Complex Decision-Making Applications for the NASA Space Launch System

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Abstract—**The Space Shuttle program is ending and elements of the Constellation Program are either being cancelled or transitioned to new NASA exploration endeavors. The National Aeronautics and Space Administration (NASA) has worked diligently to select an optimum configuration for the Space Launch System (SLS), a heavy lift vehicle that will provide the foundation for future beyond low earth orbit (LEO) large-scale missions for the next several decades. Thus, multiple questions must be addressed: Which heavy lift vehicle will best allow the agency to achieve mission objectives in the most affordable and reliable manner? Which heavy lift vehicle will allow for a sufficiently flexible exploration campaign of the solar system? Which heavy lift vehicle configuration will allow for minimizing risk in design, test, build and operations? Which heavy lift vehicle configuration will be sustainable in changing political environments?**

Seeking to address these questions drove the development of an SLS decision-making framework. From Fall 2010 until Spring 2011, this framework was formulated, tested, fully documented, and applied to multiple SLS vehicle concepts at NASA from previous exploration architecture studies. This was a multistep process that involved performing figure of merit (FOM)-based assessments, creating Pass/Fail gates based on draft threshold requirements, performing a margin-based assessment with supporting statistical analyses, and performing sensitivity analysis on each. This paper discusses the various methods of this process that allowed for competing concepts to be compared across a variety of launch vehicle metrics. The end result was the identification of SLS launch vehicle candidates that could successfully meet the threshold requirements in support of the SLS Mission Concept Review (MCR) milestone.

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1. INTRODUCTION

The decision for a new heavy-lift launch vehicle is rooted in the 2005 Exploration Systems Architecture Study (ESAS), which reinvigorated serious interest in a national heavy-lift capability. The Constellation Program (CxP), formed in response to the ESAS, established long duration exploration missions to the Moon and eventually Mars, which involved launching high-volume, large mass payloads into low earth orbit (LEO). The Ares V launch vehicle served the heavy lift need of the CxP and underwent multiple design concept studies and design analysis cycles between 2007 and 2010.

As CxP was recommended for cancellation in early 2010, the National Aeronautics and Space Administration (NASA) conducted several internal studies on heavy-lift vehicle architectures capable of performing a wide range of missions at reduced cost and schedule. The studies, most notably the Heavy-Lift Launch Vehicle (HLLV) study and the Heavy-Lift Propulsion Technology (HLPT) study, identified several families of launch vehicles whose features were distinguished by the number of stages, types of solid and liquid propulsion systems, and outer mold line (OML) design characteristics. These families included both side-mount and in-line configurations, 27.6-foot and 33-foot OML diameters, 1.5 thru 3 stages, multiple booster options, and a wide range of liquid propulsion engines and solid rocket motor options.

The NASA Authorization Act of 2010 was passed by both the U.S. House of Representatives and U.S. Senate and was signed by the President on October 11, 2010. This Act directed NASA to develop a Space Launch System (SLS) capable of delivering crew and heavy cargo to LEO and beyond. As its initial capability, the SLS must be capable of lifting 70 metric tons of payload to LEO. A full capability of 130 metric tons is achieved with the addition of a combined Upper and Earth Departure Stage to the initial configuration.

With national stakeholder needs passed into law and various vehicle options to chose from, NASA George C. Marshall Space Flight Center (MSFC) established a team to develop a decision-making framework in which to communicate effectively with agency decision-makers the characteristics and relative merits of the likely vehicle candidates. This framework will be summarized in this paper, with a specific focus on the methods themselves rather than the results produced.

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2. APPROACH

The team set out to establish a process by which the SLS Steering Committee could identify vehicle candidates that could meet documented NASA Mission Concept Review (MCR) success criteria. The process involved establishing a standardized set of process inputs, each of which have their own documented set of groundrules and assumptions. These standardized input sets and associated analytical processes were in the areas of performance, cost, and reliability estimation. By forming a common set of groundrules and assumptions for all discipline areas and associated teams, a consistent set of vehicle data was produced that would allow for relative comparisons to be made across many vehicle concepts.

As with most complex problems, it is very difficult to define a single methodology or process that will identify a clearly attractive candidate from a multitude of options. Therefore, the decision team set out to define a multifactored process that would allow the problem to be assessed from a variety of angles. This process (as shown in Figure 1) includes the following steps:

FOM-Based Assessment with figure of merit (FOM)s and criteria established from stakeholder metrics in the areas of performance, schedule, programmatics, and affordability.
Draft SLS Level 1 Requirements assessment with all concepts evaluated on a pass or fail basis against the minimum threshold values across a variety of metrics.
Aggregate Margin Assessment which compares all vehicle concepts to the draft Level 1 requirements and their margin with respect to each. This also includes supporting statistical analysis on the same metrics.

3. FOM-BASED ASSESSMENT

Stakeholders in the SLS Decision

In the heavy-lift vehicle decision process, the early establishment of an agreed upon set of FOMs derived from the stakeholders in the decision is imperative. In this manner, the stakeholders are widely represented in the decision-making process, and the resulting vehicle decision is based on this representation rather than other external factors. Furthermore, it provides a standard method for measuring and comparing competing concepts rather than independently assessing and potentially eliminating competitors without a larger-view of the trade environment.

For NASA, the decision making process is fairly straightforward. The NASA Administrator, the Office of Science and Technology Policy (OSTP), and the Office of Management and Budget (OMB) provides input to the President on existing and potential NASA programs. The President proposes new programs and/or the continuation of existing NASA programs in the annual Presidential Budget Request to Congress. The Congress debates the merits of the proposed programs and either chooses to authorize the programs or not. These authorized programs are then funded through the appropriations process. In the simplest case, the conglomeration of proposed, authorized, and appropriated programs are then passed and signed into law as the Nations Omnibus Spending Bill. This mutual agreement between the President and the Congressional Authorization and Appropriations processes are the general framework by which national decisions are made.

Therefore, the Stakeholders for this decision are defined as the President of the United States, both the U.S. House of Representatives and U.S. Senate, and the NASA resources tasked with carrying out the authorized, approved, and funded program.

Stakeholder Derived Metrics

Determining the priorities of these stakeholders and the relative importance of those priorities relative to one another is a more difficult task. The process used for this assessment was as follows:

- Gather statements made by the stakeholders through their respective publications.
- Bin those statements into general FOM categories.
- Reduce similar statements into a single sub-FOM or what could potentially be termed heavy-life vehicle Needs, Goals, and Objectives (NGO).
- Perform a first-order prioritization of those NGOs within the FOM categories.

The first step of this process is merely collecting statements regarding the HLLV made by the President in the FY2011 Presidential Budget Request and subsequent amendments thereof (speech at Kennedy Space Center (KSC) on April 15th, 2010), as well as the Senate and House of Representative Authorization Acts and Appropriations Reports. These statements were documented as "Quotes" associated with each source.

For instance, individual quotes from these sources at the time of this study as it relates to the development schedule of the heavy-lift vehicle program are:

President's Speech at Kennedy Space Center on April 15th, 2010: "And we will finalize a rocket design no later than 2015 and then begin to build it."
U.S. House of Representatives NASA Authorization Act (HR 5781): "...the Administrator shall strive to meet the goal of having the heavy lift launch vehicle authorized in this paragraph available for operational missions by the end of the current decade"
U.S. House of Representatives Appropriations Report: Not available at the time of this study
U.S. Senate NASA Authorization Act (S.3729): "...Priority should be placed on the core elements with the goal for operational capability for the core elements not later than December 31, 2016."
U.S. Senate Appropriations Report: "...The Committee invests in a new heavy lift rocket to be built by 2017, along with the Orion capsule to carry astronauts, so NASA can again send humans on new journeys of discovery."

Organization and Simplification of Stakeholder Priorities

The compilation of statements by the stakeholders was then organized in matrix format based on the general FOM areas that they targeted. These eventual general FOM areas found were *Performance*, *Schedule*, *Programmatics*, and *Affordability* aspects. Fortunately, several statements that were extracted were closely related with slight nuances between them. This led to a high level integration of closely related FOMs into what became known internally as "Integrated FOMs". These Integrated FOMs, if moved forward into the environment of a NASA program, may be considered draft NGOs for the new Heavy-Lift Vehicle program. That is, they are NGOs by which vehicle level requirements may be derived from (e.g. integrated vehicle shall deliver 70 metric tons to LEO).

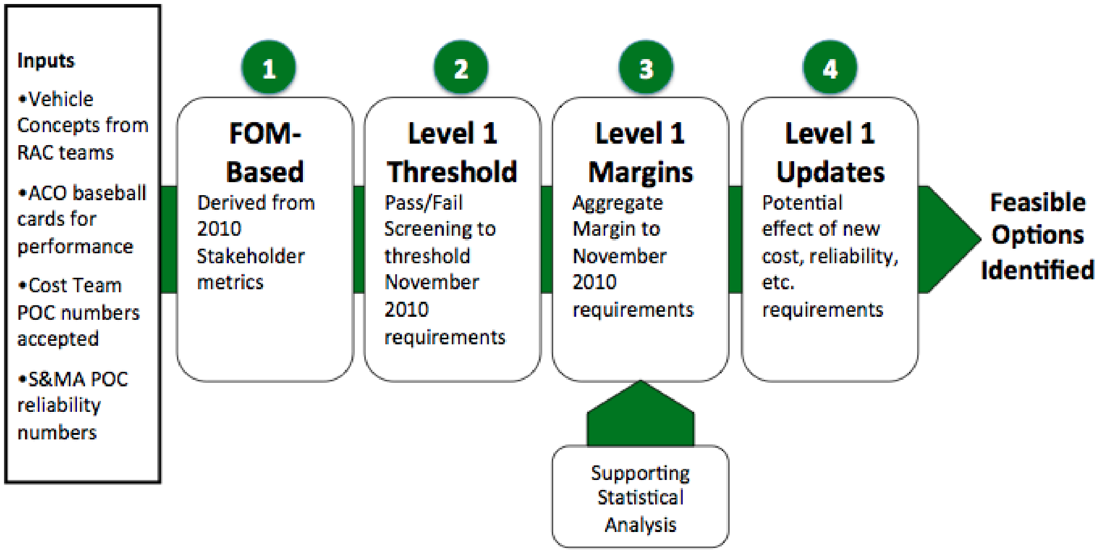

Figure 1. Decision Analysis Process

Once consolidated into the "Integrated FOMs" or NGOs, a high-level ranking of the NGOs was performed in order to reduce the quantity even further. A simple High, Medium, or Low priority was assigned to each NGO with an associated stakeholder that considers it to be of that priority. This technique was used to eliminate NGOs from the assessment which were medium or low in priority. This process resulted in all stakeholder priorities being distilled down into 16 NGOs. Four of these were universally agreed to, three were unique to the Presidential priorities, five were unique to the Congressional priorities, and four were additional derived priorities. Figure 2 lists these NGOs.

FOM Weightings

With the four FOMs (*Performance*, *Schedule*, *Programmatics*, and *Affordability*) and the criteria that composes the FOMs established (Figure 2), the team proceeded to weight the FOMs. A commonly used technique to systematically work through complex decisions is the Analytical Hierarchy Process (AHP). This technique works by decomposing a particular decision involving multiple variables into its individual components and then comparing those two components independently of all other considerations.

In this case, the individual FOMs are compared on a one-to-one basis to determine relative importance of one vs. the other. For instance, the four FOMs as listed are compared in an independent fashion systematically by answering six basic questions:

- Is Performance more important than Affordability?
- Is Performance more important than Schedule?
- Is Performance more important than Programmatics?
- Is Affordability more important than Schedule
- Is Affordability more important than Programmatics?
- Is Schedule more important than Programmatics?

These six questions are answered on a yes or no basis with a relative magnitude associated with that yes or no. A comparative matrix is composed and once completed, all values are normalized within each FOM category so that a relative comparison can be made between them. This results in an AHP factor that demonstrates the relative strength in scoring of a particular factor over all others. The AHP factor itself can be used directly as a weighting factor in most circumstances. An easier to interpret method is to derive the percentage (out of a 100% total) that one factor holds over all others. This is merely the percentage of the AHP factor that one FOM accounts for divided by the total available AHP

Common Administration and Congress Values
Performance
Deliver a 70-100 t payload to LEO with Core Elements
Schedule
Perform first flight by the end of 2018
Programmatic
Maintain critical skills & transition workforce
Afforability
Minimize life-cycle costs (2030)
Additional Administration Values
Programmatic
Provide a national advancement in technology
Develop a national RP Engine
Afforability
Eliminate unnecessary infrastructure & right size industrial capacity
Additional Congressional Values
Performance
Provide an evolved LEO capability of at least 130 metric tons with EDS
Afforability
Develop an initial capability under an $11.5B cost cap through 2017
Minimize cost risk
Programmatic
Utilize Shuttle/Ares Infrastructure/Hardware
Decrease Loss of Crew Probability (an increase in LOC calculation)
Additional Derived Values
Afforability
Proceed with a sustainable program (minimize annual recurring cost)
Minimize peak cost
Minimize cost to first flight
Life Cycle Cost Reduction Challenges

Figure 2. Final Stakeholder Derived Priorities

factors. Through this AHP process, the FOM weightings for *Performance*, *Schedule*, *Programmatics*, and *Affordability* are found as shown in Figure 3 (based on a 100% total available):

OUTPUT	
FOM Weight	
10%	**Performance**
55%	**Affordability**
25%	**Schedule**
10%	**Programmatics**

Figure 3. AHP Determined FOM Weightings

NGO Scoring Criteria and Final Assessment

Once the weighting of each FOM is found, it is imperative to set up a scoring method for each individual NGO. In this manner, data is measured using a consistently-applied process across a variety of vehicle concepts. For this assessment, NGO definitions (for the NGOs shown in Figure 2) were agreed upon and documented. However, each NGO represents a certain type of data. For instance, performance represents a calculated payload mass to a certain orbit. Cost metrics represents a cost estimate of some sort for a given configuration, schedule and flight manifest. Schedule represents a development timeline found through a critical path assessment and so on. These aforementioned examples represent standardized, quantifiable data sources. In this assessment, there are also a multitude of data that represents subjective, hard-to-quantify NGOs. Examples of this data type include workforce transition, life-cycle cost reduction challenges, and others. Therefore, a standardized scoring methodology is established for these particular attributes.

Additionally, it is required that all NGOs are measured appropriately. Two data conditioning steps must be undertaken to ensure a representative outcome:

1) Ensure singular NGO quantities do not dominate the final consolidated measurement
2) Ensure a large quantity of NGOs in a single FOM does not cause that FOM to dictate the results (regardless of the application of weighting factors)

Whereas some NGOs are on the scale of tens or hundreds, other NGOs are on the scale of billions. It is apparent that a simple summation of these would result in the value represented by the lower scale having very little impact in the overall outcome. The method used to avoid this issue is a simple normalization between a fixed lower and upper boundary. For instance, performance is measured on the order of metric tons. A given range for performance may be a desired performance between 70 to 130 metric tons. By fixing a common lower boundary at the minimum in the range and a common upper boundary at the maximum of the range, all additional values can be interpolated between those two fixed points. If this process is repeated across all NGOs, then all are measured on a common scale.

The second data conditioning technique used for this assessment is averaging within a single FOM category to avoid the quantity of NGOs within a single FOM from dictating the outcome. It is apparent that if all NGOs were merely summed for the final results, *Affordability* would dominate the final outcome based on the quantity of *Affordability* metrics within the assessment. Therefore, before application of any weighting factors, all *Affordability* NGOs are summed and divided by the quantity of *Affordability* NGOs (by stakeholder) to produce an average *Affordability* subtotal (by stakeholder and total). An important point about this technique is that this dictates that all NGOs are weighted equally within a single FOM. Once these data conditioning steps are applied, vehicle data can be imported and scoring comparisons can be made on any number of launch vehicle concepts.

4. Draft SLS Requirements Assessment

One particular shortfall of the FOM Based Assessment is that is does not capture how well the individual vehicles perform against the draft SLS Level 1 requirements as established by the SLS Steering Committee in November 2010. An assessment to these individual threshold values gives a much better indication of which vehicle concepts have the ability to meet standard NASA MCR success criteria based on eventual vehicle level requirements in all categories (cost, schedule, performance, reliability, etc.). In order to provide this insight, each individual requirement was given to the Requirements Analysis Cycle (RAC) teams as "Draft Threshold Requirements" and "Draft Objective Requirements" across a variety of metrics. All of these threshold values, if levied as program requirements, must be met in order to be considered a feasible vehicle concept for SLS MCR. With this "Pass or Fail" criteria established, the vehicle data can then be applied to determine areas where the individual vehicle families fall short of these minimal "Threshold" values. Alternatively, vehicle concepts meeting most or all of these "Threshold" values should be considered feasible vehicles for the purposes of a MCR. This process is further depicted in Figure 4.

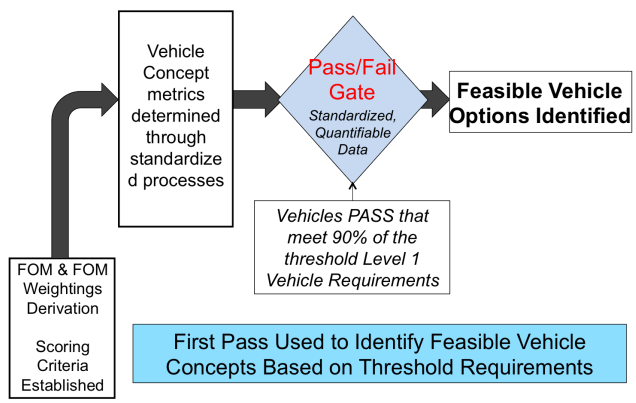

Figure 4. MCR Feasible Vehicle Identification Process

5. Aggregate Margin Study with Supporting Statistical Analysis

System Margin Assessment

At the inception of the SLS program, a measure of the "weighted system margin" is a very important metric that should be given appropriate thought when determining the preferred vehicle approach. While it is very difficult to quantify certain subjective aspects of the impending vehicle decision, the quantitative categories are easily binned according the level of "goodness" that each concept provides. These normalization bins give a relative measure of how much margin each vehicle concepts provides within the metrics established (with both the threshold and objective values considered). In addition, the weighting factors as currently understood can easily be applied to these quantitative metrics, resulting in a weighted system margin calculation.

Parametric Assessment of Vehicle FOMs

To support the assessment of the vehicle parameter space and to enable the incorporation of uncertainty and constraints in the assessment methodology, a parametric and probabilistic Monte Carlo assessment of the RAC configurations was completed. This assessment leveraged the work done by the RAC cycle and applied uncertainty on each of the FOMs for each of the vehicles. To complete the assessment, the following cases were assessed:

1) Integrated vehicle assessment using multiple FOM weightings to assess sensitivity of the recommended optimal architecture to changes in FOM weighting
2) Integrated vehicle assessment with sequential application of minimal requirements
  a) Performance (to standard orbit)
  b) Safety and Reliability (LOC/LOM)
  c) Cost (total development, near term, and recurring cost)
  d) Schedule (first flight)
3) Integrated vehicle assessments with varying level of uncertainties on each of the FOMs

The assessments were completed using reference vehicles that were defined using the draft SLS Level 1 requirements from the RAC process. Figure 5 depicts generic results of these Monte Carlo runs when implementing the Cost, Safety, and Performance gates. It can be interepreted as a probabilistic assessment of how many times out of all ran cases that the given configuration meets all levied requirement gates. The results from this assessment illustrates the sensitivity of the "optimal vehicle" to the applied constraints.

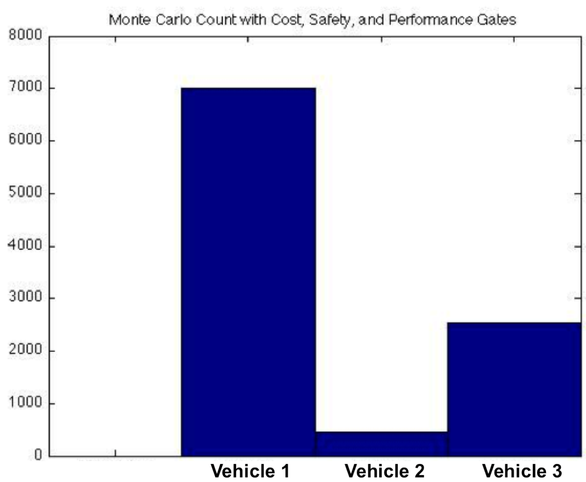

Figure 5. Parametric Assessment Sample Results

6. Conclusion

The framework that was developed allowed for vehicle concepts and associated architectures to be compared on a variety of levels. These include the ability of the configurations to meet stakeholder needs, goals, and objectives, ability to meet SLS programmatic requirements (or requirement changes), and ability to provide margin to the program that will result in SLS having the ability to maintain both national and internal performance, schedule, and affordability targets. Combined, this multifactored assessment selected vehicles that would have the ability to successfully pass NASA MCR success criteria. Furthermore, the output of the framework was vetted by agency and national leadership. In this manner, it provided insight and confidence to agency decision-makers that the SLS concept chosen for further development will be a very flexible and capable vehicle that should serve the needs of a nation in its human space exploration endeavours for decades to come.

Acknowledgments

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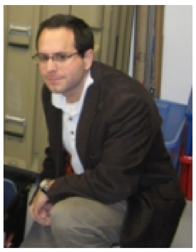
Biography

Garry Lyles is the Space Launch Systems Chief Engineer, leading the design and development of the nations next heavy-lift rocket for human exploration beyond Earth orbit. Garry has a strong technical background and extensive experience in technology programs and project management. He led the SLS Planning Teams architecture studies that led to the current point of departure vehicle now being further refined as the SLS Program advances toward its System Requirements Review, scheduled for Spring 2012. Previously, Garry was the Technical Associate Director of the Marshall Space Flight Centers Engineering Directorate, where he led systems engineering and integration for a number of NASA programs and projects. Garry holds a bachelors degree in mechanical engineering from the University of Alabama and he was inducted into its class of Distinguished Engineering Fellows in 2010. He has been honored with awards such as the NASA Medal for Exceptional Service, NASA Medal for Exceptional Engineering Achievement, and two Presidential Rank Awards for Meritorious Service one of the highest honors given for government work.

Tim Flores is currently the Assistant Manager, Advanced Development Office, Space Launch Systems (SLS) Program. Prior to SLS he was the Project Integration Manager for the Ares V launch vehicle project. He has also served as the Associate Director of the Independent Program Assessment Office (IPAO) in the Headquarters Office of Program Analysis and Evaluation (PA&E). Mr. Flores began his career at NASA in 1990 as a Test Engineer and subsequently held various technical and project management positions. He also worked at L-3 Communications on a two-year assignment in industry as the Deputy Chief Engineer and later as the Deputy Project Manager on the NASA SOFIA project. Mr. Flores holds a Bachelors degree in Aerospace Engineering from University of Texas at Arlington and a Masters in Engineering and Management from Massachusetts Institute of Technology (MIT).

Jason Hundley provides engineering support to NASA exploration systems and the Space Launch System program. Since receiving a B.S. in Physics and Mathematics from Wright State in 1998 and a Masters Degree in Mechanical Engineering from The George Washington University in 2001, he has been involved in numerous programs in the defense and space industries. He is a member of the AIAA Space Transportation Technical Committee, and he is a founder and owner of Zero Point Frontiers Corp. in Huntsville, AL.



Stuart Feldman is a founder and owner of Zero Point Frontiers Corp, an engineering firm in Huntsville, AL specializing in design integration, systems analysis, architecture development, and decision management. Mr. Feldman is providing engineering support to NASA exploration systems and heavy lift launch vehicle activities as well as to the NASA Space Launch System program. Mr. Feldman represented the Launch Vehicle team on the development of NASA Mars Design Reference Architecture 5.0. Mr. Feldman has prior program experience on Bigelow Sundancer while at Orion Propulsion, Crew Exploration Vehicle at Northrop Grumman, and Mars Exploration Rover and C/NOFS at The Aerospace Corporation. Mr. Feldman holds a B.S. in Aerospace Engineering and a Masters of Engineering in Space Systems, both from the University of Michigan, as well as an MBA from Pepperdine University, and is currently pursuing a Ph.D. in Systems Engineering at University of Alabama in Huntsville.

Timothy S. Monk is a Systems Integration Engineer at the NASA Marshall Space Flight Center. He is a 2005 graduate of Auburn University and a 2006 graduate of the University of Colorado receiving a Bachelor's and Master's Degree in Aerospace Engineering, respectively. He has provided engineering support to NASA since early 2007. Since that time, he has performed numerous trades and analyses on the Ares V, Space Launch System, and other Heavy-Lift Launch Vehicle concepts and potential mission scenarios, including extensive analysis for the Mars DRA5.0 Launch Vehicle team and co-leading the Ares V Mars DRM Assessment team. He is an engineer at Zero Point Frontiers Corporation.