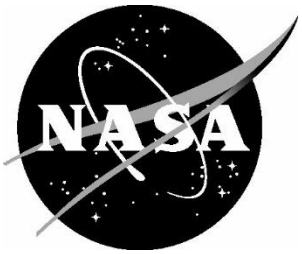
NASA/TP-20240007646



Flight Certification Approach for NASA's Space Launch System

John Kress, Ph.D.; Wayne Bordelon, Jr.; and Laurin Beech
Marshall Space Flight Center, Huntsville, Alabama

Dawn Diecidue-Conners
Consolidated Program Support Services (CPSS PP&C), Huntsville, Alabama

August 2024

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

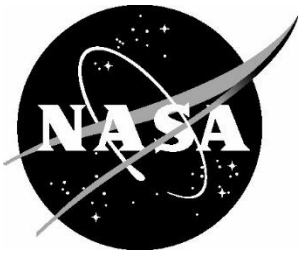
Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

.

NASA/TP-20240007646



Flight Certification Approach for NASA's Space Launch System

John Kress, Ph.D.; Wayne Bordelon, Jr.; and Laurin Beech
Marshall Space Flight Center, Huntsville, Alabama

Dawn Diecidue-Conners
Consolidated Program Support Services (CPSS PP&C), Huntsville, Alabama

National Aeronautics and

Space Administration

Marshall Space Flight Center
Huntsville, Alabama

August 2024

Available from:

NASA STI Program / Mail Stop 050

NASA Langley Research Center

Hampton, VA 23681-2199

Contents

Available from:

NASA STI Program / Mail Stop 050

NASA Langley Research Center

Hampton, VA 23681-2199

ABSTRACT

NASA's Space Launch System (SLS) vehicle was successfully launched on November 16, 2022, initiating the Artemis I mission to send the uncrewed Orion spacecraft to the Moon and further into space than any human-rated spacecraft had previously flown. Flight certification of the launch vehicle was part of the systems engineering and integration (SE&I) effort conducted by NASA to successfully certify the mission and begin a new era of human space exploration of the Moon and eventually Mars. This paper describes the SLS Program flight certification approach including the organization, processes, and reporting. This approach used traditional NASA SE&I milestone reviews and lessons learned from the Space Shuttle Program, as well as unique methods to certify the complex system, procedures, and personnel readiness. The approach utilized by the SLS Program to conduct flight certification for the Artemis I mission can be extended to address flight certification for other complex programs.

1.0 Introduction

Missions to explore and colonize the Moon and Mars require international partnerships and multiple contractors to design, develop, build, and operate the exploration systems. Although the technological advancements required for these missions is substantial, integration of the complex Moon-to-Mars organizational construct requires rigorous application of systems engineering principles and completion of the prerequisite certification processes to implement an effective flight certification process. The flight certification approach used by the Space Launch System (SLS) Program for the Artemis I mission provides an approach that can be applied to system-of-systems with similar organizational complexities.

This paper summarizes the flight certification of the SLS for the Artemis I mission with a focus on the systems engineering and integration (SE&I) flight certification approach. SE&I was distributed among the three Exploration Systems Development (ESD) programs: Exploration Ground Systems (EGS), SLS, and the Orion Program. The term for this effort was cross-program SE&I. SLS flight certification relied upon definition of the roles and responsibility of SLS SE&I in relation to the SE&I responsibilities of the EGS and Orion programs. This paper builds on an AIAA paper entitled *NASA's Space Launch System: Systems Engineering Approach for Affordability and Mission Success*, which described key aspects of the SLS SE&I approach at the time of its publication including processes for system trades, system functional decomposition, managing system interactions, design certification, flight certification, and operations support. This paper leverages the NASA Procedural Requirement 7123.1D (NPR 7123.1D) *NASA Systems Engineering Processes and Requirements* to describe the certification process.

2.0 SLS and SLS Flight Certification Objectives

The SLS launch vehicle is shown with the Orion spacecraft on the left side of Figure 1. When physically integrated with the Exploration Ground Systems, the SLS becomes part of the Integrated Exploration Systems that is shown on the right side of Figure 1.

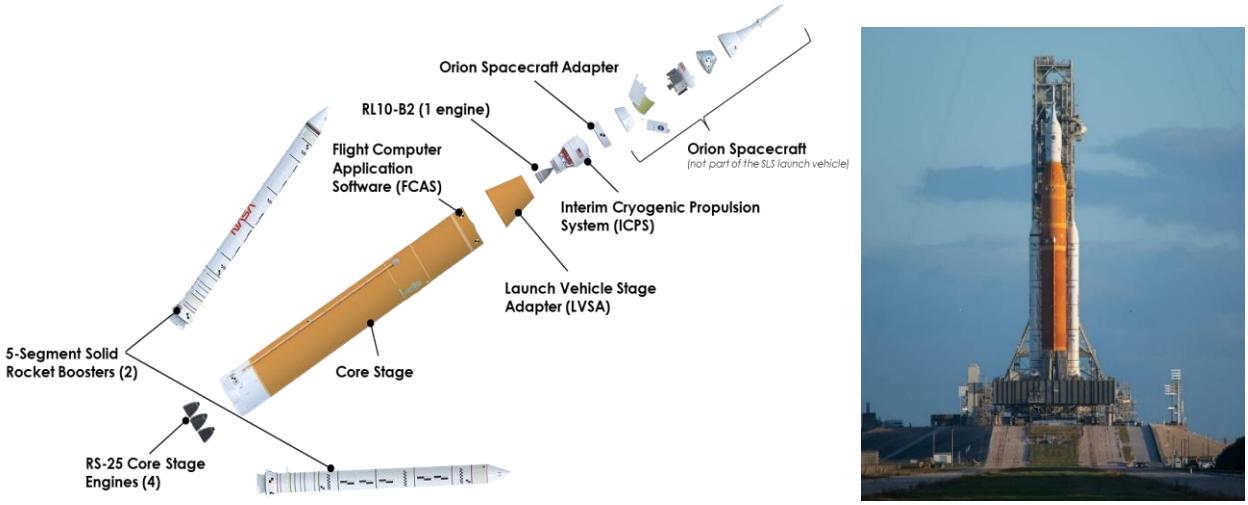


Figure 1. SLS Launch Vehicle and the Integrated Exploration Systems

The SLS launch vehicle is a two and half stage launch vehicle with solid boosters, liquid hydrogen/oxygen core stage, cryogenic propulsion upper stage, and flight software suite. The system was designed (or modified from heritage design) and certified by NASA and the SLS prime contractors for missions beyond low earth-orbit. Artemis I, an uncrewed mission, was the first mission to lunar orbit and back using the Orion spacecraft.

The objectives of the SLS flight certification process for the Artemis I mission were to:

- Affirm readiness of the SLS vehicle to execute the mission
- Communicate residual risk to safety and mission success

These objectives were met by completing a set of prerequisite certification processes and associated reviews culminating in the SLS Program Pre-FRR, wherein the SLS Program Pre-FRR Board chaired by the Program Manager signed a predefined record of completion.

3.0 Organization

3.1 Exploration Systems Development Organization

The SLS flight certification approach was influenced by the ESD organizational construct and the distributed SE&I model. The ESD organization, shown in Figure 2, is comprised of three programs: EGS, SLS, and Orion. The Cross-Program System Integration (CSI) organization focused on technical integration of the system, and the Programmatic and Strategic Integration (PSI) organization focused on the programmatic integration.

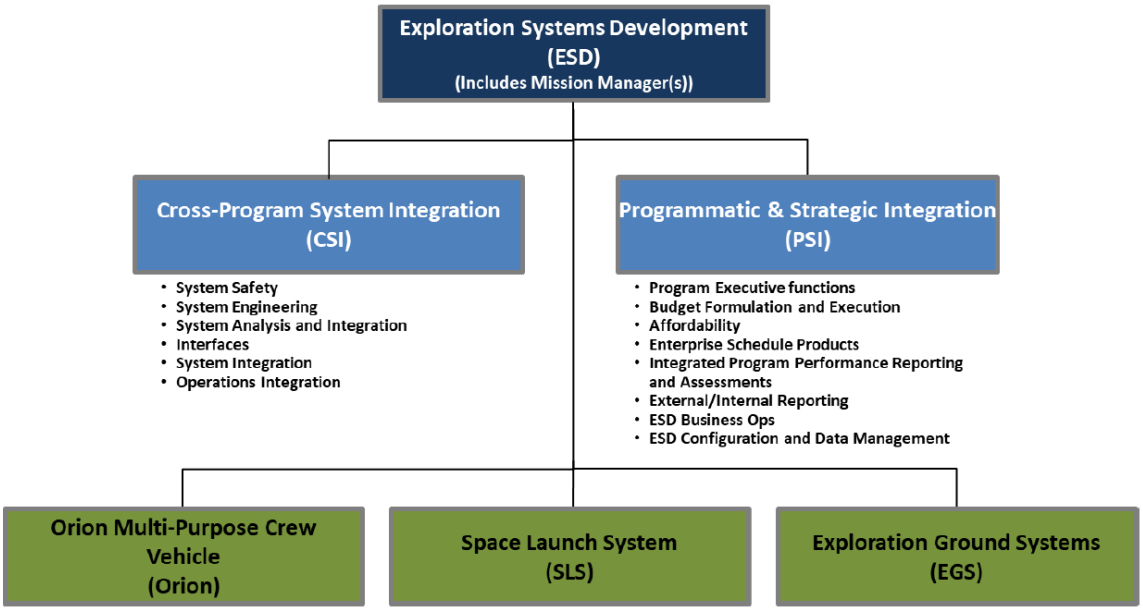


Figure 2. ESD Organization

The interconnected and interdependent relationship between the three programs and ESD is depicted in Figure 3. This figure also includes the readiness mantra for the SLS Program, "deliver Orion to an orbital and attitude state required to continue the mission". The horizontal arrows represent the cross-program SE&I functions that enable a fully integrated system. The vertical arrows depict the unique contributions from each program as part of the integrated system required to accomplish the mission.

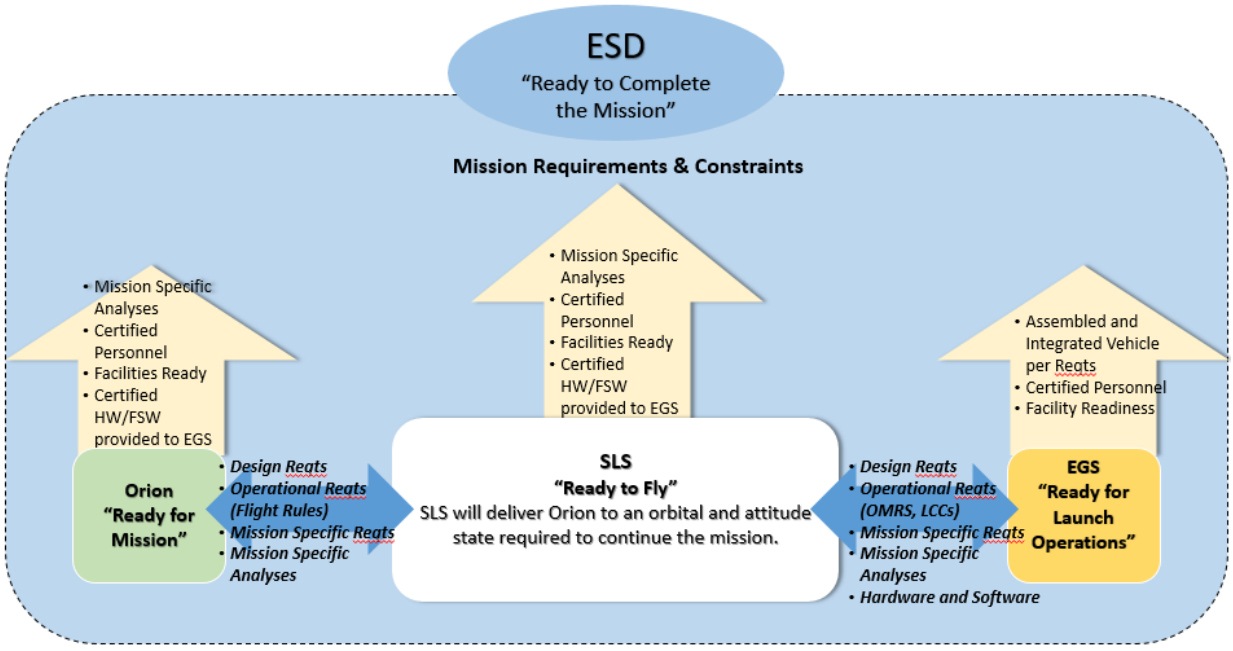


Figure 3. SLS Accountability in the ESD Environment

3.2 SLS Program Organization

The SLS Program Manager was responsible for managing program technical, safety, schedule, resources, and risks; as well as the design, development, production, and certification of SLS vehicle. The SLS Program organization is shown in Figure 4. As with other hierarchical organizations, authority and accountability were delegated to lower levels of the organization. For SLS, the delegation followed the vehicle system product structure with the product (or Element) managers having safety, technical, schedule, and cost authority and accountability for their products; and the SLS SE&I Manager and SLS Program Manager having those same authorities for the integrated SLS vehicle. Element Office products consisted of subsystem hardware delivered to EGS as shown in Figure 1, as well as documentation required to certify their element and to support vehicle integration and certification.

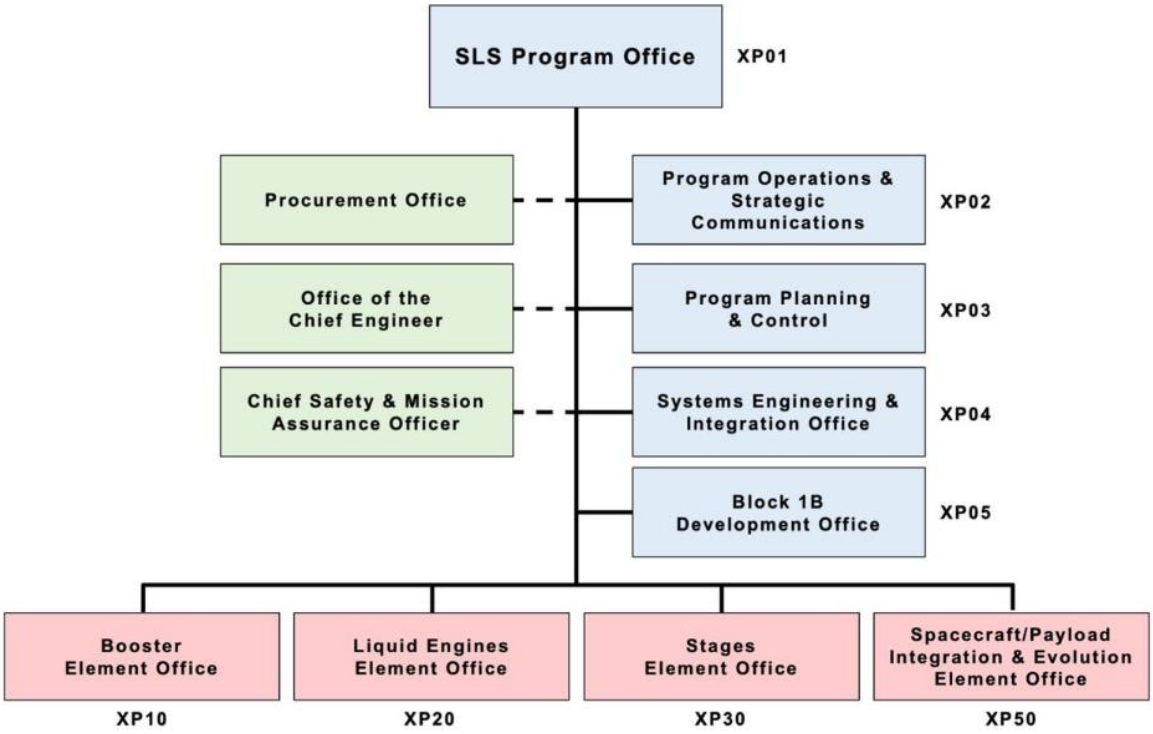


Figure 4. SLS Program Organization

3.3 SLS SE&I Organization

The Systems Engineering and Integration Office (SEIO) manager had technical responsibility for ensuring that the assembled SLS vehicle, integrated through EGS operations with Orion, was certified and ready to fly. In this capacity, the SEIO interacted with the SLS element offices, Engineering, Safety and Mission Assurance, and other ESD programs and mission support organizations. The SEIO was responsible for vehicle systems engineering and analysis, flight software, system integration lab, SLS operations support, and cross-program integration activities depicted by the horizontal arrows in Figure 3. For example, SLS generated the loads and environments for the integrated vehicle. This was accomplished through leadership of cross-program integration teams (e.g., SLS led the Joint Loads Integration Task Team) and development of the loads and environments documentation. The lead program owned the documentation for that discipline/subsystem and was responsible for cross-program integration. Many of the disciplines/subsystems required for DDT&E of the integrated vehicle were assigned to the SLS Program, SEIO. The SEIO (Figure 5) was organized to support the cross-program integration with most of

the effort in systems engineering & verification (SE&V), integrated avionics & software (IAS), and systems analysis & integration (SAI). Additional discussion of the SEIO organization can be found in Hutt, et.al. The key to successful integration was understanding that leadership was delegated to one program, but responsibility remained with the cross-program team. This will be discussed in more detail in Section IV.C.1.

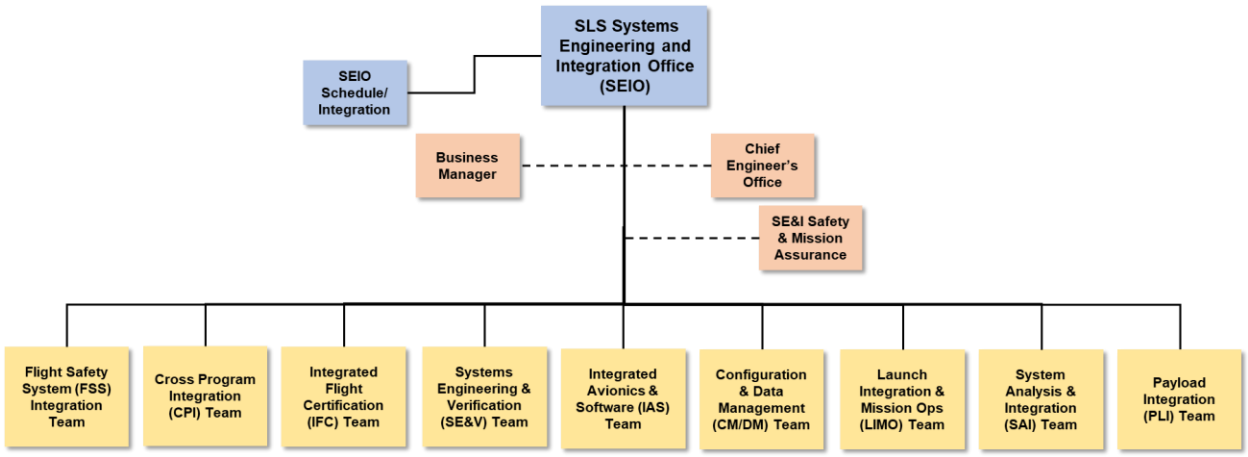


Figure 5. SLS Systems Engineering and Integration Office (SEIO) Organization

4.0 Flight Certification Process

The SLS Program chartered an Integrated Flight Certification (IFC) team within SLS SEIO to define, plan, and execute the SLS flight certification process. The SLS IFC Team leveraged and augmented existing processes within a flight certification framework to achieve a successful and complete flight certification.

4.1 SLS Flight Certification Process Development

The SLS flight certification framework was an aggregate of the applicable NPR 7123.1D life cycle audits and reviews (design certification, system acceptance, operational readiness, and mission/flight readiness) and the NASA common system engineering processes. SLS flight certification utilized SLS-defined applicable technical baselines and objective evidence/compliance packages, and it integrated the individual prerequisite processes supporting flight certification.

4.2 SLS Flight Certification Framework

The SLS Program used the NPR requirements to develop a comprehensive and logical assessment of readiness including segregating the mission readiness process from the overarching mission readiness / flight readiness process into a standalone Mission Certification Process.

A key element of the flight certification framework was defining the “finished” state. Table 1 shows the relationship of the life cycle phases to the SE processes and describes the activities, baselines, and objective evidence required for completion of each framework process.

Table 1. SLS Flight Certification Framework Processes

Design Certification: Certifies that the design meets the design requirements and establishes the system acceptance and mission suitability criteria.

SLS Activities	SLS Objective Evidence	Applicable Audit / Review	NASA SE Handbook Applicable SE Process	Technical Baseline
• Design qualification / verification inspections, tests, analyses, and demonstrations (ITAD) • Identification and acceptance of design requirement deviations and risks	• Element Certificates of Qualification (COQs) • Verification Compliance Report (VCR) and database • Certification of Configuration Compliance (CoCC) Report • System Certification Report (SCR) and database; DCR presentation packages • Baseline system safety posture, e.g., hazards / risks	• Systems Requirements Review (SRR) • Preliminary Design Review (PDR) • Critical Design Review (CDR) • Design Certification Review (DCR) • Configuration Compliance Audit (CCA), Part 1	1. Stakeholder expectation definition 2. Technical requirements definition 3. Logical decomposition 4. Design solution definition 7. Product verification	• As-required • As-designed

System Acceptance: Confirms that the as-built system meets the design, is free from workmanship defects and is assembled correctly, authorizing its shipment to the designated operation site and/or authorizing its operational use.

SLS Activities	SLS Objective Evidence	Applicable Audit / Review	NASA SE Handbook Applicable SE Process	Technical Baseline
• Element acceptance • Disposition of SLS-related Assembly, Integration, and Test (AI&T) and Integrated Test & Checkout (ITCO) nonconformances • Identification and acceptance of waivers and risks	• Acceptance Data Packs (ADPs) • As-Run AI&T procedures • Dispositioned nonconformances • Updated system safety status posture, e.g., hazards / risks	• Element Acceptance Reviews (EAR) • System Acceptance Review (SAR) • ITCO data reviews • Integrated Physical Configuration Audit (PCA) / Configuration Compliance Audit (CCA), Part 2	5. Product implementation 6. Product integration 8. Product validation	• As-designed • As-built

Mission Certification: Certifies that the mission requirements are enveloped by the design or provide flight rationale or risk acceptance for conditions outside of the design certification baseline.

SLS Activities	SLS Objective Evidence	Applicable Audit / Review	NASA SE Handbook Applicable SE Process	Technical Baseline
• Mission Certification Checkpoints • Mission Certification Status Assessments • Identification and acceptance of waivers and risks	• Documented Mission Requirements and GR&As • Mission analysis/tests and mission certification reports/charts	• Mission Concept Review (MCR) • Mission Integration Review (MIR) • Mission Certification Review (MCR)	n/a	• As-designed • As-built

Operational Readiness: Confirms that the flight and ground system work authorization documents/procedures and operational constraints are baselined, mission operational data items are certified, and that personnel and infrastructure are certified to support the mission.

SLS Activities	SLS Objective Evidence	Applicable Audit / Review	NASA SE Handbook Applicable SE Process	Technical Baseline
• Concurrence with baselined Operations and Maintenance Requirements (OMRs) for SLS Assembly, Integration & Test (AI&T), including the Integrated Test & Checkout (ITCO) campaign and launch • Concurrence with baselined Work Authorization Documents (WADs), Launch Commit Criteria (LCC), and flight rules • Development and certification of Day of Launch (DOL) Huntsville Operations Support Center (HOSC) • Certification of the SLS Engineering Support Center (SESC) personnel	• Baselined OMRs • Baselined LCC and Flight Rules • Operational procedures • Personnel training and certification • Wilco'd Program Agreement Requests (PARs)	• Flight Operations Review (FOR) • Test Readiness Review (TRR) • Operational Readiness Review (ORR) • Mission Simulations	9. Product transition	• As-designed • As-deployed

4.2.1 Flight Certification Cross-Cutting Integration Activities

Two critical cross-cutting integration activities to complete the flight certification framework were the system safety assessment and element integration.

System Safety Assessment

The SLS flight certification process relied heavily on an understanding of the baseline mission risk of the SLS and integrated system. The baseline mission risk was established through evaluation and analysis of hazards that may occur and affect the SLS and ESD safety and system performance. Implementation of hazard controls in the design and operational phases of the life cycle were used to mitigate risk. Baseline risks that met the escalation criteria were elevated to the appropriate level for risk acceptance.

As the SLS Program progressed through the life cycle phases and Artemis I integration activities, conditions arose that limited the effectiveness of hazard controls (e.g., design verification deviations, requirement, or operational non-compliances or waivers) and necessitated re-evaluation of the risk. The hazard risk was updated when an assessment of these conditions revealed an impact to the baseline risk. Continuous evaluation of these conditions in relation to the hazard risk provided a basis for communicating residual flight risk.

Element Integration

Element integration was a system-level process utilized to continually (throughout the system life cycle) evaluate element changes and/or conditions that have a potential impact or adverse effect on the integrated system technical baseline and risk posture. The primary implementation approach for element integration was achieved through hierarchical requirement verification activities and relied on a rigorous change management system to identify changes or impacts to the technical baseline. Also, Elements were tasked with elevating changes that affect the system. Requirements were not perfect and identification of changes or impacts to the technical baseline was not easily identifiable. Therefore, flight certification of each SE&I functional area relied on the responsible discipline engineers at the element level and cross-program discipline engineers to maintain insight to changes or conditions that potentially affected the integrated system baseline and system certification. Changes and conditions that had integrated system impacts identified through this process were assessed and actions taken to fully address the system impacts.

4.2.2 Flight Certification Logic Flow

The Path to CoFR in Figure 6 shows the logical progression of activities that complete the SLS flight certification framework processes listed in Table 1, including a defined end activity. In a nominal flow, the path to CoFR would progress from the lower left with completion of the element level design phase followed by the completion of the system design phase and then logically progressing through the completion of the remaining processes. For SLS, as with most development programs, several of the processes were concurrent requiring assessment and reporting of each process at SLS milestone reviews. The CoFR framework was an efficient method of organizing the data, reporting the open work, and characterizing the risk to program managers.

Figure 6 is also annotated to show the applicable baselines for each process and the relationship of one process to the predecessor process:

- Certification that the design meets the design requirements (Design Certification Process)
- Confirmation that the as-built system meets the design, is free from workmanship defects, and is assembled correctly (System Acceptance Process)
- Certification that the as-built system can achieve the mission-specific objectives and requirements (Mission Certification Process), and to identify and characterize mission risks
- Confirmation that the people, processes, paper, and infrastructure are in place to support and operate the system (Operational Readiness Process)

As the program progressed through the certification framework processes, both schedule and safety risks were identified, characterized, and communicated. The series of flight readiness reviews captured the remaining open work and communicates the risk to the mission as identified in the hazards and through elevation of concerns by responsible parties (i.e., "What keeps you up at night?").

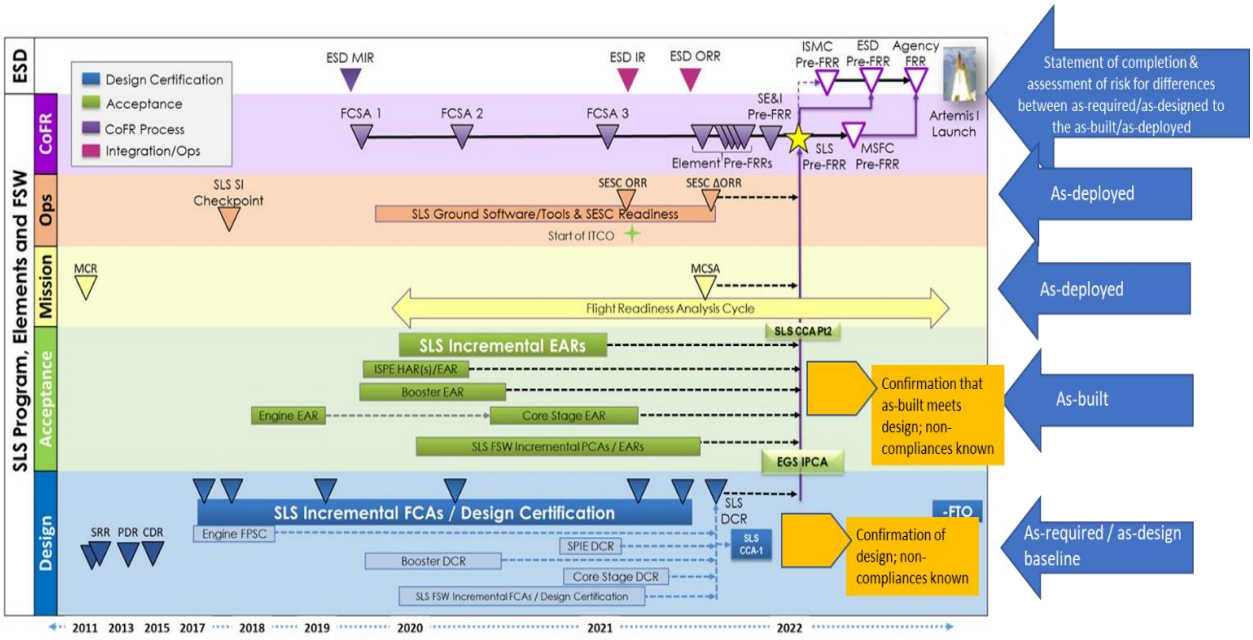


Figure 6. SLS Path to CoFR

4.3 Tools and Methods to Accomplish SLS SE&I Flight Certification

The SLS SE&I effort was driven by the distributed ESD SE&I construct which necessitated a top-down decomposition of the ESD CoFR success criteria and a bottoms-up accountability of the activities required for a complete and integrated flight certification of the SLS and ESD-delegated SE&I scope. The IFC Team leveraged heritage Space Shuttle Program (SSP) processes and relied on the existing NPR and NASA system engineering processes to define roles and responsibilities and to achieve a successful Artemis I mission flight certification.

4.3.1 SLS SE&I Flight Certification Methodology

The SLS SE&I flight certification methodology utilized an SE&I roadmap and checklist to plan and execute flight certification. The roadmap defined the work scope and work assignments, and the checklist defined the expected flight certification content to be addressed by each work area.

SE&I Flight Certification Roadmap

The IFC Team developed an SE&I flight certification roadmap to ensure SLS SE&I flight certification roles and responsibilities were clearly defined, comprehensive, and complete. The SE&I flight certification roadmap is shown in Figure 7 and represented a flight certification simplified work breakdown structure (i.e., each topic represents a piece of the overall SE&I flight certification work scope). The SLS SE&I scope fell into three types: (1) processes or "process topics", which included the flight certification framework processes; (2) environment definition; and (3) system functions/disciplines. The Shuttle SE&I CoFR roadmap, ESD SE&I delegated work scope, and the SLS system functional breakdown structure were used to develop the roadmap. Each topic was assigned a lead integrator or topic owner tasked to develop a flight

certification summary statement to ensure completeness of responsibilities and accountability for their defined scope.

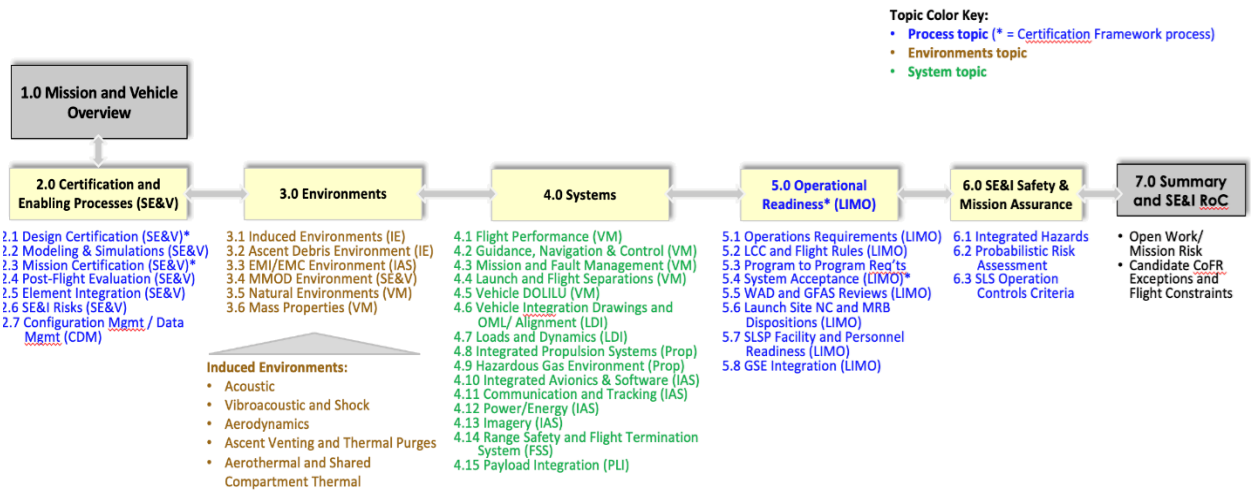


Figure 7. SLS SE&I Flight Certification Roadmap

SE&I Flight Certification Checklist

Using the NPR 7123.1 flight readiness review success criteria and the ESD FRR success criteria, a common list of items was created for all SE&I CoFR content which covered the prerequisite and cross cutting flight certification processes. Each SE&I Roadmap topic owner addressed their certification in terms of the checklist as shown in Table 2. Both the roadmap and checklist were used to create the SE&I flight certification assessment and review agenda content.

Table 2. SLS SEIO Flight Certification Checklist

Title		Description
A	Introduction	Background information on topic and organization's SLS Program and cross-program SE&I responsibilities in terms of system functionality, configuration items, and mission timeline.
B	Design Certification	Design certification certifies that the design meets the design requirements and establishes the system acceptance and mission suitability criteria.
C	System Acceptance	System acceptance confirms that the as-built system meets the design, is free from workmanship defects and is assembled correctly, authorizing its shipment to the designated operation site and/or authorizing its operational use.
D	Mission Certification	Mission certification certifies that the mission requirements are enveloped by the design or provide flight rationale or risk acceptance for conditions outside of the design certification baseline.
E	Operational Readiness	Operational Readiness confirms that the flight and ground system work authorization documents/procedures and operational constraints are baselined, mission operational data items are certified, and that personnel and infrastructure are certified to support the mission.
F	Integrated Hazards	Integrated hazard reports have been approved, hazard controls are appropriate, and hazard control verifications have been completed or have planned closures.
G	SE&I ARM Risks	Status of open technical and safety risks and a summary of accepted technical and safety risks.
H	Mission Risk	Unexplained anomalies on flight hardware, 3x5 and up hazard risks and conditions that increase mission risk from baseline risk ranking will be, at a minimum, listed in table format with summarized flight rationale.
I	Post Flight Evaluation	Plans (e.g., Post Flight Evaluation Plan, Mishap Plan, Contingency Plan, Disposal/ Decommissioning Plan, etc.) are baselined for the next milestone activity and potential mishaps/contingencies, including agreements in place to enable execution of plans.
J	Open Work	Open work (e.g. Program Directives, RIDs, RFAs, TBRs, TBXs, and actions) applicable to flight readiness has been assessed and there are no issues with flight readiness.
K	Constraints to Flight	Constraints to flight have been identified, communicated to Program, and there is a plan to work prior to flight.
L	Summary Readiness Statement	Organization's summary statement of readiness, including overall responsibility.

4.3.2 SLS SE&I Flight Certification Events

CoFR Workshop and CoFR Working Group

The IFC Team prepared for the Artemis I SLS Pre-FRR with a CoFR workshop to set reporting expectations, flight rationale development, and the CoFR series of events. The CoFR workshop engaged SLS program representatives, Element representatives, and SE&I disciplines and initiated a working relationship with the CoFR representatives from each organization and the IFC Team. The SLS CoFR

Working Group was established with representatives for the SLS Program, ESD, and elements. The CoFR Working Group met bi-weekly, as needed, following the CoFR workshop to ensure regular, consistent communication relative to the CoFR process and expectations. The CoFR Working Group proved to be a valuable forum for information sharing and discussion.

Flight Certification Status Assessment (FCSA)

The SLS Program implemented three Flight Certification Status Assessments (FCSAs), utilizing findings of the Rogers Commission (Space Shuttle Challenger accident) and Columbia Accident Investigation Board (CAIB) to improve the SLS flight certification approach. FCSA #1 focused on 1) assuring accountability of responsibilities in the complex organization and 2) culture and communication. FCSA #2 assessed element and SE&I progress toward flight certification and further developed the program's culture with a specific focus on the importance and communication of risk between the different levels of the organization.

The lessons learned and refinements implemented following FCSA #1 and FCSA #2 were captured in an updated SLS CoFR Plan. FCSA #3, the third and final Artemis I FCSA, was tailored to assess the readiness of the SLS elements and system for integration with ESD, including an assessment of the open design certification activities, incomplete acceptance activities, maturity of the operational requirements, and readiness to perform mission certification.

4.3.3 Flight Certification Content Development and Reporting

The flight certification content and reporting approach developed for SLS is shown in Figure 8. The continuous evaluation of processes, identification of open work and issues, and communication of risk was the focus of the flight certification content and reporting approach. "CoFR Assessment Topics" were assessed for flight readiness by each reporting organization within SLS. Completed work was summarized to affirm flight readiness. Open technical issues and completed work with results outside of the baseline risk required further explanation and characterization of risk to the mission. Additional emphasis was placed on issues with elevated schedule or safety risk. Open work, both standard and non-standard, was identified with plans to close. Open technical issues and non-standard open work were considered potential CoFR exceptions. CoFR Exceptions were documented at the discretion of the SLS Pre-FRR board; approved closure plans were completed and tracked via the Program Control Board.

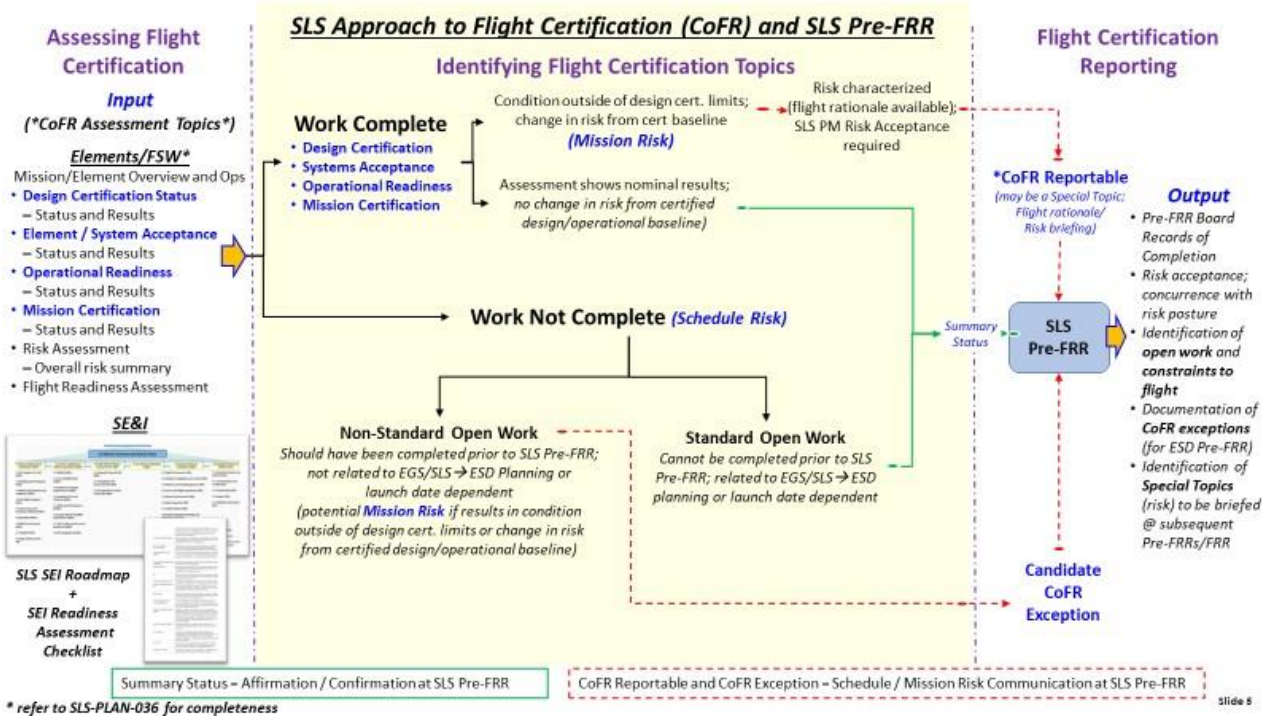


Figure 8. Flight Certification Content and Reporting Approach

5.0 Summary

The approach utilized by the SLS Program to conduct flight certification for the Artemis I mission can be extended to address flight certification for future Artemis missions and other complex programs. The SLS Program utilized systems engineering methods to develop a flight certification framework to derive the content required to meet the stakeholder expectation to "deliver Orion to an altitude and attitude state required to continue the mission". This framework, combined with the flight certification reporting approach, clearly communicated readiness and risk acceptance. Utilization of a flight certification framework in concert with the systems engineering technical management processes provides an opportunity to meet the cost, schedule, and technical goals for future missions and programs.

References

1) AIAA Hutt, John, J., 2017, NASA's Space Launch System: Systems Engineering Approach for Affordability and Mission Success
2) July 5, 2023, NASA Procedural Requirement 7123.1D (NPR 7123.1D) NASA Systems Engineering Processes and Requirements
3) Rogers, William, P., June 6, 1986, Report to the President by the Presential Commission on the Space Shuttle Challenger Accident
4) Gehman, Jr., Harold W., August 2003, Columbia Accident Investigation Board, Report Volume I