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# SPACE LAUNCH SYSTEM PROGRAM (SLSP)

# RELIABILITY ALLOCATION REPORT

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## REVISION AND HISTORY PAGE

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**NOTE: Updates to this document, as released by numbered changes (Change XXX), are identified by a black bar on the right margin.**

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# 1 INTRODUCTION

## 1.1 Purpose

The purpose of this document is to describe the process that was utilized by the Space Launch System Program (SLSP) to decompose the applicable Exploration Systems Development (ESD) mission risk requirements into quantitative reliability requirements that have been allocated to each of the SLSP elements for the launch and ascent mission phase. There is currently no ESD requirement applicable to the in-space mission phase so in-space reliability is not addressed herein.

## 1.2 Scope

The Space Launch System (SLS) includes the following major elements:

- Stages (Core Stage and Upper Stage)
- Liquid Engines (Core Stage and Upper Stage)
- Boosters (solid or liquid)
- Integrated Spacecraft and Payload Element (Interim Cryogenic Propulsion Stage, payload fairings, payload adapters, separation system)

This document addresses allocation of ascent reliability requirements for the Space Launch System. Refer to SLS-SPEC-032, SLS Program System Specification for a description of the launch vehicle and elements.

## 1.3 Change Authority/Responsibility

The NASA Office of Primary Responsibility (OPR) for this document is Safety and Mission Assurance QD35.

Changes to this document shall be controlled at the OPR level using processes defined by the OPR.

## 1.4 Applicable Documents

The following documents include specifications, models, standards, guidelines, handbooks, and other special publications. The documents listed in this paragraph are applicable to the extent specified herein.

| | |
|---|---|
| ESD-10002<br>Rev June 2012 | Exploration Systems Development (ESD) Requirements |
| MPCV 70026 | Multi-Purpose Crew Vehicle (MPCV) Program Orion-to-Space Launch System (SLS) Program Interface Requirements Document (IRD) |

| | |
|---|---|
| SLS-SPEC-032 Rev C | Space Launch System (SLS) Program System Specification |

## 1.5 Reference Documents

The following documents contain supplemental information to guide the user in the application of this document.

| | |
|---|---|
| SLS-PLAN-047 | Space Launch System Program Technical Metrics Plan |
| SLS-RPT-168 | Space Launch System Program Supportability and Operations Assessment Report |

# 2 DECOMPOSITION OF LAUNCH AVAILABILITY

## 2.1 Background

*Note: In the time since the SLS Program System Requirements Review/System Definition Review (SRR/SDR), Exploration Systems Development (ESD) chose to delete the Launch Availability requirement from the ESD Requirements and instead track it as a Technical Performance Measure. Accordingly, the SLS Program has deleted the Launch Availability requirement, and the Launch Reliability requirements that were decomposed from it, from the SLSP System Specification.*

The set of Design Reference Missions (DRMs) for SLS include several Beyond Earth Orbit (BEO) missions that require launch of multiple vehicles and payloads. An inability to complete the sequence of required launches for the BEO missions can result in loss of mission and loss of billions of dollars of previously launched hardware. As a result, ESD has allocated to SLS a Launch Availability Technical Performance Measure (TPM) that is intended to ensure a high likelihood of launching the SLS vehicles within a specified timeframe. In this context, Launch Availability is a function of both launch reliability (probability of launching on a given attempt) and maintainability (ability to repair the launch vehicle in time to achieve additional launch attempts in the given timeframe).

Launch Availability is a key TPM at the SLS vehicle level, but is not meaningful to the elements. As a result, this TPM has been decomposed into more meaningful TPMs (e.g., Launch Reliability, Maintainability) that are flowed to the elements via SLS-PLAN-047 SLSP Technical Metrics Plan. Refer to SLS-RPT-168 SLSP Supportability and Operations Assessment Report (SOAR) for a description of the Launch Reliability TPMs and their current status.

# 3 DECOMPOSITION OF LOSS OF CREW AND LOSS OF MISSION

## 3.1 Background

Loss of Crew (LOC) is a key performance requirement for the integrated Multi-Purpose Crew Vehicle (MPCV) / SLS vehicle. By definition, LOC is a subset of Loss of Mission (LOM); since every MPCV abort scenario is initiated by a LOM event. The ascent LOC assessment evaluates all credible, critical-failure sequences from the time the vehicle is crewed through the successful perigee raise maneuver to place the MPCV into a stable orbit. During the Prelaunch Phase, prior to crew ingress, catastrophic failures result in a loss of vehicle; non-catastrophic failures result in a launch scrub.

Due to the complex interactions between MPCV and the LOM Environments (LOME) resulting from uncontained failure of SLS, LOC cannot be evaluated by SLSP independently from the MPCV. The assessment of the SLS contribution to LOC is performed in a collaborative environment by the SLS Abort Integration Team (SAIT). The team consists of representatives from the SLS Probabilistic Risk Assessment (PRA) team, Mission & Fault Management (M&FM), Guidance, Navigation, and Control (GN&C), Structures, Thermal, and Environments (STE), and Systems Engineering. These disciplines exchange data and information to coordinate and produce the SLS LOC analysis. Additional cross-program coordination, representation, and input are provided through the MPCV/SLS Abort Integration Team (MSAIT), which includes representatives from the Cross Program PRA Team (XPRAT), MPCV, Ground Systems Development and Operations (GSDO), Human Exploration Range Safety Panel (HERSP), the Crew Office, and other stakeholders in the LOC analysis.

The SLS contribution to LOC is expressed as the probability of exceeding conditions specified as MPCV-SLS Interface Requirement I.MPCV-SLS.3110, SLS/Orion Ascent Abort LOC Environments Table found in MPCV 70026, Multi-Purpose Crew Vehicle (MPCV) Program Orion-to-Space Launch System (SLS) Program Interface Requirements Document (IRD). These values are jointly negotiated between SLS and Orion MPCV to define the limits of prelaunch, launch, and ascent abort environments that allow a high likelihood of successful Orion MPCV abort. The abort environment limits are derived for blast over pressure, blast fragments/debris, and blast fireball effects. The LOC requirement cannot be verified unless SLS LOM risk is controlled below specified limits. SLS LOM risk is controlled by the MPCV-SLS Interface Requirement I.MPCV-SLS.3132 in MPCV 70026. Loss of mission risk is estimated at the SLS integrated vehicle level and will be tracked as a Technical Performance Measure (TPM) by the Program.

The SLS LOC analysis assumes the following:

- The MPCV abort system functions as designed
- Failures causing explosion environments that exceed the limits in the Abort Environments Table (MPCV 70026) result in LOC.

- LOC resulting from benign and loss of control LOME, which are assessed by analysis to be abortable, are charged to MPCV and do not contribute to SLS LOC.

Limiting the risk of failure of the abort system when the Abort Environments are below the limits in the Abort Environments Table is the responsibility of MPCV and is included in the MPCV prelaunch and ascent LOC allocation.

The Ascent Reliability Requirements, documented in this report, are established for the Elements to ensure that the reliability of flight critical units (components, subsystems) is addressed during the design phase and a reliability improvement process is implemented for heritage hardware. A brief explanation of the basis for each of these requirements is discussed below.

## 3.2 Requirements

The ESD Requirements document ESD-10002 contains the following architecture level requirements:

> *(R-16) Loss of Crew*
>
> *The Architecture shall limit the Loss of Crew (LOC) to no greater than the values specified in the Loss of Crew Table R-16.*

The modified Level 1 requirement has been allocated to SLSP via the SLS Program System Specification as follows:

> *(SLS. 16) Abort Environments*
>
> *The SLS shall limit the probability of failures that exceed the abort environments to no greater than 1 in 550 per mission.*

## 3.3 Discussion

Reliability analyses are used by the element prime contractors to predict hardware reliability. These analyses are updated throughout the element life cycle and are used to identify and correct design deficiencies and mitigate the effects of failure. Pursuant to agreements between the prime contractors and the SLS Elements, reliability predictions, using established tools and methods, may be used to show compliance to their requirements. The Elements will provide their reliability analysis reports to the SLS PRA team for use in developing basic event uncertainty distributions and updating the SLS LOC/LOM PRA model. Following each major SLS Life Cycle Review, the updated SLS PRA model is provided to the Cross Program PRA Team, which is responsible for developing the integrated Cross Program PRA model.

The SLS vehicle comprises both developmental and heritage hardware from the Shuttle Program, the Ares I Project, and the Delta IV Program. For modified heritage hardware (RS-25, SRB, and RL-10) with extensive operational history, the reliability allocations are consistent with demonstrated reliability developed from test and flight history along with analysis predictions to account for modifications. For developmental hardware, allocations are generally based on

design similarity to historical systems, which include Shuttle, Ares I, and Delta IV. In general the reliability predictions based mainly on demonstrated reliability are lower than inherent design reliability predictions because demonstrated reliability includes sources of failure that are beyond the control of the design function.

Reliability predictions, developed by the Element prime contractors, to show compliance to their allocation may employ generally accepted methodologies used within the aerospace industry; these include the application of factors to account for operating environment and other stress factors and the extensive use of data from diverse sources including, commercial generic databases, vendor data, test results, operational experience, and engineering analysis. The reliability reports should provide detailed documentation of the sources and methods used to develop the reliability predictions.

### 3.3.1 Ascent Reliability Allocation

Table 3-1 summarizes the Ascent Reliability allocation to each of the SLS elements as documented in the SLS Program System Specification. The following paragraphs provide the rationale.

**Table 3-1. Ascent Reliability Allocation Summary**

| SLS Element | Mean Missions to Failure | Risk | Reliability |
|---|---|---|---|
| **Boosters (per Booster)** | 1 in 2,174 | 4.60E-04 | 0.99954 |
| **Core Systems** | 1 in 2,564 | 3.90E-04 | 0.99950 |
| **Core Engine (Per Engine)** | 1 in 909 | 1.10E-03 | 0.99890 |
| **US Systems** | 1 in 2,778 | 3.60E-04 | 0.99964 |
| **US Engine (per Engine)** | 1 in 1,250 | 8.00E-04 | 0.99920 |
| **Integrated Spacecraft & Payload Element** | 1 in 1,613 | 6.20E-04 | 0.99938 |

#### 3.3.1.1 Booster

The ascent reliability requirement for a single Block 1 expendable Redesigned Solid Rocket Booster (RSRB) is based primarily on data from the Ares I First Stage (FS) Preliminary Design Review (PDR) reliability allocation report. In the FS allocation, applicable Shuttle PRA (SPRA) data for thrust vector control (TVC) was imported and updated as appropriate. Significant new reliability allocation work was performed and documented for FS motor and

avionics systems, The FS allocations for systems that remain on the SLS boosters are combined with SPRA estimates for Shuttle heritage systems that have been added back for the side-mount booster configuration (such as the separation system) to derive a new allocation. An ascent reliability allocation of 0.99954 per booster is documented in the SLS Program System Specification.

The SLS Block 1A and Block 2 vehicles will use a competitively-procured booster design to achieve higher performance than the current RSRB derived boosters. The trade space for the competitively-procured booster includes both advanced solid rocket boosters and LOX/RP liquid boosters. As more information becomes available regarding the advanced booster procurement effort, this allocation will be revisited and adjusted if necessary.

#### 3.3.1.2 Core Stage

The Ascent Reliability allocation for the Core Stage is based on estimates from the Shuttle PRA (scaled Main Propulsion System, Thrust Vector Control, and Structures) and the Ares I (Upper Stage Avionics and Software) Ascent Risk Assessment. The initial combined Core Stage estimate was then adjusted through a negotiated agreement with the Stages prime contractor. While this slightly reduced the reliability allocation, preliminary estimates show that the SLS requirements are still achievable with the reduced requirement. The ascent reliability allocation is documented in the SLS Program System Specification as 0.99950. This requirement includes critical failures from tanking through separation. Prior to crew ingress, only catastrophic failures leading to loss of vehicle are included.

#### 3.3.1.3 Core Stage Engine

Reliability prediction data from heritage engine testing and flight history as well as analysis was compiled and used in the development of the Comparative Engine Risk Model developed by MSFC S&MA and Engineering for the Heavy Lift Launch Vehicle (HLLV) Study. The comparative model is calibrated to match SPRA estimates for the Block 2 SSME at 104.5% power level and Shuttle mission duration. In turn, the SPRA estimates are based on a demonstrated reliability analysis that uses the full SSME hotfire and failure experience. The Comparative Engine Risk Model study produced a template for estimating engine risk associated with engine cycle types, operating times, and power levels. However, this model did not include estimation for the uncontained failure probability during core stage engine start on the launch pad (pre-launch). A separate assessment estimating this probability was conducted using heritage SSME data and Shuttle PRA results. These combined data and analyses were used to estimate the reliability allocation for the RS-25 engine. The requirement value was determined by adjusting the failure probability for the SLS nominal operating power level of 109% and an operating time of 475 seconds. The mean pre-launch and ascent reliability allocation per engine is documented in the SLS Program System Specification as 0.99890.

#### 3.3.1.4 Upper Stage

The initial ascent reliability allocation for the Upper Stage is based on risk analyses developed for the Shuttle Program (MPS, TVC, and Structures). Avionics and Software risk is assumed to

be 40% of the Ares I Upper Stage value. The mean ascent reliability allocation from start of tanking to successful payload separation for the Upper Stage is documented in the SLS Program System Specification as 0.99964.

#### 3.3.1.5 Upper Stage Engine

The SLS Upper Stage Engine for Block 2 configuration is the J-2X developed by the Constellation Program for use on the Ares I Upper Stage and Ares V Earth Departure Stage. The allocation of 0.99920 is based on the reliability predictions developed for the Ares I PDR and is documented in the SLS Program System Specification.

#### 3.3.1.6 Integrated Spacecraft & Payload Element

The SLS vehicle will have an Integrated Spacecraft and Payload Element (ISPE) that provides the structural and functional interfaces between the Core Stage and the MPCV and/or payloads. For the Block 1 vehicle configuration, the ISPE also includes the Interim Cryogenic Propulsion Stage (ICPS), which performs the perigee raise maneuver to place the MPCV into a stable orbit.

The Block 1 ISPE is allocated a minimum reliability against a critical failure from the start of ICPS cryogenic propellant loading through ascent and successful perigee raise maneuver. The Boeing reliability estimate for the Delta IV-M GPS Extended mission, as described in the Evolved Expendable Launch Vehicle Reliability Report MDC 99H1117, was used and adjusted for the single start and operating time to complete the perigee raise maneuver of the SLS mission. Then an adjustment was made for the unreliability during prelaunch and ascent through Core Stage separation. The ISPE mean ascent reliability allocation is documented in the SLS Program System Specification as 0.99938.

The SLS Block 1A and Block 2 vehicles may utilize a different ISPE configuration. As more information becomes available regarding these configurations, this allocation will be revisited and adjusted if necessary for those vehicles.

### 3.3.2 Uncontained Failure Allocation

Each element was allocated an Uncontained Failure requirement to control the risk of energetic failures that are likely to lead to an Abort Environment exceedance. This allocation is a percentage of the total failure allocation for each element. Each element's allocation is based on data available from both the Ares I Project and the Shuttle Program estimates where applicable. Subsequent to a negotiated agreement with the Booster Element, the Booster Uncontained Failure requirement was deleted.

The definition of the uncontained failure is adopted from CP320R0053 Rev. F, J-2X System Specification and reads as follows:

> *Uncontained failure is defined as the energetic discharge of material or working fluids propagating across subsystem boundaries not including fluid leaks manifested as minor performance dispersions. Catastrophic vehicle loss is defined as a failure scenario from which safe crew abort is not likely. Not all uncontained failures result in catastrophic*

*loss of the vehicle. Determining which uncontained failures result in catastrophic vehicle loss is accomplished via integrated failure scenario and hazards analysis at the vehicle level.*

#### 3.3.2.1 Core Stage

The Uncontained Failure requirement for the Core Stage is based on the Ares I Upper Stage assessment. An allocation of 24% of all core stage initiated critical failures is documented in the SLS Program System Specification.

#### 3.3.2.2 Core Stage Engine

The Uncontained Failure requirement for the Core Stage Engine was determined from demonstrated reliability using the abundance of historical test and flight data of the SSMEs, as well as reliability prediction data that was compiled and used in the development of the Comparative Engine Risk Model discussed above. The allocation of 30% of all core stage engine initiated critical failures is documented in SLS Program System Specification.

#### 3.3.2.3 Upper Stage

The Uncontained Failure requirement for the Upper Stage is based on Ares I analysis of the upper stage design. An allocation of 18% of all Upper Stage initiated critical failures is documented in the SLS Program System Specification.

#### 3.3.2.4 Upper Stage Engine

The Uncontained Failure requirement for the Upper Stage Engine is based on Ares I analysis of the J-2X engine. An allocation of 20% of all Upper Stage Engine initiated critical failures is documented in the SLS Program System Specification.

#### 3.3.2.5 Integrated Spacecraft and Payload Element

The Uncontained Failure requirement for the Integrated Spacecraft and Payload Element was determined from reliability predictions of the RL-10 engine. An allocation of 12% of all ISPE initiated critical failures is documented in the SLS Program System Specification.

# APPENDIX A
# ACRONYMS AND ABBREVIATIONS

## A1.0 ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| BEO | Beyond Earth Orbit |
| DRM | Design Reference Mission |
| ESD | Exploration Systems Development |
| GN&C | Guidance, Navigation, & Control |
| GSDO | Ground Systems Development and Operations |
| HERSP | Human Exploration Range Safety Panel |
| HLLV | Heavy Lift Launch Vehicle |
| HLPT | Heavy Lift Propulsion Technology |
| IRD | Interface Requirements Document |
| ISPE | Integrated Spacecraft and Payload Element |
| LAS | Launch Abort System |
| LOC | Loss of Crew |
| LOM | Loss of Mission |
| LOX | Liquid Oxygen |
| M&FM | Mission & Fault Management |
| MPCV | Multi-Purpose Crew Vehicle |
| MSAIT | MPCV/SLS Abort Integration Team |
| MSFC | Marshall Space Flight Center |
| OPR | Office of Primary Responsibility |
| PDR | Preliminary Design Review |
| PRA | Probabilistic Risk Assessment |
| RP | Rocket Propellant |
| RSRB | Reusable Solid Rocket Booster |

| | |
|---|---|
| SAIT | SLS Abort Integration Team |
| SDR | System Definition Review |
| SLS | Space Launch System |
| SLSP | Space Launch System Program |
| SOAR | Supportability and Operations Assessment Report |
| SRR | System Requirements Review |
| SSME | Space Shuttle Main Engine |
| STE | Structures, Thermal, and Environments |
| | |
| XPRAT | Cross Program Probabilistic Risk Analysis Team |

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