AAS 25-125

SPACE LAUNCH SYSTEM BLOCK-1B USA SEPARATION ANALYSIS AND REQUIREMENTS DERIVATION FROM CLVTOPS TOOLCHAIN

Zachary T. Muscha,* Benjamin S. Burger,† Peter J. McDonough,‡ Carole J. Addona,§ Rekesh M. Ali, Jared T. Rucker,†† Michael Sanders‡‡**

Ensuring that rocket stage separation events provide positive clearance is critical to avoid loss of mission or crew. NASA's Marshall Space Flight Center (MSFC) has developed a cutting-edge toolchain to address this type of problem and it was used to set abstracted impulse requirements on, and to analyze the results of, the in-space separation event of the Universal Stage Adapter (USA) and the Exploration Upper Stage (EUS) of NASA's Space Launch System (SLS) Block-1B configuration. The toolchain is used as a hardware simulation to confirm positive body-to-body clearance during the separation event. It is also used to create a requirements-space simulation, which helps inform requirements as the hardware design matures

INTRODUCTION

NASA's Space Launch System (SLS) is a launch vehicle designed to provide launch capability that will lead to NASA landing astronauts on the moon again. SLS consists of the Core Stage (CS), two Solid Rocket Boosters (SRB), and a configuration-specific upper stage. Core Stage is based on a modified Shuttle program External Tank and is the mounting point for two SRBs. The Block-1 vehicle stacks an Interim Cryogenic Propulsion Stage (ICPS) with four RL-10 engines and the Multi-Purpose Crewed Vehicle (MPCV) on top of the CS. The Block-1 configuration was used for the Artemis I mission and is being used for the Artemis II and Artemis III missions. Further missions plan to take advantage of an update to the Block-1 configuration, named Block-1B. For Block-1B, the ICPS is swapped out for the Exploration Upper Stage (EUS) which has additional capability compared to the ICPS. It has additional delta-V and can support a large Co-manifested

* Aerospace Engineer, EV42 Guidance, Navigation, and Mission Analysis Branch, Amentum Space Exploration Division (ASED)/Amentum, Huntsville, AL 35806
† SLS Flight Mechanics Co-Lead, EV42 Guidance, Navigation, and Mission Analysis Branch, NASA/MSFC, Huntsville, AL 35812
‡ PhD, Aerospace Engineer, EV42 Guidance, Navigation, and Mission Analysis Branch, Amentum Space Exploration Division (ASED)/Amentum, Huntsville, AL 35806
§ SLS Liftoff and Separation Dynamics Technical Lead, EV42 Guidance, Navigation, and Mission Analysis Branch, Amentum Space Exploration Division (ASED)/Amentum, Huntsville, AL 35806
** Aerospace Engineer, EV42 Guidance, Navigation, and Mission Analysis Branch, Amentum Space Exploration Division (ASED)/McLaurin Aerospace, Knoxville, TN 37929
†† Aerospace Engineer, EV42 Guidance, Navigation, and Mission Analysis Branch, Amentum Space Exploration Division (ASED)/Amentum, Huntsville, AL 35806
‡‡ Aerospace Engineer, EV42 Guidance, Navigation, and Mission Analysis Branch, ASED/Amentum, Huntsville, AL 35806

Payload (CPL), which mounts on top of the EUS. The Universal Stage Adapter (USA) is a shell that also mounts on top of the EUS; it encases the CPL and is the mounting point for the Spacecraft Adapter (SA) and MPCV. Both configurations are shown in Figure 1.

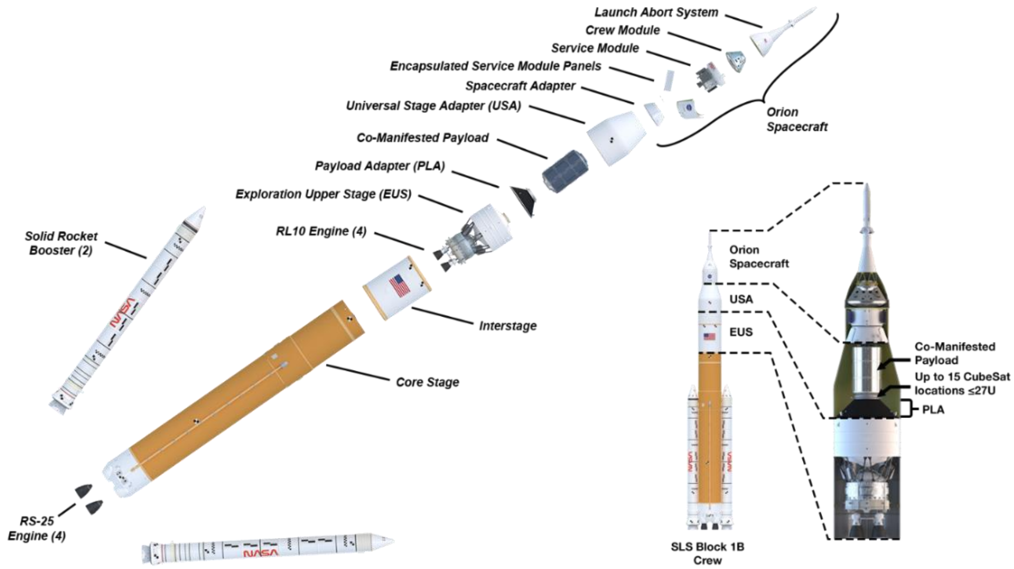

Figure 1. SLS Block-1B Expanded View[*]

This paper covers results and requirements of the USA separation event which is only relevant for Block-1B. In general, SLS's Block-1B mission profile includes launching from Kennedy Space Center, separating its two SRBs similarly to how the Space Shuttle boosters were jettisoned, then ascending until the CS separates from the upper stage. The EUS circularizes the vehicle's orbit and then executes the Trans-Lunar Injection (TLI).

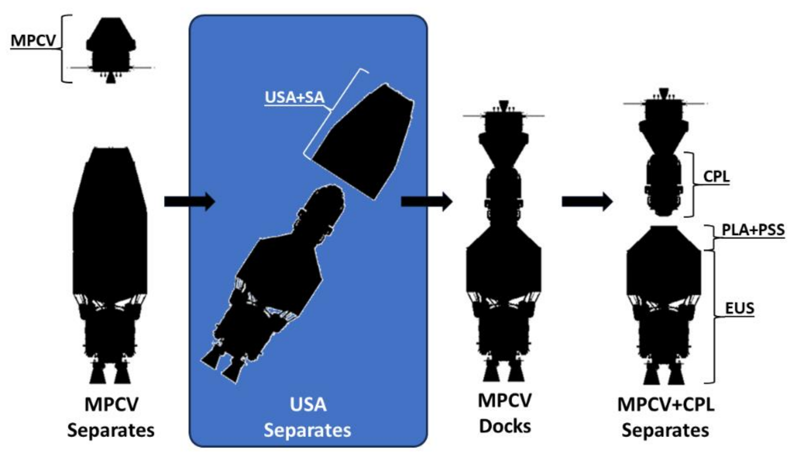

Figure 2. USA Separation Concept of Operations with USA Separation Highlighted.

The concept of operations for SLS Block-1B USA Separation is depicted in Figure 2. The MPCV separates from the SA and the EUS rotates to jettison the USA away from MPCV's location. Afterwards, the EUS rotates back to its original orientation to allow the MPCV to dock with the now-exposed CPL. The combined MPCV and CPL then separates from the EUS to continue the

[*] https://www.nasa.gov/reference/sls-space-launch-system-block-1b/

lunar mission. The USA separation event, analysis, and requirements described in this paper cover the portion of the mission where the USA is jettisoned from the EUS, highlighted in Figure 2.

The following sections will describe the USA separation hardware, the CLVTOPS toolchain used for the analysis, the initial requirements simulation design, key input models for the simulations, analysis results for baseline and single credible failure results, the updated requirements simulation, and caveats of the redesign.

USA SEPARATION HARDWARE

The USA shell has separable and non-separable portions. The bulk of the shell belongs to the separable portion, but a small section is left behind on the EUS. The non-separable section is mounted to the top circumference of the Payload Adapter (PLA), and it houses the anvils that the spring pushers act against to separate the two bodies.

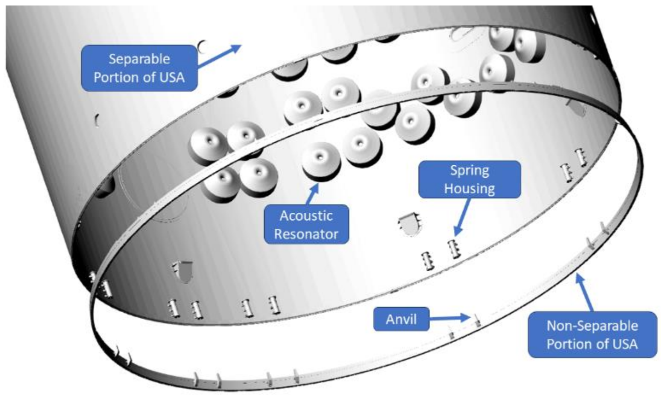

Figure 3. Separable and Non-Separable Portions of the USA.

As shown in Figure 3, the aft end of the separable portion of the USA contains the 20 spring housings and spring pushers. Four electrical umbilical connections bridge the separable and non-separable portions of the USA. Acoustic resonators may be installed along the inside of the separable portion of the USA to manage the sound environment throughout vehicle ascent. The USA forms a shell around an assembly consisting of the CPL, PLA, and Payload Separation System (PSS). At the time of jettison, the separable portion of the USA nominally travels longitudinally away from the EUS stack, revealing the encapsulated CPL.

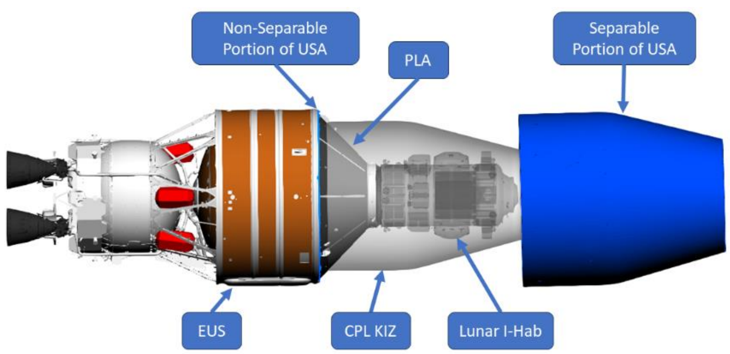

Figure 4. USA after separating from EUS, highlighted in blue.

The primary purpose for analyzing this event is to ensure that the separable portion of the USA does not encroach on a CPL Keep-In Zone (CPL KIZ), which is a defined volume intended to protect the region which will house current and future CPLs. The CPL KIZ, the semi-transparent volume in Figure 4, contains the CPL (the Lunar I-Hab* in this case) and the PAF. The separable and non-separable portions of the USA are highlighted in blue.

CLVTOPS TOOLCHAIN

The MSFC Liftoff and Separation Dynamics Team uses the NASA-developed CLVTOPS toolchain to conduct multi-body dynamics and clearance analysis for separation events, including the USA separation event.[1] The CLVTOPS toolchain is comprised of TREETOPS (a Kane's Method-based multibody dynamics engine), CLVTOPS (a TREETOPS interface for launch vehicle and spacecraft functionality), Python scripts to enable dispersed Monte Carlo simulations, a tool to calculate the minimum distance between 3D models of the vehicle, and Tree3D† (a 3D animation toolkit).[1,2] The combination of the tools in the CLVTOPS toolchain allows for quickly iterating on simulation development, analyses, and sensitivity studies.

INITIAL REQUIREMENTS DESIGN

At the start of the project, the USA and its separation system needed requirements to define the allowable, valid design space. This design space would serve to constrain the separation system performance, limiting impact to the EUS and ensuring that the design would not cause recontacts between the separating USA hardware and the CPL. Hardware-agnostic requirements and limits levied on the USA separation system were desired, as CPLs were unique to each mission and hardware components are designed by multiple vendors. Most of the uncertainty in the hardware designs can be modeled as large mass properties bounds, but the design of the simulation needs to be generalized enough so as not to be coupled tightly to any particular separation system. For example, spring-based separation mechanisms have their own nuances compared to hydraulic or motor-driven systems; rather than build an array of simulations to model general versions of each of the common types of separation systems, the simulation was generalized to instead model the *effects* of separation systems.

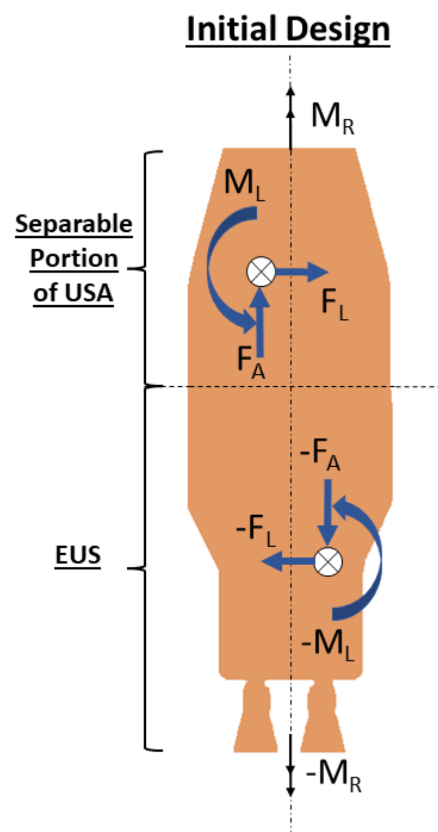

Figure 5. FBD for Initial "Requirements Simulation."

To capture the generalized effects, anything in the simulation that directly models the chosen separation system hardware was removed in favor of applying abstracted impulses. Axial force impulses (AFI) were applied to the Center of Gravity (CG) of each body, lateral moment impulses (LMI) were applied around the CGs to induce rotation, lateral force impulses (LFI) were applied at the CGs to induce translations, and roll moment impulses (RMI) were applied around the longitudinal axis to induce a roll rate. The Free Body Diagram (FBD) in Figure 5 shows a graphical representation of the abstracted impulses in the "requirements simulation."

For Monte Carlo analysis, the AFI was randomly dispersed from a minimum value, set to ensure the separation event occurs in a reasonable time, to a maximum value, which was set to limit the

* https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Gateway_Lunar_I-Hab
† https://software.nasa.gov/software/MFS-34076-1

amount of delta-V imparted to the EUS during separation. This reduces the amount of delta-V the MPCV must expend to return to the EUS and dock with the CPL LMI was dispersed with a minimum and maximum that were set using a logistic regression method. This constructed an allowable AFI vs LMI design space which served to protect the CPL KIZ. The LFI limit was set using an estimated achievable total system misalignment and wasn't tied to simulation results.

Initial USA Separation Requirements

All requirements are designed to maintain a minimum clearance between the separable portion of the USA and the CPL KIZ. The baseline scenario has three requirements: 1) an AFI vs LMI envelope, 2) a LFI fraction of AFI limit, and 3) a RMI equivalent moment arm limit. The failure scenario has the same three requirements, except the AFI vs LMI envelope is extended. Both scenarios are evaluated against Requirement 2. But since they easily satisfy Requirement 2, only discussion of the first two requirements is presented. Table 1 describes these three requirements.

Table 1. Initial USA Separation Requirements.

Requirement	Description
Requirement 1	Envelope around allowable axial force impulse and lateral moment impulse.
Requirement 2	A maximum limit for lateral force impulse fraction of axial force impulse.
Requirement 3	A maximum equivalent moment arm limit for roll moment impulse.

As the hardware design matured and started undergoing testing, a second simulation, the "analysis simulation," was developed to analyze the specific USA hardware and separation system. The following two sections will discuss the input models and results from this analysis simulation.

KEY ANALYSIS SIMULATION MODELS

There are four key input models for the USA separation analysis simulation:

- Mass properties
- USA separation system data
- Initial vehicle states
- Friction Force Analogue (FFA) model

The mass properties data includes the mass, centers of gravity, moments of inertia, products of inertia, and reference frames for all bodies of the vehicle. The separation system data includes the spring constants, spring stroke, spring housing locations, and force profiles for the electrical disconnects. The initial vehicle attitude rates were dispersed based on distributions from an independent 6-DOF vehicle trajectory simulation, Marshall Aerospace Vehicle Representation in C (MAVERIC)[3]. These first three models contain proprietary vendor data or ITAR-restricted information and will not be discussed in further detail here. The fourth model will be discussed next.

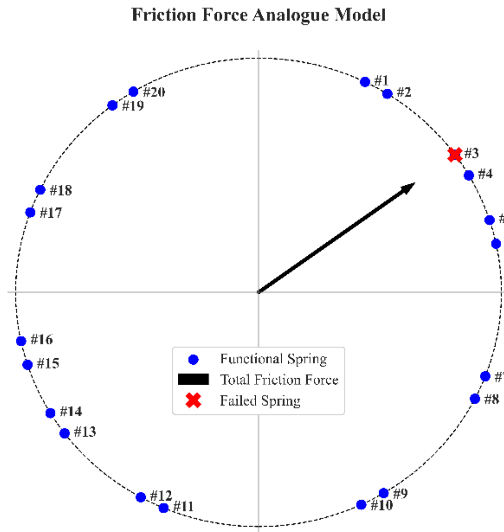

Figure 6. FFA Example Showing Friction Force Pointing Towards Failed Spring.

The FFA model, however, warrants further discussion. CLVTOPS implements an ad hoc friction model, which applies a precalculated force profile whose magnitude is the approximate sum of the lateral component of all 20 springs' friction forces. The friction force is applied at the centerline of the separable portion of the USA in the direction of the failed spring. This model is only applied in the failure case because the friction force is largest when the springs are extending asymmetrically in such a way that the separable portion of the USA tilts as it separates. Simulation results using the FFA model have good agreement with independent vendor and NASA verification and validation analyses that use high-fidelity friction models.

ANALYSIS SIMULATION RESULTS

The CLVTOPS USA separation analysis simulation is used to determine whether the current design complies with requirements and assess the clearances between the separable portion of the USA and the CPL KIZ. A Monte Carlo analysis is run and ordered statistics methods are applied to the results to determine the values to compare against requirements limits. Full details of the statistical methodology can be found in Hanson and Beard.[4] The following sections will first present the analysis simulation results, which will then be followed by discussion on how the results led to an update to the requirements simulation.

Two simulation scenarios are modeled: a baseline scenario and a failure scenario. The baseline scenario is characterized by nominal operation of all 20 separation springs and the four electrical umbilical connections. A “single credible failure” for a spring separation system is understood to mean that one spring fully fails and provides zero impulse during the separation event. The failure scenario is comprised of 19 springs, one randomly selected spring to fail, the FFA forcing function applied towards the failed spring, and four electrical umbilical connections.

The remaining content of this section includes results for the baseline and the failure scenarios. Their results are displayed side-by-side, with the baseline results on the left and the failure results on the right. The baseline scenario results show that the hardware design complies with its requirements as well as maintains positive clearance to the CPL KIZ. The failure scenario passes Requirement 1 but violates Requirement 2 despite demonstrating large positive clearance margin.

Requirement 1

Axial force impulse has a minimum limit to avoid unnecessarily long separation times and an upper limit to prevent the separation system design from imparting too much delta-V to the EUS, since the MPCV's ability to "chase" the EUS/CPL stack when in proximity is limited by its RCS capability and propellant reserves. The right side of the envelope boundary is set using methodology that allows a larger lateral moment impulse as the axial force impulse increases.

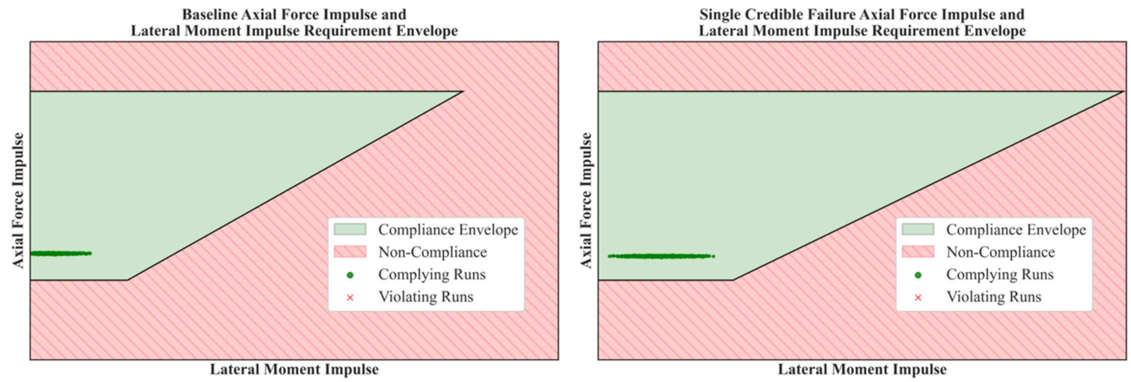

Figure 7. Baseline and Single Credible Failure Scenario Requirement 1 Results.

Figure 7 depicts AFI and LMI results relative to the Requirement 1 envelope. Both the baseline scenario and failure results comply with this requirement. The failure results have a larger LMI spread because failing one spring creates a total separation force vector whose location is further misaligned from the nominal center of gravity of the separable portion of the USA. This misalignment creates a larger moment than the baseline case, though the increase in lateral moment varies significantly with the magnitude of the misalignment. The nominal lateral center of gravity of the separable portion of the USA is located off the vehicle centerline. The separation spring locations are optimized for this off-center CG, so the resulting lateral moment induced by uneven application of forces, like when one of the springs fails, will change depending on the failed spring's distance to the CG.

Requirement 2

Requirement 2 sets a maximum limit on the LFI-to-AFI ratio. Requirement 2 permits a larger LFI for a larger AFI because LFI induces a lateral translation, and a larger lateral translation is allowed when a larger AFI is imparted since the separable portion of the USA clears the CPL KIZ faster.

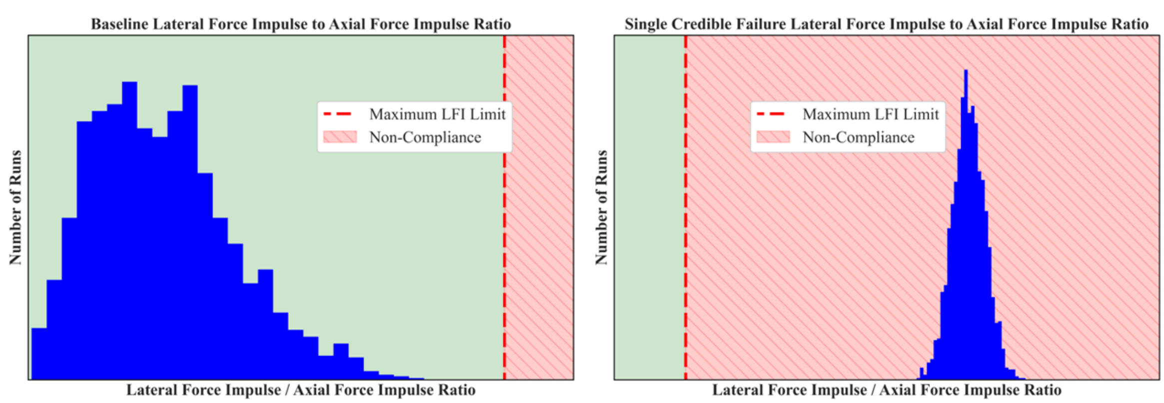

Figure 8. Baseline and Single Credible Failure Scenario Requirement 2 Results.

Figure 8 shows the LFI-to-AFI ratio results relative to Requirement 2. The baseline results show full compliance with Requirement 2, but the failure scenario's LFI-to-AFI ratio results violate this requirement. The large increase to the LFI-to-AFI ratio for the failure scenario results is due to the failure scenario's inclusion of the FFA. The FFA exerts a lateral force that acts counter to the moment induced from the changed center of pressure. With a failed spring, the center of pressure of the separation system shifts away from the CG. The combined result of this effect is that LMI is cancelled out and more LFI is induced.

Minimum Clearances

All the requirements are based on preserving a safe minimum clearance between the separable portion of the USA and the CPL KIZ. Since clearance is the primary concern, the minimum clearance is closely monitored alongside the specific requirements.

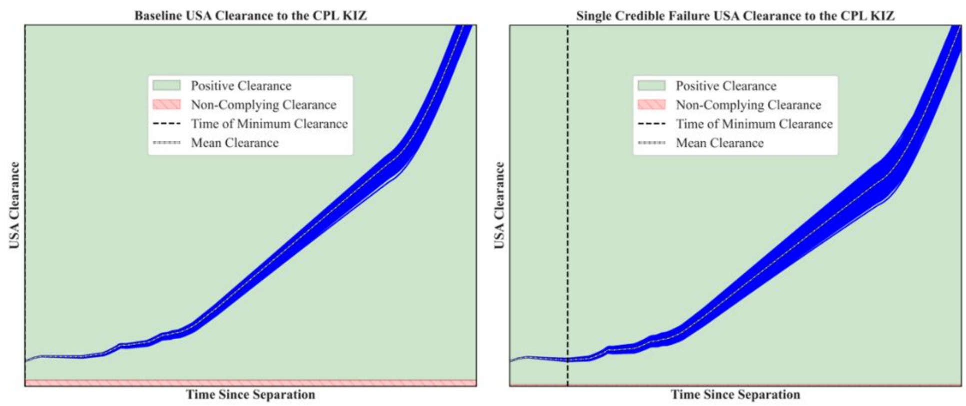

Figure 9. Baseline and Single Credible Failure Scenario Clearance Results.

The baseline scenario results shown in Figure 9 have no clearance concerns. The baseline scenario's minimum clearance occurs at the start of the simulation and clearance generally increases as the simulation progresses. Similarly, the failure scenario results show good clearance margins, with the minimum clearance not being much lower than the minimum clearance just before the USA separates. The time of minimum clearance for the failure case occurs after the baseline scenario's time, but also exhibits the same general monotonically increasing trend.

Analysis Discussion

The baseline scenario results all show compliance with the baseline scenario's requirements and show positive clearance. However, the failure results violate one requirement (Requirement 2) while showing positive clearance in addition to good clearance margin. The requirement violation shown previously in Figure 8 would predict that every run in the simulation would also violate the minimum clearance margin. However, since that requirement is not tied to minimum clearance but instead to an estimated achievable separation system misalignment, that prediction is incorrect, and every run complies with the minimum clearance. Additionally, the failure results fully comply with Requirement 1.

Because of this apparent contradiction in simulation results, Requirement 2 was revisited to reassess its methodology and identify the best path forward. Possible paths included: 1) update the limit with improved simulation design and inputs, 2) update the methodology used to determine the limit, or, 3) remove the requirement entirely, if its purpose had already been served in the early design stage. No matter which path was chosen, updating the requirements simulation inputs and design would be necessary. Fortunately, the CLVTOPS toolchain facilitates iterating upon simulation design and results processing using existing tools.

REVISED REQUIREMENTS SIMULATION DESIGN

The requirements simulation design needed to be revised in order to reevaluate Requirement 2's methodology or limit. The next sections cover the primary goal of the requirements simulation redesign, the changes made during the redesign, and a discussion about the results from the redesigned simulation.

Primary Goal

The primary goal while revisiting the requirements simulation was to redesign the applied general impulses to eliminate the need to apply an equal-and-opposite LMI. Because Requirement 1 limits LMI specifically, LMI was originally included in the simulation to make the parameter easier to track and adjust. However, this LMI application was non-physical since both bodies have significantly different mass properties. Therefore, the LFI and AFI application points were moved, improving the simulation by fully capturing the expected separation dynamics and eliminating the need for the LMI.

Redesign

To eliminate the LMI, the LFI was moved from the CG to the separation plane at the aft end of the separable portion of the USA. Here, the AFI and LFI induce an LMI and contribute to lateral force.

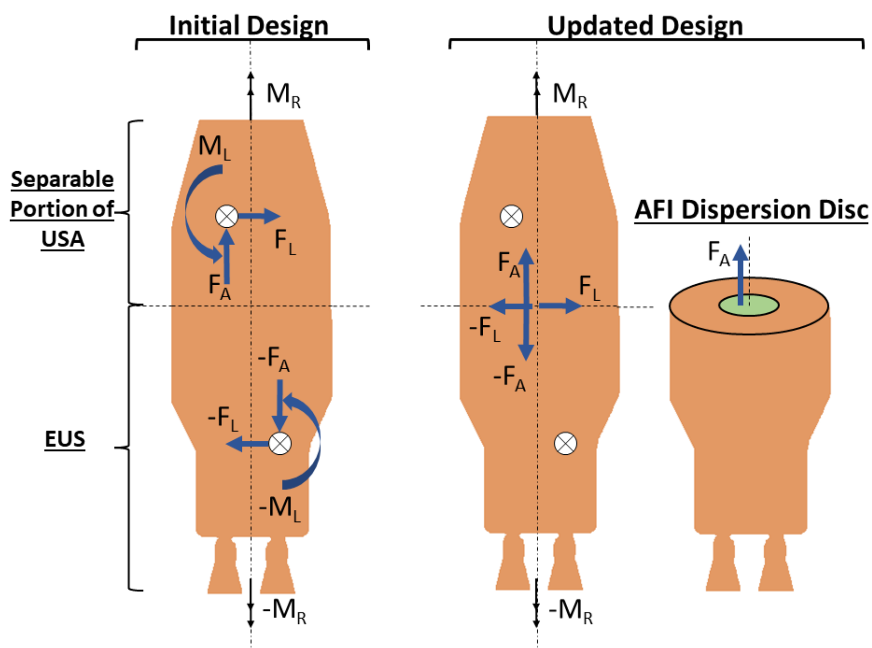

Figure 10. Initial and Updated Requirements Simulation Designs.

Figure 10 shows the initial design and the updated design of the requirements simulation. Apparent in the diagram is the removal of lateral moment impulse (M_L) and the updated application points for the axial force impulse (F_A) and lateral force impulse (F_L). That change alone creates a tight correlation between LMI and LFI, which isn't ideal since lateral forces at the separation plane aren't the only possible cause of LMI; an axial force acting off-center from the CG will also induce a moment. To account for this effect, the AFI was moved to a point on the separation plane and varied within a specified radius of the vehicle centerline, named the AFI Dispersion Disc, also shown in Figure 10.

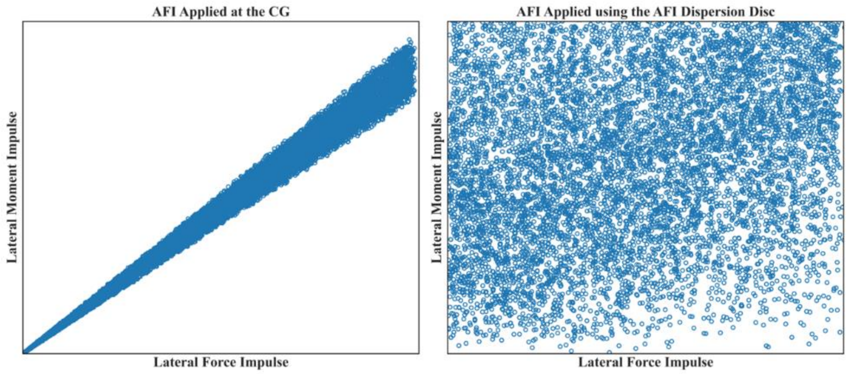

Figure 11. LMI vs LFI Before and After AFI Application Point Change.

Figure 11 shows the change in relationship between LMI and LFI before and after the addition of the AFI dispersion disc. Using the AFI Dispersion Disc decouples the LMI from the LFI. The AFI Dispersion Disc radius must be large enough to encompass the furthest extent the CG can be dispersed so that it can induce moments that contribute both constructively and destructively to the total lateral moment. This is important so that Monte Carlo runs with high resulting LMI but low resulting LFI (no translation, high rotation) and low resulting LMI and high resulting LFI (high translation, no rotation) can be generated. The LMI vs LFI design space is fully characterized by the AFI Dispersion Disc methodology.

Results Discussion

Previously, all generalized impulses were easily represented as either functions of another impulse or as histograms. However, initial plots of the updated results showed that these representations were no longer sufficient. In their stead, LMI and LFI were plotted as ratios of AFI. This is not only in line with how the requirements are defined since Requirement 1 is dependent on AFI and Requirement 2 directly limits the LFI-to-AFI ratio, but it also yields plots that represent the data well enough to draw conclusions and facilitate discussion.

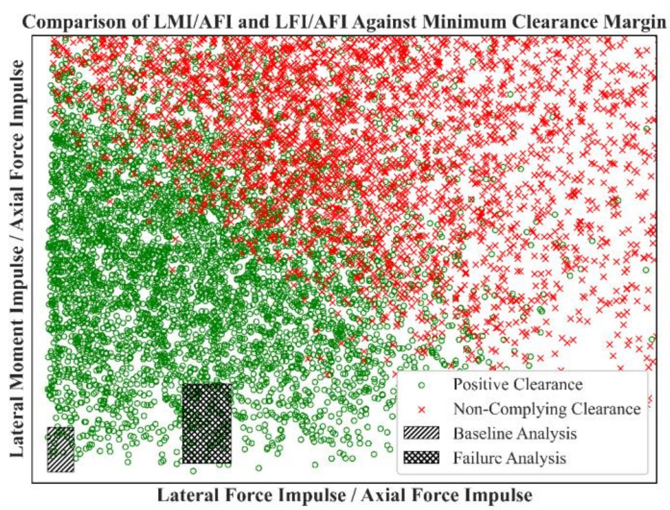

Figure 12. LMI and LFI as Ratios of AFI

Figure 12 shows the LMI-to-AFI ratio vs LFI-to-AFI ratio results from the updated requirements simulation. The green circle markers indicate requirements simulation Monte Carlo runs with positive clearance margins and the red "X" markers indicate runs with negative clearance margin. The single-hatched box bounds the analysis simulation's baseline scenario results, and the double hatched box bounds the failure scenario's results. This plot, among other supporting plots like Figure 11, confirmed that the updated requirements simulation was working as intended and produces results that fully characterize this design space. Not only are the baseline and failure analysis results well within the positive clearance region, but the margin between the failure results and the boundary between positive clearance and non-complying clearance is similar to the expected margin based on the failure scenario's minimum clearance results.

Additionally, this plot also indicated that Requirement 2, the limit on the LFI-to-AFI ratio that the failure analysis violated, was set too conservatively. However, this new design and analysis methodology shows that the current separation system and USA hardware design meets Requirement 1 and the LFI-to-AFI ratio results for both baseline and failure scenarios have significant margin to the boundary where CPL KIZ recontact start to appear. Based on these results and the expectation that the hardware will not be undergoing a clean-sheet redesign, the decision was made to remove Requirement 2. It had served its purpose of protecting for minimum clearance during the early design phase and now had generated a false negative when no clearance concerns existed.

CONCLUSION

The CLVTOPS toolchain allowed iterative, fast development of not only a hardware analysis simulation for NASA's SLS Block-1B USA separation event, but it also allowed similarly fast development of an updated requirements simulation and supporting requirements-setting methodology. The close integration of its pre-processing, simulation, and analysis components lends itself to fast iteration of ideas. Baseline and single credible failure scenarios were simulated and analyzed to determine if the USA hardware and separation system met their requirements. The failure scenario's requirement violation but large positive clearance margin indicated that Requirement 2 had been set too conservatively early on. Due to the maturity of the USA hardware and separation system design and the large clearance margin observed in both the baseline and failure scenarios, Requirement 2 was removed as a constrain on the system. Future analyses will include continued evaluation of the analysis simulation results, their minimum clearances will be checked to ensure positive clearance margins, and the analysis results will be compared against the updated requirements simulation results.

REFERENCES

[1] Burger, B., Addona, C., McDonough P., Muscha Z., et al., "Space Launch System Liftoff and Separation Dynamics Analysis Tool Chain." *AIAA Scitech Forum*, 2021.

[2] Kane, T. and Wang, C., "On the Derivation of Equations of Motion." *Journal of the Society for Industrial and Applied Mathematics*, Vol. 13, No. 2, Jun 1965.

[3] McCarter, J. W., "Simulating Flights of Future Launch Vehicles and Spacecraft", NASA Tech Briefs, 2007, [online] URL: http://www.techbriefs.com/component/content/article/ntb/tech-briefs/software/1182 [cited 30 April 2020].

[4] Hanson, J. and Beard, B., "Applying Monte Carlo Simulation to Launch Vehicle Design and Requirements Verification." *Journal of Spacecraft and Rockets*, Vol. 49, No. 1, Jan-Feb 2012.