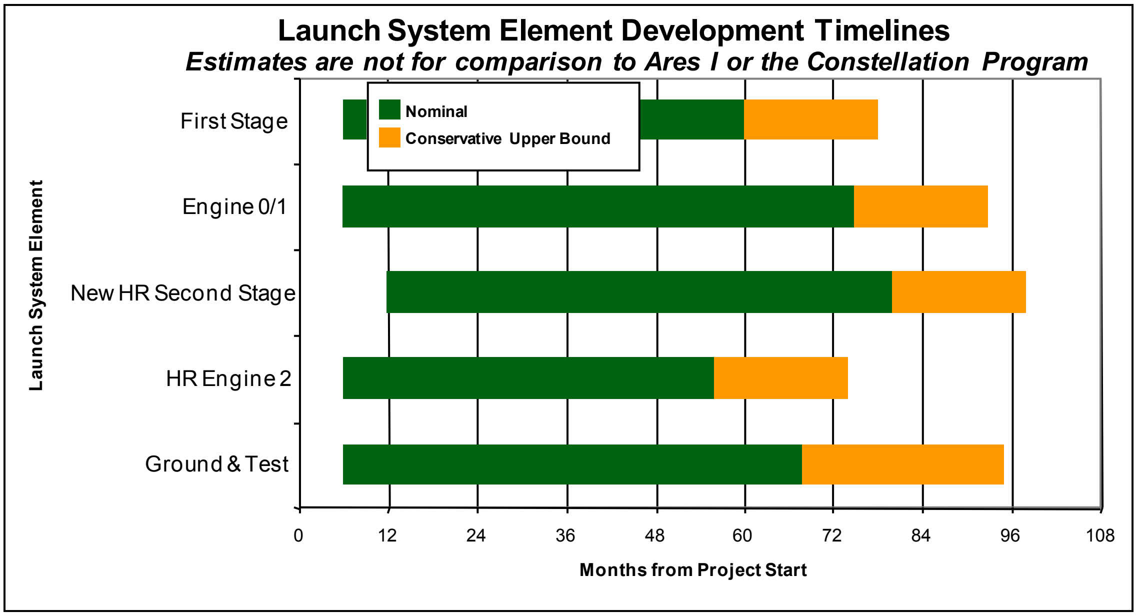

Figure 15. HR Delta IV H development time estimates
for the major launch system elements.

An operational schedule consideration is the ground- and launch-processing cycle time during operations. The elimination of the pad refurbishment time associated with the use of a solid first stage reduces the pad turn-time for HR Delta IV H relative to Ares I.

5.3 Impact on Cost for Ares V without Ares I

The primary cost impact on the Constellation program, due to substitution of HR Delta IV H for Ares I as CLV, relates to Ares I DDT&E effort that will be transferred from Ares I to Ares V. Ares V as the solution for the CaLV relies on Ares I to develop flight hardware elements, ground processing and launch infrastructure, and production facilities common to both vehicles. The two major areas of hardware commonality between Ares I and Ares V are the Ares I SRB and the J-2X engine. NASA assumes the 5-segment Ares I first-stage SRB as the point of departure for the 5.5-segment Ares V SRB. The Ares V second stage and the Earth departure stage (EDS) use the J-2X engine that is assumed to be developed by Ares I.

The additional Ares V DDT&E effort for completing the 5-segment SRB and the J-2X engine is quantifiable, based on the current DDT&E estimates for these items under Ares I. Cost impacts associated with production sustainment or impacts to other Constellation elements require further study. NASA estimates an additional $16.6B FY 2009 in carrying costs for the four RL10A-4-2 engine second-stage HR Delta IV H configuration, but not less than $14.1 FY 2009 for any HR Delta IV H configuration, beyond the total Ares V DDT&E cost impacts. Aerospace has not independently verified these figures or their underlying assumptions.

Figure 16 shows the total Ares V DDT&E costs (not including carrying costs) associated with each of the HR Delta IV H configurations examined. The vertical axis is the total DDT&E cost for Ares V for each of the CLV options shown on the horizontal axis. The left-most bar represents the total DDT&E cost of Ares V with Ares I; the next bar represents the total DDT&E cost of Ares V, with the

HR Delta IV H configuration I substituted for Ares I; and so on. Configurations 2, 3, and 4 show options A, B, and C, which correspond to the processing and launch options discussed above. Configurations 1, 5, and 6 assume option A for processing and launch.

Total DDT&E costs for Ares V range from approximately $11B FY 2009 for Delta IV H configurations using RL10A-4-2-based second stages or no second stage and SLC-37; to approximately $8.5B FY 2009 for Delta IV H configurations using J-2X-derived second stages and SLC-39. This total DDT&E cost range includes the baseline Ares V DDT&E cost of $7.4B FY 2009, plus the estimate to complete the Ares I SRM DDT&E, the J-2X engine DDT&E, and applicable SLC-39 processing infrastructure when not used by HR Delta IV H.

The baseline Ares V DDT&E cost estimate is based on an assessment of NASA's PMR 2008 Rev. 1B data, using engineering judgment to discriminate between DDT&E funding intended for Ares I vs. Ares V. The baseline Ares V vehicle first stage includes two 5.5-segment PBAN-based propellant steel-cased RSRMs. An alternative to the baseline using expendable SRBs with an HTBP-based propellant and composite casing improves first-stage performance for an additional DDT&E cost of approximately $1B FY 2009.

The Ares I budget includes non-Ares I costs removed for the Ares I cost comparison provided in section 5.1. These costs are in the total Ares I ground facilities DDT&E budget, but are not described as modifications to facilities for Ares I. They include distributed KSC workforce, sustaining engineering, Ares V facilities and infrastructure, and SRB ground infrastructure costs. The majority of these costs contribute to RSRM and Ares V processing facilities, and the distributed workforce that supports Ares I/Ares V common planning and infrastructure. These are included in the baseline Ares V DDT&E cost.

None of the HR Delta IV H configurations use a SRB first stage. In the absence of Ares I, the full DDT&E costs-to-go of the Ares I SRB would be carried by Ares V. NASA assumes that much of the development of the Ares I SRB would directly benefit the Ares V SRB. However, there are some elements, such as the nozzle, the forward reverse frustum, and the thrust oscillation management system that would not be required in the absence of Ares I. Since the fraction of Ares I SRB DDT&E costs for these elements is unknown, Figure 16 adds the full ETC cost based on PMR 2008 Rev. 1B data, starting in the fourth quarter of FY 2009, to the total DDT&E cost for Ares V. This cost assumes that the production infrastructure to manufacture test and flight articles is deferred and funded as part of an optimized industrial base sustainment program during the seven-year standdown before it is needed for Ares V. The inclusion of production infrastructure development for test and flight article fabrication would add another $1.1B FY 2009 to the Ares I SRB ETC.

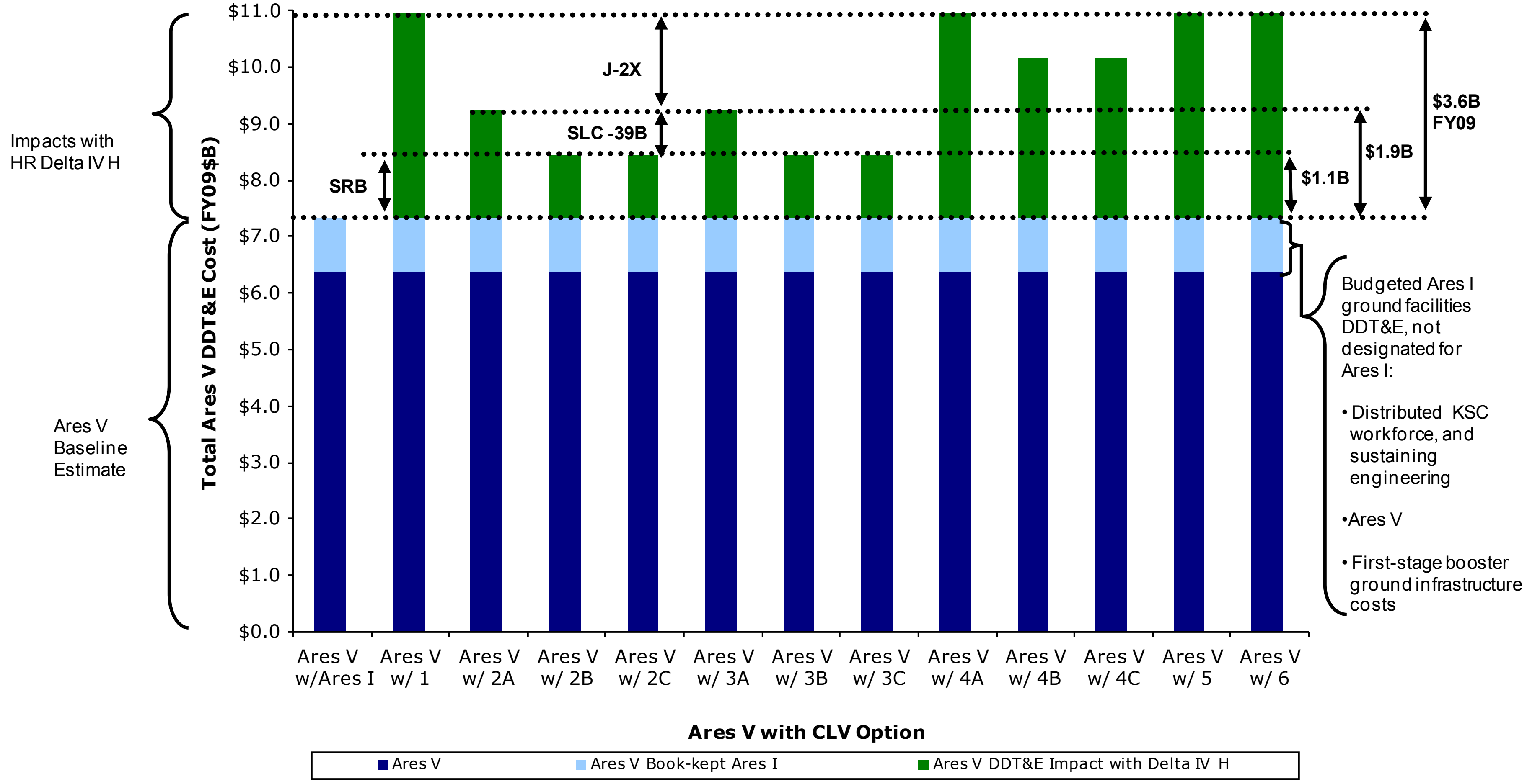

Figure 16. Total Ares V DDT&E cost impacts from HR Delta IV H.
(NASA-provided carrying costs not included)

Some of the HR Delta IV H configurations utilize a J-2X-based second stage, while others do not. For those HR Delta IV H configurations that do not utilize the J-2X engine, DDT&E cost ETC from the fourth quarter of FY 2009 is added to the Ares V DDT&E. The J-2X engine has recently passed its CDR, and long-lead items and test facilities are in development. Since there currently is no existing J-2X engine production capability, it may be possible to extend its development period and minimize the cost impact of delaying the first flight date of the engine by five years. Increased production of the RL10 and RS-68 engines associated with HR Delta IV H may offset J-2X engine production impacts.

For the HR Delta IV H configurations that use a new launch facility at SLC-37A, the DDT&E cost for selected ground processing and launch infrastructure planned under Ares I, and beneficial to Ares V, must be added to the total Ares V DDT&E. This includes VAB modifications, SLC-39 LCC and ground control center (GCC) upgrades, launch equipment test facility (LETF) upgrades, and miscellaneous GSE. For configurations where the HR Delta IV H launches from SLC-39B, these additional costs are included as part of the HR Delta IV H development program but are not added to the total Ares V DDT&E.

To account for additional program management, systems engineering, and mission assurance for these additional hardware and infrastructure developments, an LPSI wrap factor of 27 percent was applied to the DDT&E costs of the RSRM, J-2X, and ground infrastructure cost impacts. An additional 12-percent fee on those same elements was also included.

To the first order, there are no cost impacts to the Ares V EDS resulting from design changes due to the switch to HR Delta IV H. The new HR Delta IV H second stage adopts the Ares I avionics development, which is assumed to benefit the EDS avionics. Since the new HR Delta IV H second stage is designed to meet Orion interfaces, Ares V would see an equivalent benefit to EDS range safety, thermal, and separation analysis on a new HR Delta V H second stage as it would from the Ares I second stage. Some cost impacts to the EDS production are assumed under carrying costs for MAF sustainment, but have not been assessed.

It is conservatively assumed that the transition from Ares I to HR Delta IV H will have some cost impact to Ares V design and development due to displacement of some of the NASA civil service workforce. However, the magnitude of the cost impact cannot be assessed without further study.
A significant portion of the NASA workforce providing engineering and development support on the Ares I first stage, second stage, and ground infrastructure will continue in similar roles, supporting the necessary engineering analysis and acquisition planning for the human-rating modifications for HR Delta IV H.

5.4 Impact to Ares V Schedule

Specific impacts to the Ares V development schedule related to the transition from Ares I to HR Delta IV H have yet to be assessed. Aerospace has assessed the overall affordability of the Ares I/ Ares V architecture. These assessments considered budgeted cost and planned schedule for each project within the Constellation program portfolio (e.g., Ares I, Ares V, extra-vehicular activity (EVA), Orion, Altair, ground operations, etc.) in order to fit the entire portfolio to the overall program budget, by adjusting individual project schedule durations and the relative phasing between projects. Though these analyses do not have the level of fidelity normally desired to serve as a basis for decision-making, there are three observations on Ares V development time impacts that can be drawn:

- Since the Constellation program's annual budget is fixed, there are no additional resources available either to accelerate individual programs or projects, or build-up additional program-level reserves to mitigate risks. Because of this cost constraint, the IOC date for Ares V cannot be accelerated in any significant way, regardless of the choice of CLV option. Funding for Ares V development will not available until 2011, when Orion DDT&E passes its peak annual funding level and begins to ramp down. The DDT&E cost and schedule impacts to Orion, due to its transition from Ares I to HR Delta IV H, may delay the funding start for Ares V by one year.

- Under the current Constellation program planning, Constellation project interdependencies and budgets in the out-years beyond 2015 appear to be less tightly coupled and constrained as compared to the planning in the 2009-2015 timeframe. There is also considerable budget reserve planned in the out-years, such that the Ares V DDT&E and production standdown cost impacts from HR Delta IV H can be absorbed within the 2016-2020 budget allocation without impacting the Ares V baseline IOC.

- An earlier start and completion of the development of the human-rated version of the RS-68B, to support HR Delta IV H, removes this engine upgrade from the Ares V schedule and eliminates a possible critical path item. Incorporation of human-rating activities into the RS-68B development program are included in the HR Delta IV H DDT&E costs, and therefore do not impact overall Ares V development schedule.

Development schedule impacts associated with the alternative Ares V baseline that uses an HTBP-based SRM propellant and composite casing are primarily in the area of risk-reduction testing. Proof testing of the composite case joints may require multiple burst tests of the center booster segments, the interfaces between the cylindrical sections, and the dome at the forward end of the booster casing. This new booster development will require at least as many static firing tests as the Ares I booster and possibly more, considering the lack of heritage to the steel-cased STS booster. This schedule impact is estimated at 12 months, against the current Ares V baseline IOC date.

6. Summary of Key Findings

This report documents potential impacts to the Constellation program and NSS should NASA decide to move to an HR EELV for the crew-launch function. Specifically, the Delta IV Heavy was examined as to whether it could serve the crew-launch function, and if so, the impacts to the launch vehicle, production, and launch-base processing and fabrication. The impact on the Constellation architecture elements of replacing Ares I with a human-rated version of Delta IV H was assessed. Costs and development time for replacing Ares I with an HR Delta IV H as well as the impacts to Ares V cost and development time and other Constellation elements were assessed.

6.1 Technical Feasibility

It is technically feasible to human-rate the Delta IV H, following a human-rating design implementation approach equivalent to that used for Ares I. The addition of human-rating requirements results in changes to the Delta IV H hardware, software, fabrication, and processing flow, and most likely the development of a new, human-rated second stage. Hardware and software changes address improvements in fault tolerance and structural factor of safety margins, delayed destruct abort separation sequencing, and functional enhancements, including the use of Ares I-derived avionics to support crew function and interfaces between Orion and the new second stage.

Delta IV H first- and second-stage engines can be human-rated. For most HR Delta IV design options studied, the payload performance to the ISS and lunar target orbits provides significant positive margin with respect to Ares I ISS and lunar gross performance. HR Delta IV H can manage abort re-entry g-loading via constraints on ascent trajectory optimization in order to achieve abort capability over the full performance envelope. Aerospace's recommended option utilizes a new second stage with four RL10-derivative engines to meet HR requirements with the added benefit of engine out capability.

New second-stage configurations (J-2X or RL10-A-4-2) are technically feasible. Their payload performance to ISS and LEO target orbits provides significant margin with respect to Ares I for most options studied. A human-rated version of the existing Delta IV H single-engine second stage (configuration 6) may not have enough performance margin to meet Ares I performance targets. The no-second-stage configuration (e.g., the Orion service module as second stage) shows feasible performance to the ISS target orbit, but not the lunar target orbit.

The increases in production and hardware transportation for HR Delta IV H can be accommodated within existing capability. HR Delta IV H can utilize Ares I hardware and ground-processing infrastructure elements. The Decatur, AL facility production capacity can accommodate NSS and civil EELV missions plus Constellation through 2019, to support launches through 2020. Moreover, a significant fraction of the elements, workforce, and facilities existing or planned for Ares I can be used for HR Delta IV H. Launch and ground processing facilities can be modified or newly fabricated to accommodate HR Delta IV H.

6.2 Constellation Impacts

Significant payload performance margins to ISS and lunar target orbits for HR Delta IV H may make delivery of additional mass to the ISS or lunar rendezvous target possible. It is unclear to what extent increased "up mass" would benefit the existing Constellation architecture. Additional performance capability may also allow margin to be added to the vehicles to improve safety or redundancy.

The most attractive launch processing infrastructure concept is at the OPF at SLC-39 for first-stage processing, and launch from a modified SLC-39B complex. The key benefits are isolation from DOD Delta IV H operations, integration with Ares V operations, and marginal cost and schedule differences. A significant fraction of the elements, workforce, and facilities existing or planned for Ares I can be used for HR Delta IV H. For all cases considered, substantial civil service workforce at MSFC, KSC, and JSC; the A-3 test stand; and Ares I avionics were used to maximize use of in-development systems, personnel, and infrastructure. The processing time for Ares I was found to be longer than for HR Delta IV H due to longer pre-launch processing and post-launch pad refurbish times associated with the use of the SRBs.

Impacts on the Ares V SRB and second stage are highly dependent on HR Delta IV H programmatic and design assumptions. The main consideration is maintenance of the SRM industrial base required for Ares V. Both Ares I and Ares V use PBAN binder in the solid propellant mixture. For cases utilizing a RL10-based second stage, a second consideration is the development of the J-2X engine needed for the Ares V second stage. The absence of Ares I reopens the opportunity to consider expendable, composite-wrapped HTPB RSRM, which has higher performance and results in a smaller liquid core. Utilizing an RL10-based second stage for HR Delta IV H would require the Ares V program to develop the J-2X engine.

A top-level, qualitative review of the Orion modifications indicated that the technical impacts to Orion are manageable, since most impacts can be absorbed in development of the new HR Delta IV H second stage. Technical considerations for Orion transition from Ares I to HR Delta IV H include revisiting physical and functional interfaces, mission design, and environmental analysis including aero-thermal, aero-acoustic, and integrated dynamic loads analysis. In general, the HR Delta IV H launch and flight environment is expected to be more benign than that of Ares I, due to the lack of first-stage thrust oscillation and the lower-thrust, lower-mass second stage.

6.3 SRM Industrial Base Impacts

There are only two suppliers of large SRMs in the nation today: ATK and Aerojet. The SRM market is divided into three classes of products: strategic, missile defense, and launch. ATK is the only supplier of the large, segmented solids to be used on Ares I and Ares V. There is a critical need for a joint civil and military assessment of the financial viability of the SRM industrial base, assuming: 1) no Ares I SRB first stage but SRBs for the heavy lift cargo launch system; and 2) no Ares I SRB first stage and no SRBs for the heavy lift cargo launch system. This study should also determine the future national need for a large, segmented SRM capability and the funding required to ensure its viability if deemed necessary.

A NASA decision that neither Ares I nor Ares V SRBs are required, without funding to sustain the necessary set of skills over an indefinite period of time, would essentially end the national expertise in large, segmented SRMs, and result in a smaller SRM industrial base where both ATK and Aerojet had the same approximate sales volume. The impact of these actions on the remaining SRM industrial base remains to be assessed.

6.4 National Security Space Program Impacts

There are significant risks and opportunities inherent to NSS from a NASA HR Delta IV H program. The increased production rates from the human-rated launch program should have positive effects on ULA hardware cost and reliability, as well as the ULA vendor industrial base. This should result in improved support to the DOD. However, the focused demands from a human-rated space program could draw attention from critical NSS needs. The greatest risk comes from a proliferation of multiple and diverse requirements and conflicting U.S. Government demands, which may impact DOD (and potentially NASA) programs in terms of priorities or staff support. It is strongly recommended that any actions be cooperatively managed by all stakeholders via a formal risk and opportunity management program.

Multiple HR Delta IV H configurations have the potential of creating a significant impact to the NSS manufacturing and supplier base. Inconsistent requirements may cause confusion, whereas completely common systems may be unaffordable. To achieve the greatest benefit, a trade study that examines options of HLV CBC and second-stage commonality between DOD and NASA vehicles (e.g., structures, engines, avionics, controls, etc.) is needed as an opportunity pursuit. An optimum solution should be pursued that maximizes commonality as an overall cost-benefit solution from supplier manufacturing through launch operations. The trade study needs to consider that implementation of the HR Delta IV H solutions on the Air Force launch vehicles will result in an increased reliability for DOD missions.

Improved hardware production costs should be anticipated due to increased CBC, RL10, and RS-68 production rates. However, the maximum benefit can be expected only if a cooperative, joint Air Force/NASA/ULA process is pursued that maximizes the returns to all stakeholders. Most of the opportunities identified rely on a comprehensive cooperative agreement coupled with contract provisions to realize the benefits.

A significant risk to NSS missions is the potential standdown that would result from an anomaly/ failure of HR Delta IV H hardware or software, whether it occurs prelaunch or during flight. Although the HR Delta IV H is expected to have an increased overall reliability, anomalies and failures are a fact of life in space launch operations, particularly during the developmental period. This risk should also be considered reciprocal to NASA missions. Therefore, a cooperative data-sharing program is paramount to minimize residual impacts. This should be viewed as a significant benefit of the cooperative action between the Air Force and NASA.

The launch infrastructure assessment identified potential operational impacts when sharing current Delta IV H infrastructure at SLC-37. Shared operations within the SLC-37 complex could encounter operational, security, or safety conflicts, depending on the location and launch manifest requirements. Implementation of the SLC-39 launch option mitigates this risk, since the likelihood of interference is considered low and should be isolatable between programs, except for range-driven requirements. These risks should be no more significant than current risks. Operating the HR Delta IV H/Orion operations out of SLC-39 also enhances the integrated operations with Ares V, but is not considered an influence in this NSS impact assessment.

6.5 Cost Impacts

The DDT&E and lifecycle cost (DDT&E plus 14 flights to ISS through 2020) for HR Delta IV are equal to or lower than Ares I costs. There is no change in lifecycle cost for HR Delta IV H configurations that utilize the Ares I J-2X-based second stage. There is a $3B to $6B FY 2009 reduction in lifecycle cost for HR Delta IV H, depending on whether a new four-engine RL10-derivative second stage, a modified single-engine RL10-derivative second stage, or no second stage is used.

Total DDT&E cost for Ares V (not including carrying costs) ranges from $8.5B to $11B FY 2009, or an increase of $1.1B to $3.5B FY 2009 depending on the HR Delta IV H configuration. This cost range includes the baseline Ares V DDT&E cost, the balance of J-2X and SRB DDT&E cost, and new KSC launch infrastructure cost that applies to each configuration. This cost range does not include carrying costs such as the design, production, and processing infrastructure and industrial base capabilities that are needed for Ares V but are not required for HR Delta IV H. Sustaining the large, segmented SRM industrial base is the largest contributor to the identified carrying costs.

The MAF and the SRB processing facilities at KSC may incur sustainment costs until needed for Ares V. Carrying costs associated with delaying J-2X production may be offset by additional RL10 and RS-68 production for HR Delta IV H, but this requires further industry study. Other ground processing facilities at KSC, such as the launch pad, the VAB, and the OPF may incur sustainment costs until needed for Ares V, if the SLC-39 option is not used for HR Delta IV H. The cost for Orion depends, in large part, on design maturity at the point in time when the decision is made to switch from Ares I to HR Delta IV H. The primary work content for Orion would not change. However, since Orion physical and functional interfaces, mission design, and environmental analyses need to be revisited, additional cost would be incurred to support these new analyses. There may be some carrying costs associated with temporary displacement of the civil service workforce during the transition from Ares I to HR Delta V H. However, a significant fraction of the workforce would be preserved, as the HR Delta IV hardware would require a level of design, systems engineering, mission assurance, and fabrication oversight equivalent to that for Ares I. NASA estimates an additional $16.6B FY 2009 in carrying costs including impacts to Orion for the most promising HR Delta IV H configuration, but not less than $14.1B FY 2009 for any HR Delta IV H configuration, beyond the total Ares V DDT&E cost impacts shown above. NASA assumes the additional cost includes maintaining the SRB industrial capability, impacts to Orion, impacts to ground operations, and impacts associated with other programmatic and workforce considerations. Aerospace has not independently verified these figures or their underlying assumptions.

6.6 Schedule Impacts

The nominal HR Delta IV H development time is estimated to be on the order of 5.5 to 7 years. No comparative or feasibility analysis was performed for the Ares I planned IOC date. The impact to the Ares V overall schedule is expected to be minimal since the J-2X and SRB need-date is not driven by the 2015 ISS requirement but by the lunar mission requirement in the 2020 timeframe.

The HR Delta IV H ground facilities development and test program is the pacing item. However, other launch vehicle element development times are only slightly shorter, suggesting the critical path may include both launch system and ground infrastructure elements.

The overall schedule impact to Ares V is expected to be minimal. The J-2X and SRB need-date is not driven by the crew transportation to ISS requirement, but by the lunar mission cargo requirement in the 2020 time frame. This results in a delay in the start of the production of test and flight articles, during which time the industrial and technological capability to produce these launch vehicle hardware elements must be sustained.

The impact to the Orion schedule is also expected to be minimal, and enveloped by an assumed design period following Ares I cancellation. There is an assumed six-month period for assessing modification to existing Delta IV H elements, and a 12-month period to re-compete the contract for the new second stage. These assumptions place Orion at its current level of design maturity that will be described at the August 2009 PDR. Since the delay due to Orion impacts is less than the delay due to the overall HR Delta IV H development, Orion would not be on the critical path.

Aerospace did not assess uncertainty or viability of the current Constellation program IOC date. The current Constellation program IOC commitment data and IOC cost-level estimate do not consider schedule uncertainty. NASA is currently performing a schedule risk analysis at level 2 for each of the Constellation program elements, including Ares I. This analysis was not available for inclusion in this study.

6.7 Conclusion

In 2008, NASA asked Aerospace to examine EELV to assess affordability of replacing Ares I with an HR EELV as a means of human spaceflight to the ISS and lunar target. In early 2009, Aerospace was asked to refine and update the analyses with new assessments of HR Delta IV H production and ground processing infrastructure; payload performance to ISS and lunar target orbits with Orion abort constraints; hardware changes associated with human-rating the Delta IV H booster and second-stage engine; and cost and schedule estimates of an HR Delta IV H development program. Aerospace was also asked to develop a plan for a future, more comprehensive study on a specific implementation approach for Delta IV H, consistent with the Ares I implementation.

This report represents a summary of these assessments. It documents the results and findings of analyses to date, including a more recent examination of potential impacts to the Constellation program and NSS should NASA decide to move to an HR EELV for the crew-launch function.

The Aerospace Corporation has prepared this HR Delta IV H study to contribute to the vision for the Constellation program and the nation’s future space exploration.

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7. Acronyms

AF	Air Force
ATK	Alliant Techsystems, Inc.
ATP	Authority to proceed
CaLV	Cargo launch vehicle
CBC	Common booster core
CCAFS	Cape Canaveral Air Force Station
CDR	Critical design review
CEV	Orion crew exploration vehicle
CIL	Critical items list
CLV	Crew launch vehicle
COCO	Contractor-owned, contractor-operated
CxP	Constellation program
DAC	Design analysis cycle
DCSS	Delta cryogenic second stage
DDT&E	Design, development, test, and evaluation
DFMR	Design for minimum risk
Delta IV H	Delta IV Heavy launch vehicle
DOD	Department of Defense
DOC	Delta Operations Center
ECS	Electronic control system
EDS	Earth departure stage for Ares V
EELV	Evolved expendable launch vehicle
EIS	Environmental impact statement
EPDC	Electronic data processing center
ESAS	Exploration Systems Architecture Study
EVA	Extravehicular activity
ETC	Estimates to complete
FITO	Flight and Integrated Test Office
FMECA	Failure modes, effects, and criticality analysis
FSB	First-stage booster for Ares I
FUT	Fixed umbilical tower
GCC	Ground control center
GNC	Guidance, navigation, and control
GOCO	Government-owned, contractor-operated
GSE	Government supplied equipment
GSE	Ground support equipment
HIF	Horizontal integration facility
HLV	Heavy launch vehicle
HR	Human-rated
HTPB	Hydroxyl terminated polybutadiene
HVAC	Heating, ventilation, air conditioning
HUG	Delta IV Heavy Upgrade
ICBM	Intercontinental ballistic missile
IOC	Initial operational capability
ISS	International Space Station
IVHM	Integrated vehicle health management
KSC	Kennedy Space Center

LAS	Launch abort system
lbf	Pounds force
LCC	Launch control center
LCC	Lifecycle cost
LEO	Low Earth orbit
LETF	Launch equipment test facility
LH2/LOX	Liquid hydrogen/liquid oxygen
LOC	Loss of crew
LOM	Loss of mission
LOV	Loss of vehicle
LRSW	Launch and Range System Wing
LSPI	Launch system project integration
LV	Launch vehicle
m	Meter
MAF	Michoud assembly facility
MLV	Medium launch vehicle
MLP	Mobile launcher platform
MPTA	Main propulsion test article
MSFC	Marshall Space Flight Center
m/s	meters per second
MST	Mobile service tower
mT	Metric ton
MTBF	Mean time between failures
NASA	National Aeronautics and Space Administration
nmi	Nautical miles
NSS	National security space
OML	Outer moldline
OPF	Orbiter processing facility
PBAN	Polybutadiene acrylonitrile
PM	Program management
PMR	Program management review
PRA	Probabilistic risk assessment
PWR	Pratt-Whitney-Rocketdyne
QA	Quality assurance
RIFCA	Redundant inertial flight control assembly
RSPF	Rotation, processing, and surge facility
RSRM	Reusable solid rocket motor
RSS	Rotating service structure
S&MA	Safety and mission assurance
SE&I	Systems engineering and integration
SE/SRQA	Systems engineering/safety, reliability, quality assurance
SDHLV	Shuttle-derived heavy lift vehicle
SLC	Space Launch Complex
SRB	Solid rocket booster
SRD	Systems requirements document
SSC	Stennis Space Center
SRM	Solid rocket motor
STS	Space Transportation System
t	Tons

TLI	Translunar injection
ULA	United Launch Alliance, Inc.
UT	Umbilical tower
VAB	Vehicle assembly building

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