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CONSTELLATION ARCHITECTURE AND SYSTEM MARGINS STRATEGY

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ABSTRACT

NASA's Constellation Program (CxP) is responsible for the definition, design, development, and operations of the flight, ground, and mission operations elements being developed by the United States for the human exploration of the Moon, Mars, and beyond. This paper provides an overview of the latest CxP technical architecture baseline, driving requirements, and reference missions for initial capability to fly to the International Space Station (ISS) and to the Moon. The results of the most recent design decisions and analyses supporting the architecture, including the Ares I, Ares V, Orion crew exploration vehicle, and the Altair lunar lander will be presented.

Of particular importance to the success of the Constellation Program is the systems engineering approach being used to establish and manage performance and mass margins. The margins of interest include those for the systems to access low Earth orbit for ISS and for injection into a trans-lunar trajectory. These margins are tightly coupled, given the parallel development of the launch vehicles and payloads. The overall CxP technical margins definition and management strategy will be presented, as will the results of a new state-of-the-art technique to quantify margins based on stochastic analyses using historically based probability density functions.

Introduction

NASA's Constellation Program (CxP) is responsible for the design, development, and operations of the flight, ground, and mission operations elements needed for humans to explore the Moon and ultimately to explore Mars. The program is being developed in phases starting with Initial Capability (IC), with missions to the International Space Station (ISS) (and possibly other targets). The next phase is Lunar Capability (LC), with missions that include lunar sorties to anywhere on the Moon. The third phase is the establishment and operation of a permanent lunar outpost. The major elements of the CxP are shown in Figure 1.

The lunar capability architecture was defined at the Lunar Capability Concept Review (LCCR) held June 18–20, 2008. The LCCR was conducted to define an integrated point of departure (POD) transportation architecture including capabilities to deliver and return a crew to the surface of the Moon for short durations, i.e., human lunar return (HLR), and to support a range of lunar exploration scenarios and possible surface system architectures, including establishment of a lunar outpost.

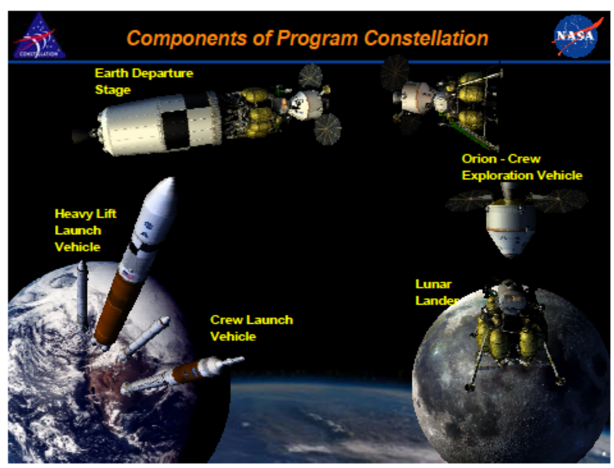

Fig. 1: Major elements of the CxP architecture.

The review also satisfied Mission Concept Review criteria for the Ares V cargo launch vehicle and the Altair lunar lander (crewed and cargo) including identifying conceptual designs and key driving requirements, technology drivers, and alternative designs and design concepts that meet mission and programmatic requirements.

The Constellation Architecture Team (CxAT) Lunar team was tasked to establish a lunar transportation architecture by LCCR that provides crew and cargo delivery to and from the Moon, the capacity and capabilities consistent with candidate surface architectures, sufficient performance margins, and that remains within programmatic constraints and results in acceptable levels of risk.

At the same time, CxAT Lunar was expected to establish lunar surface architectures and campaign strategies which satisfy NASA's needs, goals, and objectives to an acceptable degree within acceptable schedule, are consistent with capacity and capabilities of the transportation systems, and include a set of options for various prioritizations of cost, schedule, and risk.

The review assumed the capabilities of the IC elements of the Ares I crew launch vehicle and Orion crew exploration vehicle for the lunar design reference missions. Lunar surface system concepts were extensively explored, but no POD was required to be selected as part of this review.

The LCCR was about establishing ***a*** POD transportation architecture not ***the*** final baseline.

The baseline Constellation architecture for LC is derived from the Exploration Systems Architecture Study (ESAS) of 2006 (Reference 1) and uses what is called the 1.5 strategy. The crew launches first into low Earth orbit (LEO) in the Orion spacecraft on top of the Ares I vehicle; this is the 0.5 part. This is the same configuration used for the IC missions to the ISS. On a nominal launch day, 90 minutes later the Ares V heavy-lift launch vehicle injects the Altair and the Earth departure stage (EDS) into LEO; this is the 1.0 part. The Orion, Altair, and EDS rendezvous in LEO and wait for the trans-lunar injection (TLI) window to open. Apollo was a 1.0 strategy with injection stage, lander, and crew on one vehicle. The need for the 1.5 strategy is driven by the size of the systems needed for establishing a significant outpost capability on the Moon. While there are operational advantages of a 1.0 design, the size of such a vehicle could not be accommodated by NASA's existing launch infrastructure; indeed, the vehicle would literally be through the roof of the Vehicle Assembly Building at the Kennedy Space Center. In addition, the Ares I configuration has been designed to maximize the reliability of the system for the delivery of crew to LEO.

Major Program Elements

The Orion (Figure 2) is a new generation vehicle building on the heritage of Apollo and the Space Shuttle. It is designed to carry six crew members to the ISS and four crew members to the Moon. For the purposes of the lunar architecture, its capabilities and mass were assumed to be those specified in the Constellation Architecture Requirements Document.

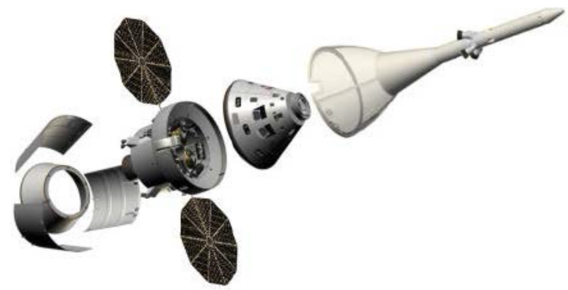

Fig. 2: Orion spacecraft.

The Ares I is designed to deliver the Orion into LEO on a trajectory compatible with going to the ISS or rendezvousing with the Altair and EDS for flight to the Moon.

The Altair (Figure 3) is designed to carry four crew members to and from the surface of the Moon for a minimum of 7 days on the surface with the capability to extend to lunar outpost crew rotation of 6 months. It can carry an airlock for surface activities. The vehicle can also provide global access capability and anytime return to Earth.

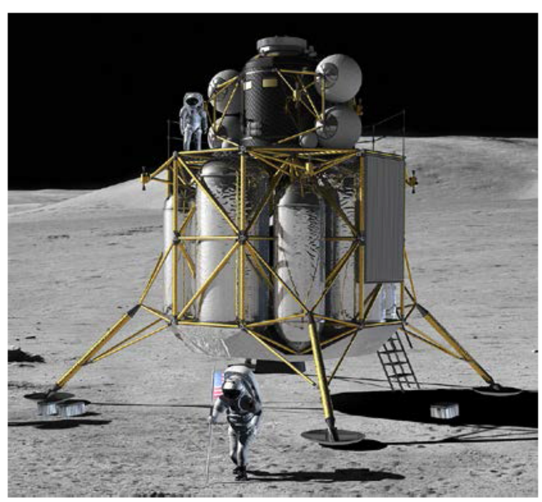

Fig. 3: Altair lunar lander.

In addition to carrying a crew, Altair has a cargo-only capability to land 14 to 17 metric tons (mT). The descent stage uses liquid oxygen and liquid hydrogen propulsion with a throttled single engine and the ascent stage uses hypergolic propellants or possibly liquid oxygen and methane with a single engine. The baseline vehicle used in this architecture is parametric 804 version D (p804–D).

The heavy-lift launch vehicle needed for this lunar architecture is called Ares V, of which there are a number of possible configurations. The common characteristics are shown in Figure 4. The specific vehicles focused on for the final closure of the architecture include:

- 51.0.39, standard core with 5 RS-68 engines, 5-segment Polybutadiene Acrylonitrile (PBAN) solid rocket booster (SRB) with reusable steel cases and a performance at TLI of 63.6 mT.
- 51.0.48, optimized core length with 6 RS-68 engines, 5.5-segment PBAN SRB with reusable steel cases and a performance at TLI of 71.1 mT.
- 51.0.47, optimized core length with 6 RS-68 engines, 5-segment Hydroxyl Terminated Polybutadiene (HTPB) composite SRB and a performance at TLI of 74.7 mT.

Common Design Features
Composite Dry Structures for Core Stage, EDS & Shroud Height = 116 m
Metallic Cryo Tanks for Core Stage & EDS
RS-68B Performance: I_{sp} = 414.2 sec Thrust = 3547 k N @ vac
J-2X Performance: I_{sp} = 448.0 sec Thrust = 1308 k N @ vac
Shroud Dimensions: Barrel Dia. = 10 m Usable Dia. = 8.8 m Barrel Length = 9.7 m

Fig. 4: Ares V features and configuration.

Architecture Performance Summary

Vehicle designs, mission designs, operational concepts, and margins analysis show that an Ares 51.0.48, Altair 804–D, and Orion 606–D provide a sound point of departure for the CxP lunar capability architecture and meet the needs and requirements as currently defined with only minor updates.

The current capabilities of the Ares 51.0.48 provides an acceptable probability of meeting mission needs at this time, and the 51.0.47 provides a more robust capability (approximately 4 mT more payload at TLI) should it be needed at some point in the future.

For polar outpost missions (sortie or long duration) the current capabilities of Orion and Altair meet all requirements.

For global sortie missions, Altair is the dominant limitation in degree of surface access. Altair, with 1,000 meters per second (m/s) delta-Velocity (delta-V) capability at Lunar orbit insertion (LOI), plus loiter, provides the best balance of surface (greater than 70%) and temporal coverage (greater than 50%).

Extension to "anywhere" coverage can be achieved with a combination of specific mission timing and additional LOI and trans-Earth injection (TEI) loiter.

Strategic Analysis Summary

Associated with the development of the technical architecture are a set of figures of merit (FOMs) that are used to assess the quality of the options during study and of the overall selected architecture. The FOMs include: affordability, benefit, safety and loss of mission (LOM) risk, programmatic risk, and sustainability. Representative campaigns, including mobility and habitats, have been developed, sensitivities analyzed, and all FOMs satisfactorily assessed.

The proposed architecture and initial campaign analysis is within a reasonable confidence range of fitting within the current funding profile. The size of the funding shortfall appears to be manageable within the degrees of freedom available.

The scenario-level loss of crew (LOC) and LOM estimates have been developed but do not yet meet the Program architecture requirements. As with the initial capability, this is on-going work and risk drivers and mitigation strategies are continuing to be worked. There are no identified show stoppers.

Key campaign objectives are being met including: HLR by 2020, early outpost capability, lunar/Mars extensibility, science, mobility, and cargo enabled. Also satisfactorily addressed are economic expansion, global partnerships, and public engagement.

Performance and Mass Margins Strategy and Management

A key element in the success of any spacecraft development is the establishment and management of margins; most significantly at the point of transportation architecture definition, the launch vehicle (LV) performance and payload mass margins. The designation of required and needed margin levels by mission phase is a standard practice in spacecraft development, but there is a wide range of practice and opinion on what those margins should be. In the world of human-rated vehicles, no system like this has been developed in more than 40 years so there is little statistical basis for specific numbers or percentages.

Figure 5 shows a set of data for the mass growth from initial concept to flight for a wide range of human-rated vehicles, from commercial aircraft to experimental spacecraft. Based on this data and current practices at NASA's robotic spacecraft centers—the Jet Propulsion Laboratory (JPL) and Goddard Space Flight Center (GSFC)—a set of total mass margin ranges has been specified in the CxP requirements documentation. It should be noted that this data shows the net change in mass and does not show how many times a specific project may have repeated major mass reduction efforts prior to flight (see Reference 2 for more details).

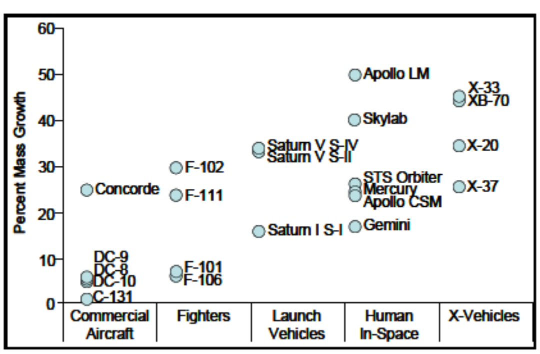

Fig. 5: Percent of growth from Phase A to completion for crewed vehicles.

For the purpose of understanding the margins specified below, the following definitions are used:

- Total Margin: The difference between the basic and the control mass.
- Mass Growth Allowance (MGA): The margin calculated based on an existing design, as reflected in a detailed master equipment list, and the maturity of the design, e.g., concept sketches: 25%, preliminary designs: 10%. MGA schedules are based on historical experience and are intended to cover uncertainties in the design as it exists but does not cover significant changes in the design, "I-forgots," or unknown-unknowns. MGA burns down to zero over the course of the development.
- Project Managers Reserve (PMR): Intended to cover threats and opportunities and unknown-unknowns within the existing scope of the project, and is closely managed by the project systems engineering team but controlled by the project manager. High-likelihood threats effectively encumber reserves. The PMR generally burns down to zero by launch.
- Program Manager Reserve (PgMR): Intended to cover threats and unknown-unknowns outside the scope of the projects, including, at the Program Manager's discretion, impacts of one project on another. Also provides for operational flexibility. The PgMR has a residual throughout the life of the program to cover operational options and issues.

The following are the total margins on dry mass, by project phase, which are currently specified to be met by all projects:

- Pre-phase A: 30–40%, applies to Altair, Ares V, and surface system elements.
- Start of Phase A (System Requirements Review (SRR)): 25–35%.
- Start of Phase B (System Definition Review (SDR)): 20–30%.
- Start of Phase C (Preliminary Design Review (PDR)): 20%. This is where Orion and Ares are at the time of this paper.
- At Critical Design Review (CDR): 10%.
- Start of Phase D (Hardware deliveries to test): 5%.
- Launch: 1%.

It is very important to note that mass margin levels on multi-staged systems must be defined and managed carefully since there are significant "gear ratios" at work. Margin eats into payload as will be discussed later in the lunar capabilities section.

To address this issue of multi-staged systems, a method derived from the Monte Carlo analysis of costs and risk was applied to the performance and mass margins for the integrated transportation system (Reference 4). The approach treats the Ares V/EDS gross payload delivery capability and the TLI masses of Orion and Altair as random variables. For various vehicle requirements, vehicle control masses, and design reference missions, the critical probability that the delivery capability exceeds that injected mass was estimated using Monte Carlo simulation (Figure 6). This critical probability was used to establish program performance and mass margins, and in conjunction with other measures, provide the basis for trades at the program level and baseline vehicle selection.

To implement this stochastic approach, what was needed was the ability (i.e., a model) to predict the actual TLI mass based on current mass information and the uncertainty in that estimate. In other words, to propagate current best estimates stochastically to a TLI mass probability density function (PDF). Since no flight hardware has been built, current mass information for the Constellation TLI stack comes from estimates based on a preliminary bottom-up equipment list or parametric model for each stack element. To generate a useful model, historical mass data were collected from previous NASA missions. In particular, a time-series of dry mass estimates, using original sources wherever possible, was collected and provides a means to ensure that consistent definitions were used in what was being reported.

Setting the Program Manager Reserve (PgMR) and Project Manager Reserve(s) (PMR) in the CxP is part of the margin management process. Figure 6 provides the summary view and relationships of mass margin concepts used in the CxP (Reference 4).

The stochastic margins analysis process started with Ares V/EDS vehicle performance PDFs for three vehicle options: 51.0.39, 51.0.48, and 51.0.47. Figure 7 shows the PDFs used.

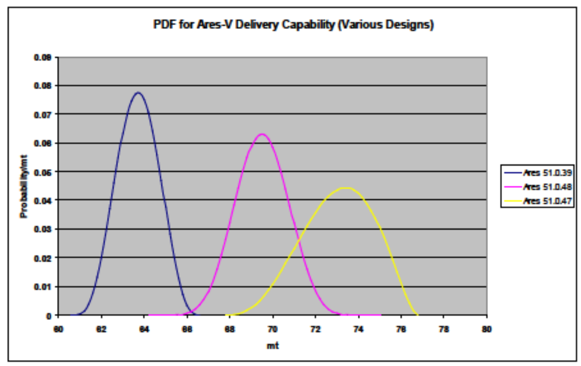

Fig. 7: Probability density functions for Ares V delivery capability.

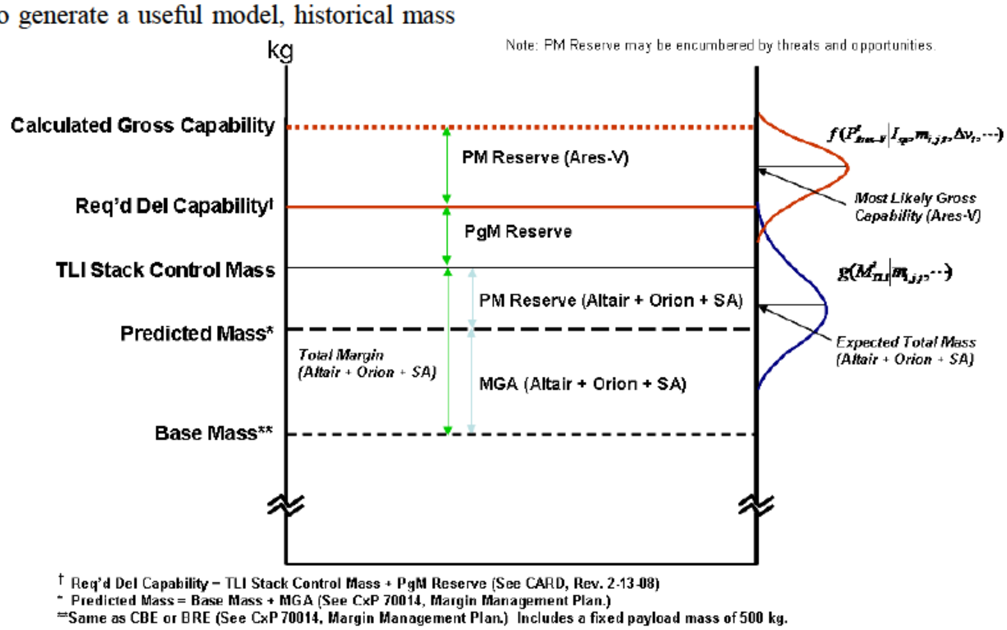

Fig. 6: Summary view and relationships of mass margin concepts used in CxP.

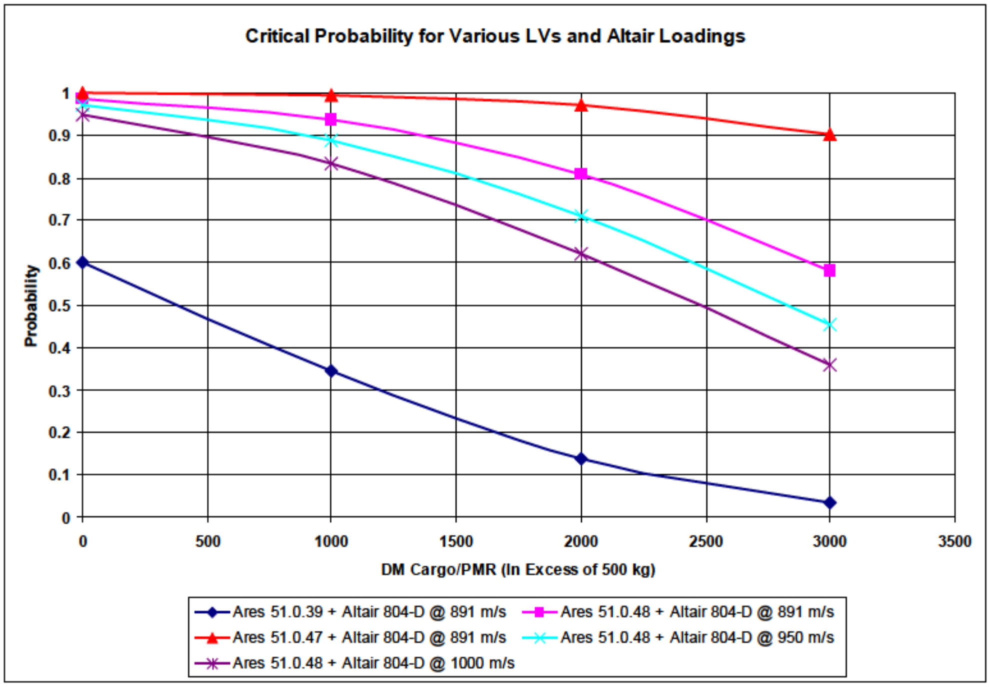

Fig. 8: Probabilities of having adequate margin.

The 51.0.39 PDF was based on a stochastic model built using probabilistic inputs to an integrated performance model; the other two PDFs were based on engineering judgment. The historical data were used to propagate current TLI stack mass information to PDFs to stochastically evaluate the magnitude of margin uncertainty and the confidence in the margins. The historical data started from subsystem data generated by JPL/Aerospace from 23 different robotic missions (JPL, GSFC, and others). However, it was necessary to go to system-level data to incorporate large mass crewed flight systems.The next step involved developing a family of Altair PDFs with different cargo and delta-V capabilities. This work, conducted by the Altair project team, started with parametric "fully functional" design p711–B and was completed based on the finalization of an integrated design cycle in the p804–D vehicle.

Using the Ares V and Altair PDFs and the Orion control mass of 20.2 mT deterministically, Monte Carlo runs were made to derive probabilistic representations of margin as a function of Altair delta-V capabilities and additional landed payload to the Moon. Figure 8 shows the results of these initial calculations. It must be noted that these early results, while promising, are still relatively immature and therefore the statistical confidence is relatively low. Further refinements in the Ares V models and maturing of the Altair design will increase the overall confidence in the model results over time.

The conclusions from this analysis are shown in Figure 8 and summarized below:

- The Ares V 51.0.39 with crew optimized Altair and 891 m/s delta-V (polar mission) has an approximately 60% likelihood of having adequate margin; this is high risk for running out of margin.
- The Ares V 51.0.48 with crew optimized Altair and 891 m/s delta-V (polar missions) has approximately a 99% likelihood of having adequate margin and a low risk for running out of margin.
- The Ares V 51.0.47 with crew optimized Altair and 891 m/s delta-V (polar missions) has a greater than 99% likelihood of having adequate margin and a very low risk for running out of margin.
- For global access, additional Altair delta-V capability to 950–1,000 m/s is needed with subsequent reductions in probability of having adequate margin. The Ares 51.0.48 has a 95–97% likelihood of having adequate margin and a moderate risk for running out of margin.

- The Ares V 51.0.48 and 51.0.47 have the potential for injecting more than 500 kilogram (kg) payload on Altair crewed missions. The 51.0.47 has approximately a 97% likelihood of being able to carry about 2 mT of additional payload. This additional payload capability will continue to be assessed in future architecture studies.

Lunar Capability Point of Departure Baseline

Based on the work of CxAT Lunar and all the CxP project teams, the LCCR was successful and the following recommendations were baselined.

The Ares V POD baseline is the 51.0.48 to maximize commonality between Lunar and Initial Capabilities. This vehicle provides architecture closure adequate margin and has high commonality with Ares I. At the same time, CxP will continue to study the benefits and risks of the improved performance of the Ares V 51.0.47. This vehicle's additional performance capability may be needed for margin or to meet requirements and allows for a competitive acquisition environment for the booster. Further study and technology investment funding are already planned. The final decision on the Ares V booster is expected at the CxP CDR, currently scheduled for around June 2010.

The Altair POD baseline of the p804–D provides a robust capability to support Lunar Outpost Missions with a crew optimized design (500 kg of cargo plus airlock) and a cargo delivery capability with approximately 14,500 kg in cargo-only mode. Altair will be sized for global access while allowing future mission and system flexibility. Altair tanks will be sized for 1,000 m/s LOI delta-V and for an additional 4 days of low Lunar orbit loiter (site specific). The margins strategy includes approximately 1,000 kg of Program reserve at TLI and a minimum of 40% total margin.

For Orion it is critical to continue to hold the control mass to 20,185 kg at TLI. The Program will continue to monitor the maturing Orion vehicle design with an emphasis on mass control. There will also be an increased emphasis on evolutionary options to improve margins and performance.

Lunar Architecture Team Forward Work

Again, it is important to recognize that the baseline discussed here is ***a*** lunar capability architecture not necessarily ***the*** lunar architecture. There are a number of additional and on-going tasks the Program will be working on as it refines and updates the architecture.

The team will continue an integrated system performance assessment and trades including: updated Ares V 51.0.48 and 51.0.47 designs and stochastic models and evolving Altair and surface system concepts. We will conduct further decomposition and refinement of the lunar requirements, evaluate the technical baseline with respect to operability, supportability, maintainability, and sustainability, and refine the lunar supportability concepts including transportation and eventual lunar outpost missions.

With respect to costs, we will continue tracking and refining transportation and lunar surface system elements estimates, uncertainties, and cost risks.

At the same time, the CxAT Lunar team will provide oversight and help manage the most significant risks to the architecture including the Ares V and Altair mass and performance, Orion's mass, LOC/LOM requirements achievability, and environmental issues such as galactic cosmic radiation effects and associated mitigation strategies.

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