

Use of DES Modeling for Determining Launch Availability for SLS

Eric Staton¹

Jacobs Engineering/Jacobs ESSA Group, Huntsville, Alabama, 35806

Grant Cates²

The Aerospace Corporation, Cape Canaveral, Florida, 32920

Ronald Finn³

ARES Corporation, Houston, Texas, 77058

Karen M. Altino⁴

NASA – Marshall Space Flight Center, Huntsville, Alabama, 35812

K. Lee Burns, Ph.D.⁵

Raytheon/Jacobs ESSA Group, Huntsville, Alabama, 35806

and

Michael D. Watson⁶

NASA – Marshall Space Flight Center, Huntsville, Alabama, 35812

Abstract – The National Aeronautics and Space Administration (NASA) is developing new capabilities for human and scientific exploration beyond Earth’s orbit. This effort includes the Space Shuttle derived Space Launch System (SLS), the Orion Multi-Purpose Crew Vehicle (MPCV), and the Ground Systems Development and Operations (GSDO). There are several requirements and Technical Performance Measures (TPMs) that have been levied by the Exploration Systems Development (ESD) upon the SLS, Orion, and GSDO Programs including an integrated Launch Availability (LA) TPM. The LA TPM is used to drive into the SLS, Orion and GSDO designs a high confidence of successfully launching exploration missions that have narrow Earth departure windows. The LA TPM takes into consideration the reliability of the overall system (SLS, Orion and GSDO), natural environments, likelihood of a failure, and the time required to recover from an anomaly. A challenge with the LA TPM is the interrelationships between SLS, Orion, GSDO and the natural environments during launch countdown and launch delays that makes it impossible to develop an analytical solution for calculating the integrated launch probability. This paper provides an overview of how Discrete Event Simulation (DES) modeling was used to develop the LA TPM, how it was allocated down to the individual programs, and how the LA analysis is being used to inform and drive the SLS, Orion, and GSDO designs to ensure adequate launch availability for future human exploration.

¹ Supportability Engineer, Operation Engineering Branch, NASA/MSFC EO40, Non AIAA member.

² Senior Project Leader, Civil and Commercial Operations, Aerospace/KSC C/CVNRL, Senior Member.

³ Senior System Engineer, NASA JSC/GV, Senior Member.

⁴ Flight Vehicle Atmospheric Environments, Natural Environments Branch, NASA/MSFC EV44.

⁵ Sr. Physics Engineer II, Natural Environments Branch, NASA/MSFC EV44, Non AIAA member.

⁶ System Engineer, System Engineering Management Office, Chief Engineers Office, NASA/MSFC.

Nomenclature

| | | |
|-----------------|---|--|
| <i>C-RAST</i> | = | Constellation-Requirements Assessment by Simulation Technique |
| <i>DES</i> | = | Discrete Event Simulation |
| <i>DRMs</i> | = | Design Reference Missions |
| <i>EDS</i> | = | Earth Departure Stage |
| <i>ESD</i> | = | Exploration Systems Development |
| <i>GLS</i> | = | Ground Launch Sequence |
| <i>GR&A</i> | = | Ground Rules and Assumption |
| <i>GSDO</i> | = | Ground Systems Development and Operations |
| <i>HEFT</i> | = | Human Exploration Framework Team |
| <i>ICPS</i> | = | Interim Cryogenic Propulsive Stage |
| <i>ISS</i> | = | International Space Station |
| <i>LA</i> | = | Launch Availability |
| <i>LCA</i> | = | Launch Climate Analysis |
| <i>LEO</i> | = | Low Earth Orbit |
| <i>LRB</i> | = | Liquid Rocket Boosters |
| <i>KSC</i> | = | Kennedy Space Center |
| <i>MAST</i> | = | Manifest Assessment Tool |
| <i>MMT</i> | = | Mission Management Team |
| <i>MPCV</i> | = | Multi-Purpose Crew Vehicle |
| <i>MSFC</i> | = | Marshall Space Flight Center |
| <i>MSI</i> | = | Maintenance Specific Items |
| <i>MTBF</i> | = | Mean Time between Failure |
| <i>MTTB</i> | = | Mean Time to Repair |
| <i>NASA</i> | = | National Aeronautics and Space Administration |
| <i>NEA</i> | = | Near Earth Asteroid |
| <i>NEO</i> | = | Near Earth Object |
| <i>PACER</i> | = | Probabilities of Atmospheric Conditions and Environmental Risk |
| P_{CA} | = | Climatological Availability Probability |
| P_{FM} | = | Failure Mode Probability |
| P_v | = | Probability of Violation |
| <i>SLS</i> | = | Space Launch System |
| <i>SSME</i> | = | Space Shuttle Main Engines |
| <i>TBD</i> | = | To be Determined |
| <i>TBR</i> | = | To be Reviewed |
| <i>TIM</i> | = | Technical Interchange Meeting |
| <i>TPM</i> | = | Technical Performance Measure |

I. Introduction

The new heavy lift launch system being developed by NASA for human and scientific exploration beyond Earth orbit is comprised of the SLS, Orion, and GSDO. The launch architecture is being developed using a block approach to support a number of Design Reference Missions (DRMs) from lunar fly-by to multi-launch Mars missions. The desire of the system is to ensure a high confidence of successfully launching the exploration missions, especially those that require multiple launches, have a narrow Earth departure window and high investment costs. Therefore, there is a need to develop an ESD LA TPM to measure the probability of launching the vehicle after the start-of-countdown. This paper discusses the process used by the Cross-Program team to develop the ESD LA TPM and allocate it to each of the Programs through the use of DES.

II. Launch Availability Development

In late 2010 through early 2011 timeframe the Human Exploration Framework Team (HEFT) was developing suggested objectives for the SLS. One of these objectives was Launch Processing which was focused on launch countdown. The launch processing objective was subsequently proposed to be an ESD LA requirement that would be imposed upon the SLS, GSDO, and Orion Programs. The desire to have the requirement be more quantitative and related to Near Earth Object (NEO) and Mars DRMs resulted in the following proposed values:

- Threshold (minimum capability required to meet mission requirements): Provide an integrated launch system including payload (crew if applicable) and supporting infrastructure (including range) that has a 60% likelihood of launching on the planned launch date at the start of launch countdown or commitment to launch (~3 days prior to launch). The integrated launch system shall have an 89% chance of launching within 10 days of that planned launch date and a 95% chance of launching within 30 days.
- Objective (desired capability): Provide an integrated launch system including payload (crew if applicable) and supporting infrastructure (including range) that has a 70% likelihood of launching on the planned launch date at the start of launch countdown or commitment to launch (~3 days prior to launch). The integrated launch system shall have a 91% chance of launching within 10 days of that planned launch date and a 97% chance of launching within 30 days.

The crewed exploration mission to an asteroid being studied at that time had an earth orbit departure window of 30 days. Future mars injection windows were thought to range from 30 to 60 days. There was also an expressed desire that we not launch the crew too early relative to the opening of the departure window so as to minimize their time in space. Consequently, a high cumulative probability of being able to launch the crew within a 30-day window seemed to be of critical importance.

In early-mid 2011 ESD established LA as requirement R-19. The actual R-19 requirement language and supporting rationale is shown in Figure 1.

R-19 Launch Availability

- R-19: Launch Availability. The Architecture shall have a 95% (TBR-ESDR-010) likelihood of launching within 30 days of the planned launch date evolvable to (TBD-ESDR-010) at the start of launch countdown and allocated per Table R-19. This requirement is not applicable to the Tactical Timeframe.

| SLS | MPCV | 21CGS |
|--------------|--------------|--------------|
| TBD-ESDR-011 | TBD-ESDR-011 | TBD-ESDR-011 |

- Rationale: The CDF DRMs involve challenging launch constraints driven by previously launched hardware loitering on orbit with a limited lifetime and/or limited injection window opportunities for beyond-LEO destinations. Launch availability will have to evolve to a (TBD-ESDR-010) higher level to support the NEA and Mars DRMs, which have the greatest loiter durations for previously launched hardware and most challenging injection windows. This requirement includes all launch delay sources including, but not limited to, ground systems, launch systems, launch site weather, SLS, MPCV, range constraints, crew and payload. This requirement will be used to derive requirements for probability of launch, turn-around times post launch scrub, and number of consecutive launch days. **The TBR/TBD values will be reconciled via future integrated trade studies.**

Figure 1. Launch Availability Requirement Language

III. Why DES was the Right Tool

Since no one program owns LA it required Cross-Program coordination to resolve the requirement TBD and TBR values. In December of 2011 a very productive face-to-face Technical Interchange Meeting (TIM) initiated by the SLS Operations Discipline Lead Engineer was held at MSFC to determine the path forward for meeting the ESD R-19 requirement and resolution of the TBD and TBR values.

Understanding the operations required to process and launch the SLS vehicle is not something that can easily be analyzed using spreadsheets or flow charts, it is a complex system that is best represented using a model. A DES is an efficient tool for modeling complex systems and analyzing how real world activities will perform under different

conditions. One of the benefits of using a DES is that the model can continuously be refined over time as more additional data becomes available, therefore increasing the understanding of how the system will respond. This process of continual refinement allows for a more accurate approximation to be achieved relatively quickly and at a low cost.

NASA has a long history of using DES to model launch vehicle designs. Currently all three Programs (GSDO, SLS, and Orion) are using DES models to simulate their systems.

A. GSDO DES Model Overview

In 1999, KSC entered into a Space Act Agreement with the University of Central Florida to develop a DES model of the entire Space Shuttle operational flow. The goal of this effort was threefold: first to demonstrate the utility of DES based analysis; second to develop a cadre of DES expertise at KSC; and finally to provide a useful tool for helping NASA increase the flight rate¹. While all of these goals were met, NASA's plan to increase the flight rate was reversed and instead flight rate reductions were called for in order to achieve budget reductions.

Nonetheless, the Space Shuttle model that was developed was subsequently leveraged in 2002 to develop the Manifest Assessment Simulation Tool (MAST). MAST was first used in January 2003 to provide NASA with an assessment of the likelihood of achieving U.S. Core Complete of the International Space Station (ISS) by February 19, 2004². MAST was used by the NASA Chief Engineer in 2004 and then again in 2005 by the Shuttle/Station Configuration Options Team (S/SCOT) to explore the questions of: 1) when will assembly of the ISS be completed; and 2) how many Space Shuttle missions can be flown by the end of 2010? The NASA administrator subsequently reduced the number of planned flights remaining in the Space Shuttle manifest based upon the analysis results^{3 4}.

MAST was also used to analyze potential rescue missions for Space Shuttle orbiters should one be damaged again during ascent as had happened to Columbia. Estimating the probability of being able to launch a rescue mission in a timely fashion became a standard part of the reviews leading up to the flight readiness reviews. This capability of being able to provide a probability estimate was a key factor in the decision to reinstate the previously cancelled Hubble reserving mission⁵.

DES analysis was used to support the Constellation program. The most notable model being the Constellation-Requirements Assessment by Simulation Technique (C-RAST). C-RAST was intended to provide a demonstration of how DES could be used to help the Constellation program analyze program level requirements. The pathfinder model analyzed the two-launch solution for lunar missions in which the Ares V would launch an Earth Departure Stage (EDS) and the Altair lunar lander into low earth orbit. The next day, the Ares I would launch the crewed Orion to rendezvous and dock with the Altair. C-RAST was used to analyze the probability of launching both the Ares V and the Ares I in a timely fashion^{6 7}. The C-RAST model is the direct predecessor to the Integrated Launch Probability model described in this paper.

B. SLS DES Model Overview

The SLS DES Model is the product of a continuous DES development effort at the MSFC since 2002. The initial model developed in 2002 was the Space Shuttle Main Engines (SSME) Turnaround Time Model which simulated the operations required to refurbish the SSME from landing through launch. This model was the point of departure for developing the MSFC DES Rocket Engine Turnaround Processing Model which was used to simulate a generic engine such as RS-84 that would employ aircraft like operations. The Rocket Engine model introduced a number of new features to simulate aircraft like operations while retaining the ability to simulate the SSME operations⁸.

In 2005, at the start of the Constellation program the MSFC DES Rocket Engine was used as the point of departure for the development of the Ares I Availability Model. The Availability Model was used by Ares I to model the manufacturing operations of the Upper Stage to ensure that an adequate production rate was achieved to support the Launch Rate requirement. The Availability Model was also used to calculate the probability that the vehicle would be ready for a specific launch date as well as the probability of launching the vehicle. The Availability Model was focused on the vehicle design and the probability of a hardware/software failure occurring and what was required to fix the failure and return back to nominal operations. The SLS DES Model is the next evolutionary step in the development of the Ares I Availability Model which continues to increase the flexibility and capabilities within the model in support of numerous analyses.

C. Orion DES Model

The Orion DES model was developed by Lockheed Martin, during the Constellation Program to assess key operations and logistics requirements that would support the Launch Rate requirement. The expectation was

through use of the analysis that the vehicle could verify the capability to support the hardware delivery and launch schedules and compliance with the 98% LA requirement. It could also be used to identify design changes which could improve operability. This could remove potential processing bottlenecks and plan for accessibility to Line Replaceable Units (LRUs) to allow for access without the need to rollback to a different processing facility.

The Orion model takes into account the hardware delivery schedule and LRU build quantities as well as maintenance operations to help establish a LA to meet the required flight rate. The model focused on the build quantities and maintenance to analyze processing times, and hardware failures. The Orion model utilized the program operational phase for mission manifest, which included 12 ISS missions planned for 2015 through 2020 and 29 lunar missions between 2018 and 2032. Additionally it considered operations phases including; production, integration, launch, mission, landing, recovery, deservicing and contingency operations. For processing data the model accounted for task sequence and duration, facility resources and subsystem power-on time. Finally, it considered over 1400 identified Maintenance Significant Items (MSIs), their access, design mission life, Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR). The model development and testing was completed in early 2009 and the analysis results were included in the Orion PDR package in the late summer of 2009.

IV. Model Development

For this effort the Cross-Program team decided that the Integrated Launch Probability model developed by GSDO would provide the “official” integrated assessment of LA with inputs from all the Programs because; 1) Its history with the C-RAST model which was used to model the probability of launching both the Ares V and Ares I rocket in a timely fashion, and 2) The capability to model launch delay risks associated with SLS, Orion, GSDO, and natural environments. It was also decided to propose the addition of Natural Environments to Table R-19 since none of the Programs had control over the natural environments on the day of launch.

Major elements of the SLS trace their heritage directly to the Space Shuttle. The 5-segment SLS Solid Rocket Boosters (SRB) consisting of solid rocket motors, aft skirts, thrust vector control; forward skirts and associated avionics are nearly identical to the 4-segment SRBs used by the Space Shuttle. Many of the SRB components that will be used for the early flights of the SLS have flown on previous Space Shuttle missions. Likewise the SLS RS-25 engines that will be used on the first few SLS missions are former SSME. The SLS Core Stage is analogous in function and form to a combination of the Space Shuttle external tank and the orbiter’s aft engine compartment.

In addition to the SLS’s Space Shuttle heritage, the Orion spacecraft is roughly analogous to the Space Shuttle orbiter’s crew compartment. The SLS will be launched from Kennedy Space Center’s (KSC) Launch Complex 39, the same complex used by the Space Shuttle, and the integrated SLS-Orion will be subject to similar, though not identical, weather criteria for launch.

Given the above factors, use of Space Shuttle historical data relative to launch countdown provides useful information for estimating the integrated launch probability of the SLS. The Space Shuttle was launched 135 times and many missions experienced launch scrubs—a delay during countdown of 1 or more days—such that there were a total of 255 launch attempts. In addition 56 of the 135 launches occurred late relative to the planned lift-off time. The reasons for the 120 launch scrubs and 56 launch delays are well documented such that there is a rich historical data base from which to draw information^{9 10}.

Each identified launch scrub and delay was analyzed to determine if that particular scrub/delay was relevant to our needs. The mapping process included determining which major elements—SLS, Orion, GSDO or other such as Range and weather—or sub elements it might apply to. For example, Space Shuttle SRB issues map directly to SLS SRB launch probability. Likewise, SSME issues map directly to the SLS Core Stage main engines.

Based on the mapping process a basis of estimate was developed and sub-divided over seven phases of a 72 hour countdown period, consistent with how the Space Shuttle operated. The seven phases are; L-2 Day, L-1 Day, Mission Management Team (MMT) pre-Tanking, Tanking, Post Tanking, MMT Commit to Launch, and Ground Launch Sequence (GLS). The launch/delay probabilities associated with each of these decision points along the countdown procession models were estimated. Figure 2 shows an example of the basis of estimate for the SLS Core Stage.

| Countdown Decision Points | L-2 Day | L-1 Day | MMT pre-Tanking | tanking | post tanking | MMT Commit to Launch | GLS |
|--|---------|---------|-----------------|---------|--------------|----------------------|--------|
| Times we have experienced an effective delay of 1 or more days | 2.0 | 1.1 | 1.7 | 3.2 | 1.3 | 2.8 | 2.7 |
| Times we have gotten to this point | 184.0 | 198.0 | 229.0 | 212.0 | 190.0 | 187.0 | 163.0 |
| Plus effective times we delayed but launched same day | | | | | | 1.3 | 0.2 |
| Total Delay Opportunities (n) | 184.0 | 198.0 | 229.0 | 212.0 | 190.0 | 188.3 | 163.2 |
| Empirical Probability Point Estimate | 0.0109 | 0.0055 | 0.0072 | 0.0149 | 0.0070 | 0.0151 | 0.0164 |

| | # of x CDF |
|---|------------|------------|------------|------------|------------|------------|------------|
| X-Days Delay Duration information for distribution creation | 1 1.0000 | 3 1.0000 | 0 1.0000 | 1 0.2500 | 0 1.0000 | 7 0.7778 | 3 1.0000 |
| | 2 1.0000 | | 2 0.6667 | 2 0.5000 | 0 2.0000 | 1 0.8889 | 1 2.0000 |
| | 3 1.0000 | | 3 0.6667 | 3 1.0000 | 0 3.0000 | 3 1.0000 | 3 0.8000 |
| | 4 1.0000 | | 4 0.6667 | 4 1.0000 | 1 4.0000 | | 4 0.8000 |
| | 5 1.0000 | | 5 0.6667 | 5 1.0000 | 0 5.0000 | | 5 0.8000 |
| | 6 1.0000 | | 6 0.6667 | 6 1.0000 | 0 6.0000 | | 6 0.8000 |
| | 7 1.0000 | | 7 0.6667 | 7 1.0000 | 0 7.0000 | | 7 1.0000 |
| | 8 1.0000 | | 8 0.6667 | 8 1.0000 | 0 8.0000 | | 8 1.0000 |
| | 9 1.0000 | | 9 1.0000 | 12 1.0000 | 0 12.0000 | | 12 1.0000 |
| | 10 1.0000 | | | 13 1.0000 | 13 | | 13 1.0000 |
| Inputs for Lognormal Distribution | | | | | | | |
| γ location | | | 0 | 0 | 0 | | 0 |
| m most likely | | | 1 | 1 | 1 | | 1 |
| q quantile (percentile) | | | 99 | 90 | 90 | | 95 |
| X_q quantile maximum | | | 9 | 3 | 4 | | 7 |
| Arena Lognormal Parameters | | | | | | | |
| μ mean | | | 2.181061 | 1.678677 | 2.084189 | | 2.592522 |
| σ^2 variance | | | 1.800949 | 1.078381 | 1.656428 | | 2.441912 |

| Rollback Probability Estimate | 0.6667 | 0.2500 | 0.2500 | 0.6000 | 0.6667 | 0.0909 | 0.2857 |
|---|--------|--------|--------|--------|--------|--------|--------|
| Delay Duration Estimate for upperstage repair / swapout in the VAB: | 15 Min |
| | 60 Max |

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Sheet: SLS Corestage

Figure 2. SLS Core Stage Basis of Estimate

The next step was to develop the duration of the delay for each basis of estimate. The Shuttle historical data were used to estimate the time between launch attempts. The duration of the delay/scrub until the next launch attempt is dependent upon the reasons for the delay/scrub. Based on the Shuttle data the following observations were made; 1) STS weather delays/scrubs have a 67 percent chance of being a one day duration, 2) Flight hardware delays/scrubs are more likely to require a greater number of days, 3) Operational prerogative and infrastructure delays seem to fall between the weather and flight hardware delays in terms of durations, and 4) A delay for an engine abort requiring an RS-25 engine replacement is modeled as a rollback scenario. The probability distribution for the duration of the delay/scrub for hardware anomalies requiring an on-pad repair are estimated based upon the available historical data and subject matter expert inputs. Where there is an insufficient number of data points to develop a probability distribution, the approach developed by Averill M. Law of “selecting a distribution in the absence of data” was used¹¹. The Shuttle delay durations were reviewed to determine if a similar situation on the SLS vehicle would be likely to require a rollback resulting in a longer delay due to the “Clean Pad” approach being taken.

The mapping process and development of the basis-of-estimates was complicated by the differences between Space Shuttle and SLS/Orion. For example, the Space Shuttle utilized fuel cells for electrical power whereas SLS will be using batteries and Orion will be using both batteries and solar panels. The approach for addressing these issues included assigning a factor ranging from 1 to 0, with 1 indicating the Space Shuttle scrub/delay mapped directly and 0 indicating the Space Shuttle scrub/delay had no applicability. For many cases the assigned value was determined to be between 1 and 0. In those cases we initially used our best engineering judgment and then followed this up with a request to have subject matter experts provide their estimate.

A multiplier value was also assigned to address differences in the numbers of subelements. For example, the SLS will have 4 main engines as opposed to 3 on the Space Shuttle. Consequently, we applied a 4/3 multiplier to SSME related engine scrubs/delays.

During a cross-program face-to-face TIM the basis-of-estimates for each Program was reviewed to ensure agreement on how the Shuttle data was allocated. Figure 6 shows an example of the Shuttle data that was allocated to the Core Stage and used in developing the basis of estimate. As part of the face-to-face TIM a detailed review of

the values in the “Factor” column were performed. This review of the factors was supported by a point-of-contact from each of the Programs, SLS Elements, SLS Avionics, and Natural Environments.

| STS | Delay Duration (Days) | Delay Duration (Minutes) | Time of Decision | Time of Decision | Reason for Delay | Core-Stage Rollback Required? | Factor | Factor Rationale |
|---|-----------------------|--------------------------|----------------------|------------------|--|-------------------------------|--------|--|
| 1 | 2 | 0 | MMT Commit to Launch | T-9 minutes | Timing skew between primary and B/U FLT computers | No | 0.2500 | Factor based upon perceived complexity difference between Core-Stage Avionics flight computer's and STS orbiter's 5 GPC's. Also this was a first launch occurrence. |
| 2 | 8 | 0 | GLS | T-31 sec | Launch delayed due to an apparent low reading on fuel cell oxygen tank pressures. Countdown proceeded but was aborted at T-31 seconds when clogged APU fuel filters caused high oil pressures and over-temp in two of three APUs. Gear boxes flushed and filters replaced. | Yes | 0.5000 | Presence of batteries on Instrument Unit (analog to Fuel Cells). Factor based upon perceived complexity / risk difference between: (1) fuel cell base system and battery based system; and (2) Core-Stage TVC system and STS hydraulic system. |
| 2 | 0 | 160 | MMT Commit to Launch | N/A | Launch delayed 2 hours, 40 minutes to replace multiplexer/demultiplexer (MDM OF-3), and an additional nine minutes, 59 seconds to review systems status. | No | 0.2500 | Factor based upon perceived complexity difference between Core-Stage Avionics and STS avionics. |
| 41-D | 1 | 0 | MMT Commit to Launch | T-9 minutes | Launch scrubbed during T-9 minute hold because Orbiter's B/U GPC (GPC-5) failed. | No | 0.3000 | Factor based upon perceived complexity difference between Core-Stage Avionics flight computer's and STS orbiter's 5 GPC's. Assume computers have a .75 complexity. Assume also that there are 2 as opposed to 5 GPC's. |
| 41-D | 1 | 0 | L-1 Day | T-11 hours | Flight Software for Master Events Controller discrepancy noted. SAIL pre-launch analysis discovered MEC HW/SW timing incompatibility. | No | 0.5000 | Factor based upon similar complexity level between Core-Stage Avionics Master Events Controller (or similar item) and STS orbiter's MEC's. Orbiter has 2 units and it signals the separation of the SRBs and ET. SLS will have analogous events. Discounted 50% for lessons learned. |
| 51-I | 2 | 0 | MMT pre-tanking | MMT Tanking mtg? | Orbiter's #5 GPC failed | No | 0.1500 | Factor based upon perceived complexity difference between Core-Stage Avionics flight computer's and STS orbiter's 5 GPC's. Assume computers have a .75 complexity. Assume also that there are 2 as opposed to 5 GPC's. "Multiple occurrence (2) rule in effect." |
| Continued | | | | | | | | |
| File: Launch Data Through STS-335 2011_12_04.xlsm | | | | | | | | |
| Sheet: SLS Corestage no R SLS Tables | | | | | | | | |

Figure 3. Space Shuttle Historical Delays

Natural environments are important considerations for the design and operation of launch vehicles. Spacecraft must be able to survive the environmental conditions encountered in each phase of a mission timeline. For launch vehicles, design engineers and mission planners need to understand launch site weather in order to develop robust vehicle designs and operational concepts that will allow high launch probabilities. In addition to vehicle-specific environmental constraints, Range Safety environment constraints must also be considered. For crewed missions, conditions at potential abort landing sites are important and must be included to ensure crew survivability and recoverability in the event of a launch abort. NASA's Natural Environments Branch, located at MSFC, has the ability to perform launch climate analyses (LCAs) for potential launch and landing sites¹². For the ESD LA, two different scenarios need to be analyzed – SLS cargo-only missions and SLS-Orion missions.

The natural environments criteria for launch and off-nominal aborts can be found in “SLS-SPEC-159 Cross-Program Design Specification for Natural Environments”¹³. The Range Safety environmental limits used are defined in the Space Shuttle Program document “NSTS 16007: Launch Commit Criteria and Background”¹⁴. For cargo-only missions, the following natural environment parameters were assessed:

- Surface peak winds at/near launch pad.
- Temperature.
- Presence of thunderstorms in the area.

Additionally, for Orion missions, the following parameters must also be assessed:

- Significant wave height.
- Sea surface mean wind speed.
- Average wave period.

Range Safety constraints include:

- Distance to nearest lightning strike.
- Cloud ceiling height.
- Visibility.

The values of various environmental parameters at a given site are not statistically independent. For example, the presence of thunderstorms is generally associated with lower cloud ceiling heights compared to clear days. However, the exact relationship between pairs of variables is stochastic and cannot be treated deterministically. Thus, an integrated approach is required to determine the effect of environmental conditions on overall launch

availability. The Natural Environments Branch has developed the Probabilities of Atmospheric Conditions and Environmental Risk (PACER)¹⁵ analysis tool to compute integrated climatological availabilities based on given sets of parameter constraints. PACER employs different climatological datasets to characterize different environmental parameters. Functionally, PACER first determines the number of reporting intervals with valid observations for all parameters within the overlapping period of record for all datasets used for analysis. Then, for each valid reporting interval, each parameter value is compared to its corresponding constraint threshold. If at least one parameter threshold is violated, that reporting interval is flagged as a “fail”. PACER computes the probability of violation (P_V) as the ratio of the number of failing reporting intervals divided by the total number of valid intervals. The climatological availability probability (P_{CA}) is the value P_V subtracted from unity.

The Natural Environments Branch provides both monthly and annual results for the ESD LA. However, computational results are tabulated by hour of day to show diurnal variability, and by month to show seasonal variability. In addition to the integrated P_{CA} results, PACER also computes failure mode probabilities (P_{FM}) for each individual parameter. These can be used to assess relative contributions each parameter constraint makes to the overall climatological availability with the caveat that, in general, P_V is not equal to the sum of the individual P_{FM} values due to the aforementioned lack of statistical independence between environmental parameters. As design and vehicle capabilities are finalized and the Programs move closer to launch operations, this LCA can be updated to show how a change in ascent track, landing location, or environmental limits could potentially affect the overall ESD LA.

PACER is only used to analyze surface environmental parameters by checking climatological data against specified criteria thresholds. The model does not consider dynamic vehicle responses to given environments. As such, aloft winds are not assessed in PACER because it is not possible to define a specific constraint without doing a six degrees-of-freedom trajectory simulation incorporating a detailed vehicle configuration. It should also be noted that, in relation to sea surface conditions at abort landing zones, the climatology of hurricane conditions are included in the reanalysis dataset used by PACER. Other analyses of historical hurricane tracks in the Atlantic and Pacific oceans, including land-falling hurricanes near the launch and/or landing sites, could provide important information for mission planning and operations development activities, but should not be explicitly included in ESD LA calculations due to the possibility of adding undue conservatism and artificially lowering the computed availabilities.

As stated previously, the Space Shuttle historical launch delay data was sub-divided into seven phases over the 72 hour countdown period and the basis-of-estimates were developed the same way. However, based on the SLS design, the countdown period is 24 hours and not 72 hours as it was with Shuttle. Therefore, the launch delay data associated with the time frame before 24 hours was removed from the LA TPM analysis. That information is included in a separate analysis looking at the probability of the vehicle being ready for start-of-countdown.

Figure 4 summarizes all of the delay categories that were taken into consideration when developing the LA TPM and which of the three Programs or Natural Environments they were assigned to.

| SLS | MPCV | GSDO | Environments |
|----------------------|--------------------|------------------|---|
| Twin SRB | Orion | Ground Systems | Range Weather |
| 4 Core Stage Engines | Crew Health | Human Errors | Launch Weather |
| Core Stage | Crew Ingress | Range Conflicts | Abort Weather (for "on pad" or near pad aborts) |
| Instrument Unit | Crew Actions | Range Systems | Sea State (and other environments in abort landing locations) |
| iCPS | COLAs | Range Intrusions | Winds Aloft* |
| iCPS RL-10 Engine | Mission Systems | Hurricanes | Wind Placard** |

* The current Environments analysis does not include Winds Aloft. Potential that winds aloft could cause a scrub is currently modeled under SLS with the assumption that SLS will implement a system analogous to the STS DOLILU capability.

** The current Environments analysis does not include wind placards. Wind placards are a potential new constraint on launch.

Figure 4. Delay Category Assignments

In addition to the categories in Figure 4 we also had to establish some additional Ground Rules and Assumptions (GR&A) related to each of the programs. The SLS block approach resulted in 9 different possible configurations as shown in Figure 5.

Block 1: Two SRB, Core Stage, 4 Core Stage Engines, Interim Cryogenic Propulsive Stage (ICPS), and Orion.

Block 1A:

- Two SRB, Core Stage, 4 Core Stage Engines, CPS, and Payload.
- Two Liquid Rocket Boosters (LRB), Core Stage, 4 Core Stage Engines, CPS, and Payload.
- Two SRB, Core Stage, 4 Core Stage Engines, CPS, and Orion.
- Two LRB, Core Stage, 4 Core Stage Engines, CPS, and Orion.

Block 2:

- Two SRB, Core Stage, 4 Core Stage Engines, Upper Stage, CPS, and Payload.
- Two LRB, Core Stage, 4 Core Stage Engines, Upper Stage, CPS, and Payload.
- Two SRB, Core Stage, 4 Core Stage Engines, Upper Stage, CPS, and Orion.
- Two LRB, Core Stage, 4 Core Stage Engines, Upper Stage, CPS, and Orion.

The Block 2 configurations with Orion were disregarded because the overall vehicle height was greater than the capability of the VAB. The LA Cross-Program team agreed that the assessment should be based upon an SLS having LRB. That vehicle configuration would have the most challenging LA due to the increased likelihood of launch delays stemming from LRB as opposed to SRB.

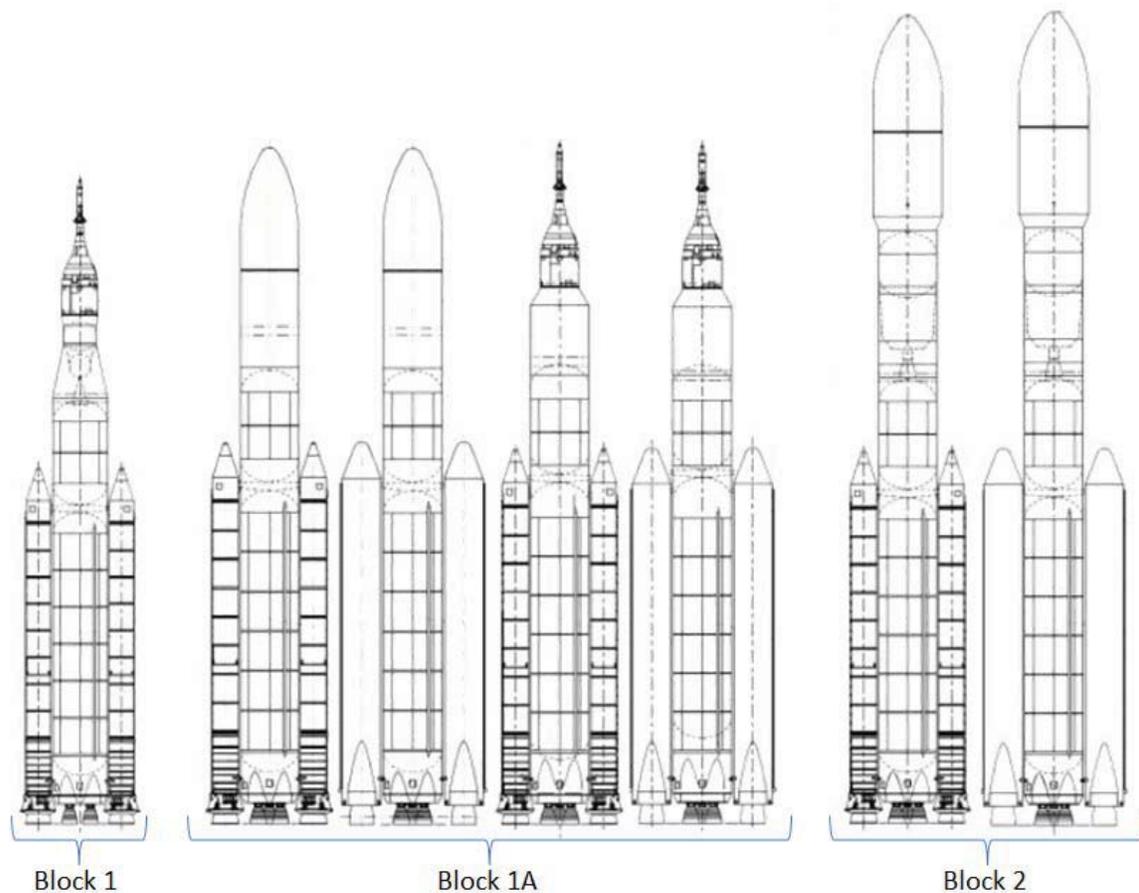


Figure 5. SLS Block Configurations

NASA has taken a “Clean Pad” approach for SLS which has limited the access to the vehicle at the Launch Pad. Access exists to the crew compartment of the Orion, to the Core Stage forward skirt, to ICPS, and from the Mobile Launcher Deck. This is a departure from Shuttle which has access to the vehicle while at the Launch Pad. Due to the “Clean Pad” approach the basis-of-estimates needed to be reviewed because Shuttle failures that were repaired on the Launch Pad would now require a rollback because the access at the pad is not available for SLS.

The Shuttle program had a 24-hour scrub turnaround capability, but the SLS utilizes more liquid hydrogen. For this analysis it was assumed that upon a launch scrub, after tanking has occurred that it would be a minimum of 48 hours before another launch could be attempted because of propellant storage limitations in the ground systems. A 24-hour scrub turnaround capability may be achieved in the future with modifications to the ground systems. Any delay that could be repaired in less than 48 hours would automatically experience additional wait time.

Availability of the Eastern Test Range a.k.a. “the Range,” influences the LA TPM. The Range is able to support one and only one launch on any given day. The Range allows each launch vehicle user to reserve one day on the Range for a planned launch date. The Range will typically protect the following day in case of a scrub. However, days after that are subject to Range availability. Other Range users such as Delta IV, Atlas V, Falcon 9 and other users may have reservations on the Range. The LA TPM takes into consideration this Range availability dynamic by assigning a Range availability probability that is based upon historical and projected utilization of the Range.

The abort scenario for the Orion during ascent places the Orion capsule in the Atlantic Ocean. Rescue of the crew can be hampered by rough seas. If the seas in the abort landing zones are too rough, the launch may be scrubbed. The LA TPM assumes that the launch will be scrubbed if the significant wave height is greater than 4 meters. For the LA TPM, it is assumed that the ascent trajectory is over the central Atlantic. For a mission to the ISS, the trajectory would be over the northern Atlantic where the seas are generally rougher. The sea state scrub threshold in the LA TPM will be updated to reflect the actual flight rules once they are developed.

The Natural Environments categories that can scrub launch vary on a monthly basis. Winter months are more likely than summer months to have Natural Environments related scrubs. The LA TPM assumes that future launches may be planned for any month of the year. Rather than have 12 LA TPMs, one for each month, the LA

TPM represents an annualized average. This is done by varying the planned launch date in the DES simulation. In addition, the launch probability for Natural Environments was calculated over a 30 day period, rather than for a single day. By allowing a 30 day window, the effects of the Natural Environments on LA is greatly reduced. These effects are more prominent when calculated for a single day and would vary significantly based on the month chosen for the launch.

V. TPM Results

With the model, inputs, and GR&As agreed upon by the Cross-Program team the next step was to perform the analysis. The first run that was performed looked at the LA for the integrated system with all the risk delays turned on. The subsequent runs isolated each of the Program risks to look at the individual Programs contribution to the combined LA. The results of the LA analysis are shown in Figure 6. The analysis showed that for the integrated system a 90.7% LA with a 95% confidence could be expected. Based on the analysis it was determine that the threshold value for the LA TPM would be set to 90%.

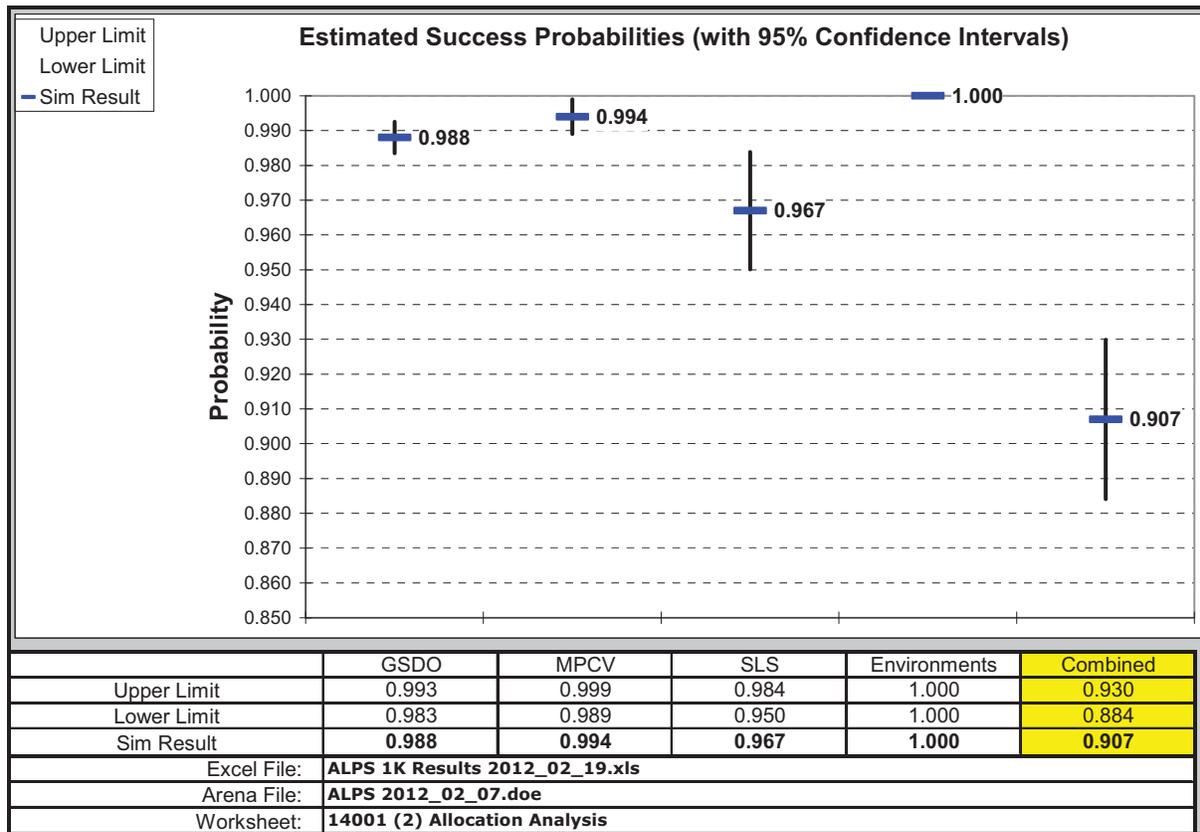


Figure 6. Launch Availability Results

The next step was to determine what the objective value for the LA TPM should be set to. Using the same model, inputs, and GR&As the cross-program team looked at a number of buy back options that the Programs could invest in to increase the integrated LA. The LA buy back options that were considered are:

- 1) Ability to perform consecutive cryogenic propellant tankings.
- 2) Ability of range to support dual operations.
- 3) Access to umbilicals at the Launch Pad.
- 4) Having 2 Crawler/Transports.
- 5) Ability of Orion, Crew, and Rescue Forces to support launch regardless of sea state conditions.
- 6) SLS reliability improvements.
- 7) Program major Elements spares.
- 8) Ground based diagnostics.
- 9) Wet Dress Rehearsal.
- 10) Negative buy-back: 1 shift a day (8 hours) 5 days a week processing limitations.

The first of the five buy back options were able to be quantified at this point in the design and were incorporated into the model and analysis. Figure 7 shows the results of those buy backs on the integrated LA analysis. The “Expected Pad Access” result is the baseline case (with minimum pad access) that was used to calculate the threshold LA value. The “Without Pad Access” result shows the impact of having no access to the vehicle at the Launch Pad. The impact on LA of removing Launch Pad access, with the exception of crew access to the Orion, was a decrease in LA from 90.7% to 78.5%. The Programs ability to meet LA is heavily dependent upon having vehicle access at the Launch Pad. When adding Pad access back into the analysis along with items 1-4 from the buyback list the integrated LA increased to 92.6%. When adding in the ability of Orion, crew, and rescue forces to support launch regardless of sea state conditions (Item #5) the LA increased to 94.1%. Knowing there were possibly other areas of improvements that could be made over time it was decided that based on the buyback analysis that the objective values for the LA TPM would be set to 95%.

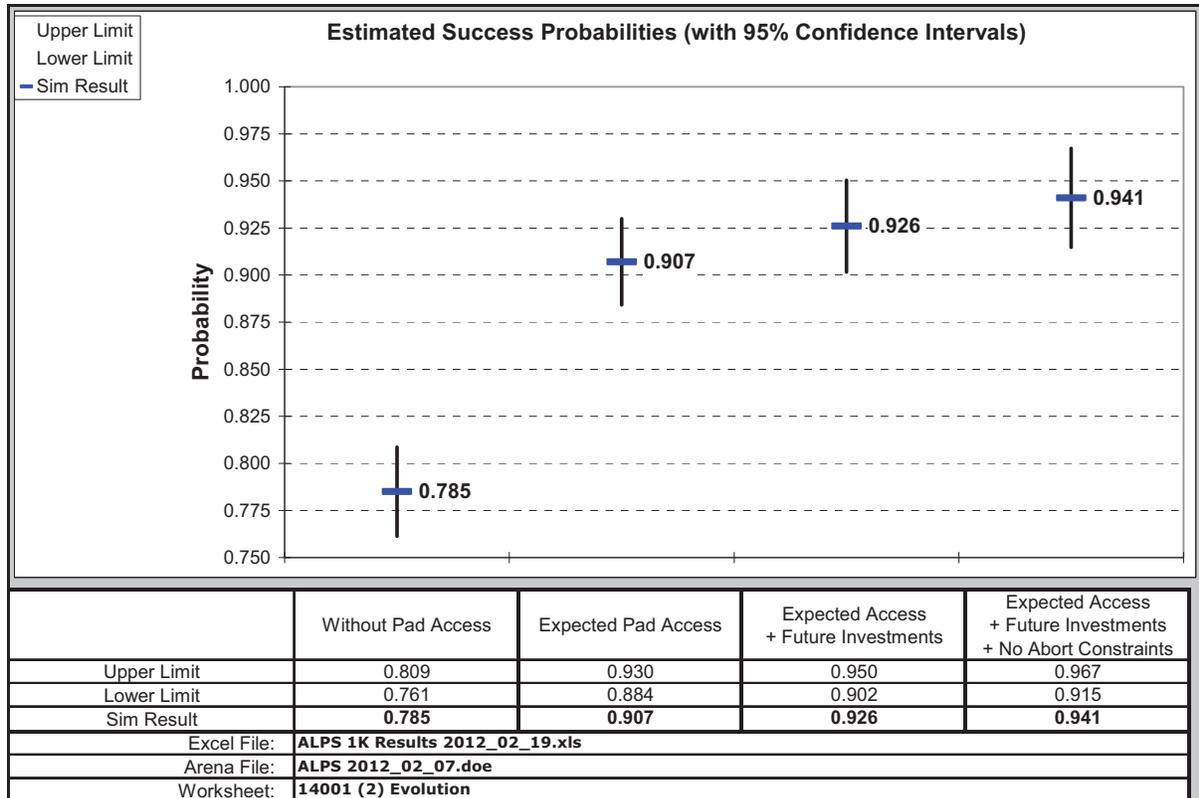


Figure 7. Launch Availability Buy Back Results

Over the course of working a resolution to the ESD R-19 requirement and resolution of the TBD and TBR values, philosophy discussions were had that led to a decision to convert the LA requirement into LA TPM. The rationale for this significant change was based upon the following factors. First of all, it was not clear what the driving design reference mission would be for the SLS, would it be to an asteroid, Mars, the moon or a lagrangian point? The choice of mission would have a significant bearing on what level of LA would be needed. Secondly, and perhaps more importantly, any allocation of limited resources should take into consideration the most efficient way to improve overall mission success. Trying to maximize LA might well take away resource that might be better spent on improving the reliability and longevity of the payload elements being launched. Since the payload elements were not being designed at the time, it was impossible to perform the necessary trade studies to determine the efficient utilization of limited resources.

The final TPM language along with the threshold and objective values was similar to the previous requirement and is shown in Figure 8. Although the LA TPM was only applicable to the Strategic mission, LA for the tactical missions, i.e., early Block 1 flights, was calculated to predict LA of these early tactical missions.



ESD Technical Performance Assessment

◆ ESD TPM Description:

• ESD-7B Strategic DRM 30-Day Launch Probability:

– **Description:** The probability of launching within 30 days from start of countdown for the initial launch attempt with a 95% confidence level. Provides an indication of the overall system architecture strategic capability to launch the crew in support of a deep space mission with a constrained earth departure opportunity.

– **Included Programs:** SLS, MPCV, GSDO

– **Reporting Unit:** Percent (%)

– **Threshold Value:** 90%

– **Objective Value:** 95%

– **Applicable DRMs:** Strategic

– **Flight phases:** L-1 through launch

– **GR&A's:**

- Configuration: SLS = Block 1A (liquid boosters) with CPS, MPCV (with crew), GSDO = clean pad with 24-hour scrub recycle capability and no SLS engine pad change-out capability.
- Central Atlantic ground track with an abort significant wave height (SWH) limit of 4-meters. CDF is an annualized average.
- Threats & Opportunities shall also be identified and quantified.

Figure 8. LA TPM

With the threshold and objective values set for the LA TPM the next step was to allocate the LA threshold value down to the individual Programs. It was decided that Natural Environments would have its own LA allocation since none of the Programs had control of the natural environment on the day of launch. Based on the analysis results shown in Figure 6 the following LA allocations were made; GSDO – 98.8%, Orion– 99.4%, SLS – 96.7%, Natural Environments – 100%.

It is important to note that the LA allocated to the Programs and Natural Environments do not add up to the combined LA due to the interactions of the risks. An example of this is Natural Environments which was allocated a LA of 100%. When running the DES model with only the natural environment risks turned on there is a 100% chance that over the course of a 30 day launch window that there will be a day when the natural environments would allow the vehicle to be launched. However, when running Natural Environments along with the other Program risks, there is no guarantee that the vehicle will be ready to launch on a day when the natural environments are good for launch, there could be a number of issues that preclude a launch attempt on that day.

There are also several interactions between GSDO and Orion/SLS that are only realized when the integrated system is analyzed, tanking being one of these interactions. SLS and Orion are the prime reasons for a failure that would require a re-tanking to occur but the tanking constraints are a part of the GSDO allocation since the systems are owned by GSDO. Therefore, when the individual Programs LA analysis are performed the impacts associated with tanking are not realized until the integrated system is analyzed.

VI. Conclusion and Forward Work

The Cross-Program team successfully developed a methodology and tools for resolving the TBR and TBD in the ESD LA Requirement. The model is being used to inform ESD on the expected LA of SLS/Orion/GSDO on a quarterly basis. The team also successfully allocated the LA TPM to each of the Programs and Natural Environments allowing them to analyze their contribution to the overall LA TPM. The model and methodology is constantly being evolved to increase the accuracy of the analysis.

The analysis associated with the ESD LA TPM is continuously being updated to see how the Block 1 design is measuring up against threshold and objective values. The analyzed SLS Block 1 and GSDO designs would will have an easier time meeting the LA TPM threshold because of the SRB configuration which has a higher reliability versus LRBs. Several recent changes to the design and GR&A have resulted in the integrated LA results dropping below the threshold. One of the major changes has been the removal of the Core Stage forward skirt access arm along with the ICPS access arm. Another impact has been the changes to the re-tanking capability of GSDO which

has gone from being able to re-tank the vehicle every 48 hours to re-tanking the vehicle 48 hours after the first launch attempt and then an additional 11 days before the next tanking could occur. The incorporation of the ICPS into the design of Block 1 has also decreased the launch window from an assumed 30 calendar days to 5-7 calendar days which resulted in a greater number of rollback occurring because of the limited Pad access and the fact that if a repair cannot be completed before the close of the window then the vehicle is automatically rolled back to the VAB because the next launch attempt is not for approximately 30 days. This launch window limitation also makes the Natural Environment impact on LA more prominent. This analysis is being updated to reflect these changes.

As an on-going effort to continually improve the LA analysis, an effort is underway to replace the Shuttle historical data associated with the SLS Core Stage with reliability and maintainability data being developed by Core Stage. The first step of this process is to break the basis-of-estimates for Core Stage into two categories, those delays associated with hardware/software failures and all other delays. The delays associated with hardware/software failures would be those that would be replaced with data from Core Stage and outputs from the SLS DES Model. The other delays would still be included in the integrated analysis since they are not directly controllable by the SLS design, however, these delays will require future reviews by Core Stage to see if they are applicable or not. Once this process has been developed for replacing the Shuttle delay data with the SLS Core Stage design data, the same can be done for the other elements.

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