Evaluating Liftoff Debris for NASA's Space Launch System (SLS) Prior to the Artemis I Launch

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I. Introduction

The SLS Artemis I launch vehicle is the first of several planned Artemis launch vehicles, with a number of design differences from earlier NASA missions that incur launch debris risk to the mission. As a test vehicle, the Artemis I hardware also endured environments and tests not planned for future missions, which led to several additional factors contributing to an evolving liftoff debris risk to the SLS vehicle. This paper summarizes these risk factors and addresses the processes used to evaluate and communicate the risks to support a successful Artemis I launch.

Both liftoff debris and ascent debris contribute to the mission risk. Liftoff debris is debris released by the vehicle or from the launch pad during liftoff through launch tower clear. Ascent debris is released from the vehicle during the launch phase between launch tower clear and Booster separation. Both liftoff and ascent debris are well understood from previous NASA programs' experience and from tests of materials, processes and functions that are known to release debris. These expected sources were assessed and cleared well ahead of launch day. However, given the ever-changing schedules and environments, evaluations and reviews were required for unexpected observations of potential debris after tests and after events leading up to launch. Mitigation of several identified debris risks were accomplished by pre-launch repair, replacement, or removal of thermal materials or potential pad debris. Finally, processes were developed to evaluate any additional potential launch debris risks identified in the days leading up to launch and on launch day to support a successful launch. This paper will address many of these identified risks and the SLS debris day of launch (DOL) procedures that were used for Artemis I and will be used for subsequent Artemis missions.

II. Nominal Launch Debris Assessment

Although many of the Artemis vehicle hardware components are similar to those on the NASA Shuttle Program, there are important differences in the architecture of the Artemis I vehicle which require new assessments of liftoff debris risk for the SLS Artemis missions. The SLS Artemis launch vehicles are generally less vulnerable to launch debris than the Shuttle predecessor, given the more favorable crew module location and less sensitive surfaces. However, design differences can increase the risk to the SLS mission. The longer vehicle enables higher debris transport impact energies on aft components increasing their vulnerability to impact damage. The proximity of the liquid engines to the Booster nozzles enables Booster nozzle throat plug debris to become potential threats to the RS-25 nozzles and other aft components. Because there is no design requirement to limit or prevent launch debris release

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or to withstand debris impacts, a hazard assessment is necessary to describe the risk of mission loss due to potential debris impacts.

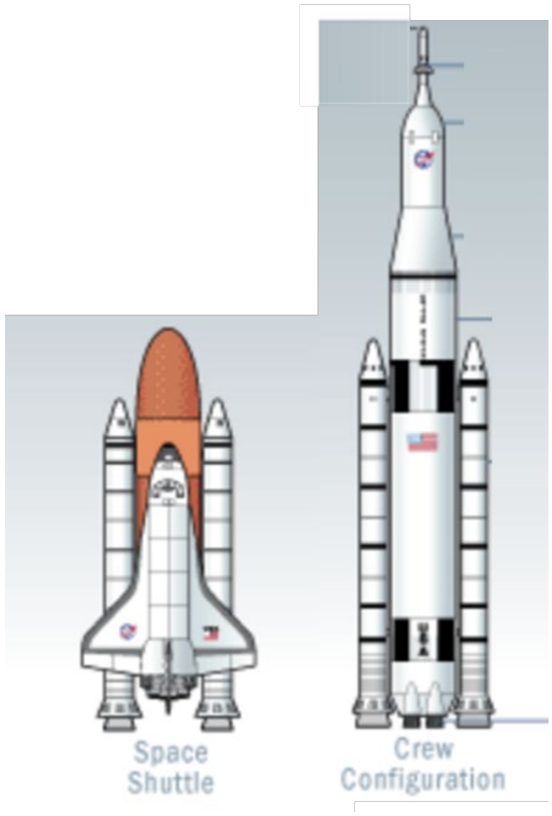

Fig. 1 Comparison of Shuttle and Artemis I Vehicle Configurations

Assessment of the launch debris hazards to the SLS mission are performed as a nominal process using a widely reviewed and historically developed process that begins with the definition of debris sources that are expected to release during the liftoff and ascent phases of the mission. The defined debris parameters are typically maximum expected sizes based on historical data and test data or conservative sizes based on analyses and test data. Once defined, debris transport analyses are performed for each of the debris sources to predict impact energies on the components on the vehicle. The vehicle components are assessed for impact damage tolerance from the predicted impact energies by either deterministically clearing the predicted impacts or identifying impacts as concerns for further evaluation. Figure 2 shows a general process flow for assessment of expected launch debris.

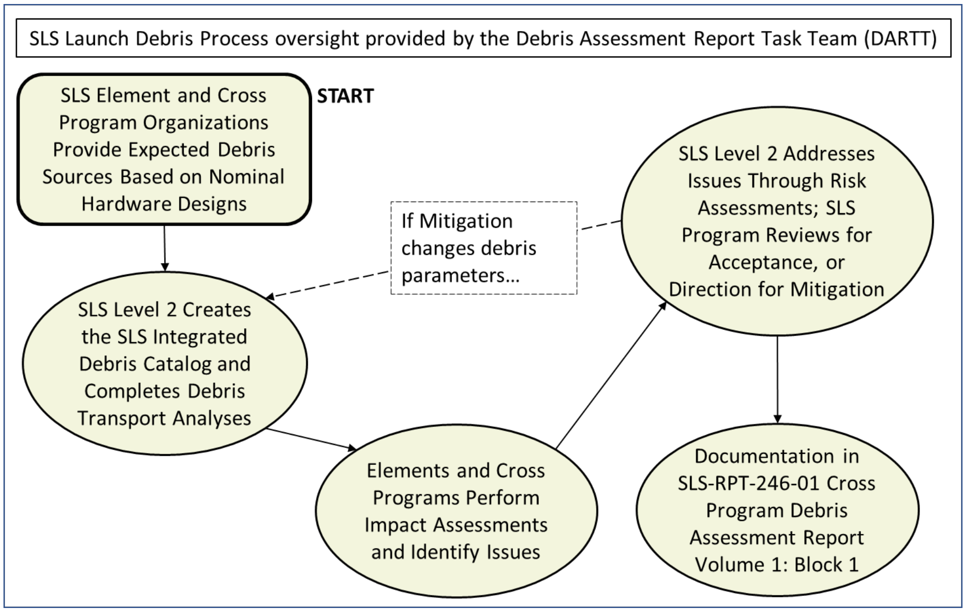

Fig. 2 Simplified Launch Debris Assessment Process

For Artemis I, two major issues were identified during the nominal launch debris assessment process which required additional test data and/or risk assessment to define the hazard to the vehicle. The risk assessments included evaluation of the predicted debris released, probability of impact, and probability of damage given an impact. Since there are several different debris materials, release mechanisms, and transport mechanisms, each predicted issue can require a unique approach to risk assessment, with careful consideration of the details of each source-component combination. The two sections below address the risks evaluated for the Artemis I mission from the Booster Throat Plug Foam predicted impacts to the liquid engine nozzles, and from the Core Stage thermal protection system foam impacting aft Booster separation motor covers.

A. Throat Plug Foam

Each of the two Solid Rocket Boosters (SRB) that are part of the SLS architecture include throat plugs in the nozzles. The purpose of the throat plugs is multi-purpose: to maintain environmental conditions within the inner bore the SRBs, to prevent Foreign Object Debris (FOD) intrusion, and to prevent premature ignition of the solid propellant. The latter function, preventing premature ignition, is of especial importance during a potential on-pad shutdown wherein the RS-25 engines are lit but are commanded to shut down prior to Booster ignition. Thus, the throat plugs must seal the inner bore from water intrusion from the Ignition Overpressure and Sound Suppression (IOP/SS) water deluge system as well as flame intrusion from the RS-25 plumes and any free burning hydrogen released during the main engine start-up / shutdown operations.

The throat plugs on the Artemis I mission are stronger than those used during the heritage Shuttle missions. Part of this reason is due to the closer proximity of the throat plugs in relation to the four RS-25 engines compared to the relative locations of the SRBs to the 3 Space Shuttle Main Engines (SSMEs) on Shuttle. The Artemis I design utilizes a stronger foam that makes up the majority of the mass of the throat plug. Each throat plug is sealed into the Booster nozzle inner surface with a ring of polysulfide. The aft facing surface of the throat plug has a red room temperature vulcanizing (RTV) layer to serve as a flame barrier and water barrier. During the Booster ignition sequence, a shock wave is created by the Booster ignitor located on the forward end of the inner bore of each Booster. The igniter shock travels aft through the inner bore and then impacts the throat plug, fracturing it and accelerating the fragments downward towards the IOP/SS water.

The SLS program identified a potential liftoff hazard during the Booster ignition process in regard to the SRB throat plugs. The hazardous condition would be a scenario in which the throat plug fragments are sufficiently slowed by the IOP/SS water that they can be redirected upward and outward by the developing Booster plume and potentially impact adjacent SLS components. The SLS program created an Issue Resolution Team (IRT) to address this risk from a multi-disciplinary effort that was anchored by multiple test campaigns. Several full-scale static-fire tests of SRBs at Promontory, Utah were conducted that included the Artemis I version of the throat plug design [1]. Ultimately, the

SLS Program accepted the throat plug risk for Artemis I with direction to study the results of Artemis I to inform the risk for future, crewed missions. The SLS and Exploration Ground Systems (EGS) teams conducted extensive post-launch walkdowns to retrieve the throat plug fragments after the Artemis I mission. The results from the walkdowns and accompanying catalogs and analysis are being used to inform the risk moving toward the Artemis II launch [2].

Fig. 3 Booster Throat Plug Fragment Recovered after Artemis I

B. Booster Aft BSM

The aft Booster Separation Motors (BSMs) single covers were identified during the nominal debris assessment process as vulnerable to impact damage from two Core Stage Thermal Protection System (TPS) foam designs and locations: the most forward location of the Liquid Oxygen Feedline Brackets closeout foam, and the Liquid Hydrogen Tank to Intertank Flange foam. The purpose of the TPS foams in these areas is to insulate the Core Stage surfaces to help prevent boil-off of the cryo-propellant. Multiple releases of foam can occur from each location, driven by a process known as cryo-ingestion/cryo-pumping. Pressure can buildup in potential voids under the foam during ascent as the propellant level drops and the external surfaces heat up, thereby pushing divots of foam off the surface of the vehicle to become debris. This is an expected debris release often observed in historical vehicles.

Ascent Debris Transport tools, validated during the Shuttle program, were used to predict the worst-case impact energies on vehicle components for these foam debris releases. The Aft BSM single cover was assessed by the SLS Booster Element organization, with a result predicting shear-out failure of the cover at fastener locations. This failure would allow hot-gas ingestion into the cover cavity which could cause BSM failure, potentially causing early Booster separation or preventing nominal Booster separation.

The risk assessment addressed risk of debris releases, risk of impact, and risk of exceeding failure thresholds given an impact. For both foam types and locations, the total risk to the Booster aft BSM single covers was found to be acceptable by the SLS program.

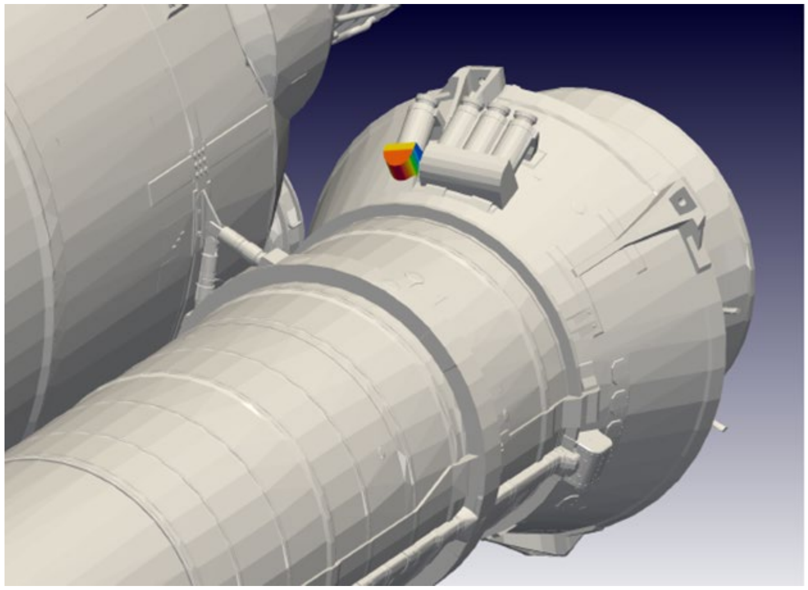

Fig. 4 Aft BSM Single Cover Location

III. Day of Launch (DOL) Debris Evaluation Plan

As the SLS program had decided the launch debris environments should be addressed by hazard assessments rather than as a design environment, no design thresholds for damage to critical components were determined, and therefore were not expected to be available for Artemis I launch day evaluations of unexpected debris. Previously cleared impact energies for various debris types on many critical components were available for quick-look evaluations of unexpected debris but were not indicative of actual damage thresholds. Some SLS Elements made efforts to extend damage thresholds based on historical test data to support DOL assessments, but most actual thresholds remained unknown. To assist in the evaluations of unexpected debris that might be observed on launch day, a new process was developed to help determine the risks to the mission, especially where damage thresholds were unknown or exceeded.

The SLS day-of-launch (DOL) Launch Debris Process was developed and coordinated with inputs from the SLS Elements and Cross Programs, and in cooperation with the SLS and Cross Program imagery teams. This standard operating procedure involves active communications over voice loops on launch day by the Cross-Program team of debris Subject Matter Experts (SMEs) to evaluate unexpected debris observed through imagery, and to communicate in real time potential risks to the vehicle, up through program and mission management teams. The lead console for debris related items during day-of-launch is the Console Imagery Coordination and Evaluation (CICE). This process proved successful in evaluating debris risks from observations during the first two Artemis I launch attempts as well as during the final successful launch.

The process defines the roles and responsibilities of each debris and imagery SME, and of each SLS and Mission Management participant. Working hand in hand with the imagery procedure, debris observations noted by imagery SMEs in the NASA Imagery Reporting Database (NIRD) are reviewed by the pertinent Element debris SME to determine the need for further evaluation. If the potential debris is not within expected debris parameters, the debris is evaluated by liftoff or ascent debris transport SMEs to predict impact energies on vehicle components. Filtered on previously cleared impact energies, if the predicted impact energies are noted as potential issues, the Element or Cross Program debris SMEs evaluate the impact energies for concerns. Concerns are reported to the SLS and Cross Program management and to the mission management team, with inputs from the pertinent SMEs and Chief Engineers, to evaluate the risk to the mission, to make a launch decision.

The inaugural use of this process for Artemis I showed its effectiveness in dealing with unexpected launch debris due to weather events and/or potential process misses. As minor corrections and changes to the Artemis vehicles are made, this process will continue to be helpful for subsequent missions in evaluating evolving risks to mitigate launch debris hazards and communicate updated risk to the SLS vehicle.

IV. Green Run

The Green Run test campaign was performed on the B-Stand at NASA's Stennis Space Center (SSC). The SLS Artemis I Core Stage (CS1) was vertically integrated into the stand on January 22, 2020 after being delivered to SSC from Michoud Assembly Facility (MAF) via NASA's Pegasus barge. The Artemis I Core Stage remained in the B-Stand at Stennis for an extended period of time while the Green Run test campaign was performed. There were a number of test points along this campaign to demonstrate the capability of the integrated stage with the four RS-25 engines that would propel the Artemis I mission into an orbit around the moon. The Green Run campaign run at Stennis was the first opportunity to test a configuration of four RS-25 engines and the new liquid hydrogen tank and liquid oxygen tank components of the Artemis I Core Stage along with extensive Developmental Flight Instrumentation (DFI) and new designs for sub-systems such as the Thrust Vector Control (TVC) system. Near the completion of the Green Run test campaign, the final two milestones were the Wet Dress Rehearsal (WDR) and Hot Fire tests. The Wet Dress Rehearsal test was the first opportunity to fuel the liquid hydrogen and liquid oxygen tanks on CS1 with cryogenic fluid. The initial WDR for Green Run was unable to fully complete all objectives and thus a second WDR was required. The second Green Run WDR was successful, and the program pressed toward towards the Green Run Hot Fire Test—which involved a full-duration burn of all four RS-25 engines and TVC gimbaling. The initial Green Run Hot Fire Test was prematurely aborted due to triggering of a system redline. The Artemis I Core Stage was able to safely perform engine shutdown and then drain the remaining cryogenic propellant. The second Green Run Hot Fire Test was fully successful and achieved full duration burn along with nominal TVC performance.

Fig. 5 Artemis I Core Stage and Stennis B-Stand

Throughout the Green Run WDR and Hot Fire tests, engineers from Boeing and NASA carefully monitored the integrity and performance of external TPS systems. The Stennis B-Stand has multiple imagery assets that captured the functionality of the TPS systems during cryogenic fueling operations and during the RS-25 firing. Cryogenic loading of the hydrogen and oxygen tanks revealed locations of potential damage due to cracks in the foam, which can be attributed to mechanisms such cryo-pumping. Cryo-pumping is a phenomenon related to liquid hydrogen systems wherein the air surrounding a liquid hydrogen pressure vessel is cooled by the liquid hydrogen to the point of liquifying. Any liquid air (primarily liquid nitrogen) that becomes trapped between the tank wall and the external TPS provides a potential TPS liberation location with the Core Stage enters a Hot Fire (or Launch) state and the liquid hydrogen levels start dropping. When the trapped LN2 is warmed up to its boiling point, it then expands rapidly. If there is not sufficient communication to the outside surface, the trapped and boiling LN2 can produce a debris liberation.

After the Green Run test campaign concluded and the Core Stage was removed from the Stennis B-Stand on April 20, 2021, the Artemis I Core Stage had been located outside for over a year and had undergone 4 separate cryogenic loading cycles and 2 hot fire cycles as well as numerous weather events. Areas of TPS damage were identified and repaired before the Artemis I Core Stage entered the next phase of pre-launch testing at Kennedy Space Center (KSC): Wet Dress Rehearsal for the integrated vehicle.

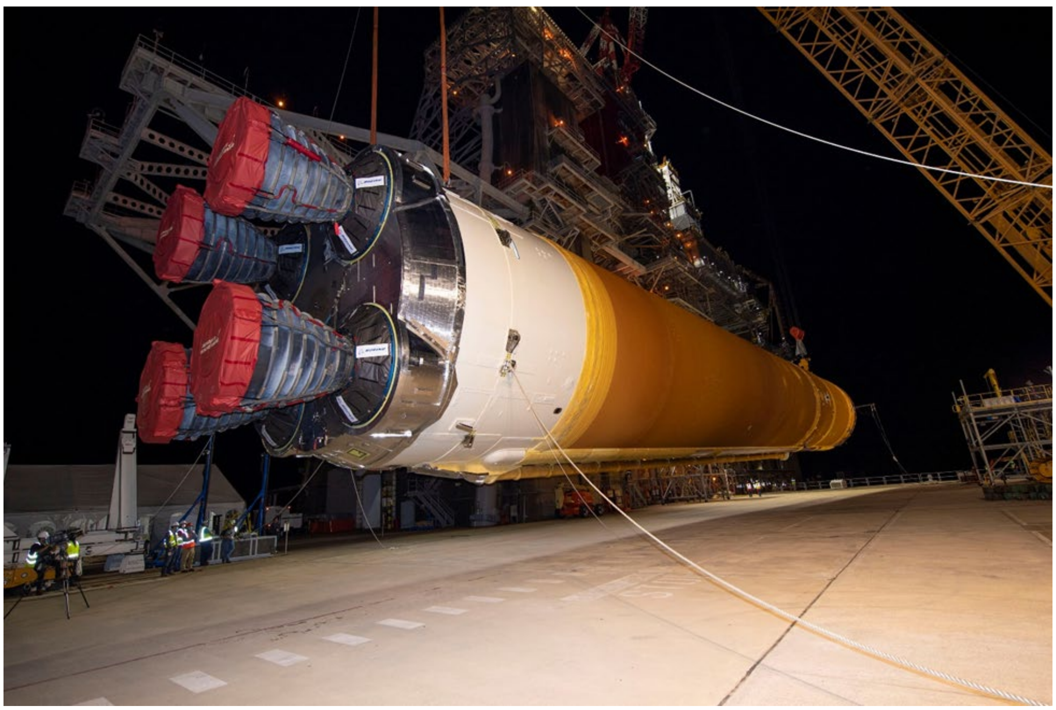

Fig. 6 Removing the Artemis I Core Stage from the B-Stand at Stennis Space Center

V. Integrated Vehicle Wet Dress Rehearsals and Activities Through Launch

When the Artemis I Core Stage was delivered to KSC after the Green Run test campaign, it was integrated with the Orion Multi-purpose Crew Vehicle (MPCV) and the other SLS Elements (Boosters, Interim Cryogenic Propulsion Stage (ICPS), Launch Vehicle Stage Adapter (LSVA), and MPCV Stage Adapter (MSA)) within the Vertical Assembly Building (VAB). The competed vehicle was rolled out to Pad 39-B on March 17-18, 2022.

A. WDR 1

The Wet Dress Rehearsal 1 was performed on April 3, 2022. The EGS Debris Team performed an extensive series of walkdowns and vehicle out mold line (OML) inspections prior to the call to stations for this WDR test event. During the walkdowns, a number of FOD items were collected from the Mobile Launcher from the 0 Deck extending up the tower. Though these FOD items had been removed from the Mobile Launcher (ML) and proximity to the SLS Vehicle, the cross-program debris team evaluated these items as potential liftoff debris sources for impact to the SLS Vehicle. Another item of interest that was noted during WDR 1 was minor damage to the TPS layer on the Launch Abort

System (LAS) ogive. It was noted that these areas would be repaired upon roll-back to the VAB once the WDR testing was completed. WDR 1 was ultimately scrubbed prior to beginning cryogenic loading of either the Core Stage or ICPS due to a facility issue.

B. WDR 2

The Wet Dress Rehearsal 2 was performed on April 4, 2022 after the facility issue had been resolved from the day before. Due to the FOD collected prior to WDR 1, additional FOD walkdowns were performed while the facility issue was being addressed. Another batch of FOD was recovered during these efforts. The cross-program Debris Team performed a similar set of evaluations of the recovered FOD. The WDR 2 was scrubbed prior to cryogenic loading of the ICPS tanks and the Core Stage liquid hydrogen tank. The Core Stage liquid oxygen tank was filled to approximately 50%.

C. WDR 3

The Wet Dress Rehearsal 3 was performed on April 14, 2022 and was able to achieve approximately 50% fill of the Core Stage liquid oxygen tank and approximately 5% of the Core Stage liquid hydrogen tank. A hydrogen leak was detected in the Tail Service Mast (TSM) and the test was not able to achieve full fill of all 4 cryogen tanks onboard the Core Stage and the ICPS. The integrated vehicle was drained and placed into a safe state after attempts to fix the leak remotely were unsuccessful. Prior to call to stations for WDR 3, the EGS Debris Team performed additional FOD walkdowns. Several items were discovered but the number of FOD items was significantly decreased from the initial walkdowns prior to WDR 1 and WDR 2. As the cryogenic loading process was able to progress further than prior attempts, the cross-program debris team was able to observe ice and frost formation on a number of critical locations on the SLS vehicle and the ML umbilicals. One item of interest was the discovery of a partially loose metal identification tag, or “dog tag” on the ICPS Umbilical. Dog tags are required to be connected on at least two locations and this dog tag had a single connection.

D. WDR 4

The Wet Dress Rehearsal 4 was performed on June 20, 2022. Further EGS Debris Team FOD walkdowns were successful in recovering a number of FOD items that were cataloged and communicated to the cross-program Debris Team during the WDR 4 test. Additional regions of loose Orion LAS ogive TPS were noted. This was similar to previous Items of Interest (IOIs) noted on WDR 1, WDR 2, and WDR 3. Another loose dog tag was noted on the Tail Service Mast Umbilical (TSMU), where a metal dog tag had one of its two connections either broken or omitted and was swinging freely from its single connection point. Action was noted for future roll-back to VAB to address this and any other metal dog tags that only had a single secure point. Another point of interest was the video discovery of several sticky-backed Go-Pro mounts that had been left on the ICPS Umbilical (ICPSU). The discovery of these two sticky-backed Go-Pro mounts is a demonstration of the efficacy of the imagery teams actively monitoring the OML of the SLS Vehicle and the ML and umbilicals throughout the WDR testing campaign. Due to Quick Disconnect (QD) leakage of hydrogen gas, the WDR 4 was scrubbed prior to fully achieving a simulated terminal count process.

E. Launch Attempt 1

The initial Artemis I launch attempt was August 29, 2022. Stages CICE noted the discovery of several connected pieces of tape. The tape pieces were measured via imagery and evaluated by the cross-program Debris Team and were able to be cleared for launch. The Core Stage liquid oxygen and liquid hydrogen tanks were able to be completely filled during this launch attempt. Additionally, the ICPS liquid oxygen and liquid hydrogen tanks were able to be filled during this launch attempt. Ultimately, the launch attempt 1 was scrubbed due to an issue on a sensor on one of the RS-25 engines. One IOI of note was the evaluation of ice finger growth on the one of the Gaseous Oxygen (GOX) vents on the ICPS. After launch attempt 1 was scrubbed, the imagery team noted several cracks in the foam TPS on the Core Stage Liquid Hydrogen (LH2)/Intertank (IT) flange close outs. The cross-program debris team evaluated these cracks in the time prior to launch attempt 2.

F. Launch Attempt 2

The second Artemis I launch attempt was September 3, 2022. The cross-program debris team confirmed threshold values associated with the potential debris liberations from the cracks on the CS LH2/IT flange close-out foam. An IOI was noted for tape that was left on the Vehicle Stabilization System (VSS) on the ML structure. Immediately prior to call-to-stations for launch attempt 2, the EGS Debris Team located 2 FOD items that were in locations on the ML that were inaccessible in the timeframe prior to cryogenic loading operations. The two debris IOIs were able to be cleared through the cross-program Debris Team DOL process. After the launch attempt was later scrubbed by the Launch Director, these two FOD items were able to be removed.

G. Tanking Test

The Tanking Testing for Artemis I was performed on September 21, 2022. During this tanking test, all four of the cryogenic vessels on the integrated Artemis I vehicle were successfully filled. This test did note an IOI regarding loose tape on one of the Core Stage umbilicals.

H. Rollback for Hurricane Ian

The onset of Hurricane Ian prompted a decision to safe the Artemis I vehicle and Mobile Launcher by rolling them back to the VAB to weather the incoming storm. This operation had to be done quickly because the presence of high winds during a roll-back operation would be potentially harmful to the vehicle given the non-static base and the vibrations from the roll-back procedure. The SLS Vehicle and Mobile Launcher were able to be safely returned to the VAB prior to the advent of high winds from Hurricane Ian. The damage to Kennedy Space Center was minimal and no critical hardware received significant damage. The integrated SLS Vehicle and Mobile Launcher were then returned to Pad 39-B to continue launch preparations for the Artemis I mission.

I. Weathering Hurricane Nicole

The onset of Hurricane Nicole was a faster developing storm that put the advent of high winds at such a short interval that a roll-back would potentially not be completed in time, putting the SLS vehicle and Mobile Launcher in a riskier state than remaining at Pad 39-B. While it is never the first option to leave an integrated vehicle and launcher on the pad to weather a storm, the SLS Program decided that, given the predicted winds at Kennedy Space Center at landfall, and the high likelihood of getting substantial winds while still en route to the VAB, the overall decision to safe the SLS Vehicle and Mobile Launcher would represent the least hazardous option. An extensive loads analysis was performed to make sure that the SLS Vehicle and Mobile Launcher would be able to withstand the wind loads and accompanying vibrations during the duration of Hurricane Nicole. A dedicated ride-out team at Kennedy Space Center monitored the state of the vehicle and weather conditions throughout the duration of the storm. Additional imagery support was provided throughout the storm at the MSFC HOSC facility where a team of analysts monitored the numerous cameras viewing the Mobile Launcher, Pad 39-B and the SLS Vehicle. The ride-out crew at KSC lived up to the "Rocket Like A Hurricane" moniker associated with that crew dedicated to the success of the Artemis I mission.

After Hurricane Nicole had passed, the MSFC and KSC teams reviewed the footage of the vehicle during the storm, performed extensive walkdowns and evaluated noted damage to the Mobile Launcher and the SLS Vehicle. Damage to systems such as the umbilicals (given their cantilevered status and wide surface areas) were some of the more obvious issues. Damage was also noted on the Crew Access Arm (CAA) that had the potential to release FOD during liftoff. Given the uncrewed nature of the Artemis I launch, the potentially FOD producing areas of the CAA were able to be isolated without detriment to the overall mission. On the vehicle itself, RTV was noted to have been liberated during the sustained winds.

J. Launch Attempt 3—Successful Artemis I Mission

The third, and ultimately successful, launch attempt for Artemis I was on November 16, 2022. The EPA team requested size estimates for the ice growth on the ICPS LOX vent. The team was able to confirm that the growth of vent ice on the ICPS LOX vent was within previously assessment of an IOI from launch attempt 1. Particular attention was given to monitoring the status of several known cracks in the foam on the Core Stage LH2/IT flange close-outs. Stages CICE confirmed that the cracks appeared to have some frost growth but no confirmed ice growth. The successful launch attempt was mostly quiet from a debris standpoint except for a final, last-minute evaluation of a potential TPS release source on Orion that was able to be cleared just prior to the start of Terminal Count.

VI. Prelaunch Risk Analyses

In spite of the comprehensive tests and analyses of Artemis I expected liftoff debris, a number of additional tests/processes were completed prior to the Artemis I mission that were required to support a complete understanding of a new launch vehicle, but increased the risk of releasing liftoff debris. The hardware endured several additional cryogenic loading cycles, including the Green Run tests at Stennis Space Center, Wet Dress Rehearsals at Kennedy Space Center, and multiple launch attempts. Each of these cycles induced stresses in the TPS materials, increasing the risk of damage to and release of the TPS. Additionally, induced and weather environmental factors that could increase the likelihood of debris release were significant. Vibrations and stresses in the TPS were induced by a required roll-back to the Vehicle Assembly Building before Hurricane Ian to protect the vehicle from damage by high winds. Wind damage and potential internal stresses to several outer mold line materials on the integrated SLS vehicle and mobile launcher were caused by weathering Hurricane Nicole at Pad 39B the week before launch. A thorough imagery scan of the vehicle was performed after each event and the damage observed was repaired, removed, or assessed and the risk to the mission evaluated.

VII. Conclusion

An integrated approach to DOL debris assessment across NASA SLS, Cross Program, and contractor organizations led to successful and efficient evaluations of unexpected launch debris and a successful Artemis I launch. Awareness of potential launch debris issues has improved, and mitigated activities more accomplished as a result of the activities leading up to launch. The many evaluations of expected and unexpected launch debris for Artemis I provide a sound basis for support to Artemis II and beyond.

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