NASA Space Launch System Operations Outlook

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The National Aeronautics and Space Administration's (NASA) Space Launch System (SLS) Program, managed at the Marshall Space Flight Center (MSFC), is working with the Ground Systems Development and Operations (GSDO) Program, based at the Kennedy Space Center (KSC), to deliver a new safe, affordable, and sustainable capability for human and scientific exploration beyond Earth's orbit (BEO). Larger than the Saturn V Moon rocket, SLS will provide 10 percent more thrust at liftoff in its initial 70 metric ton (t) configuration and 20 percent more in its evolved 130-t configuration. The primary mission of the SLS rocket will be to launch astronauts to deep space destinations in the Orion Multi-Purpose Crew Vehicle (MPCV), also in development and managed by the Johnson Space Center. Several high-priority science missions also may benefit from the increased payload volume and reduced trip times offered by this powerful, versatile rocket. Reducing the life-cycle costs for NASA's space transportation flagship will maximize the exploration and scientific discovery returned from the taxpayer's investment. To that end, decisions made during development of SLS and associated systems will impact the nation's space exploration capabilities for decades. This paper will provide an update to the operations strategy presented at SpaceOps 2012. It will focus on: 1) Preparations to streamline the processing flow and infrastructure needed to produce and launch the world's largest rocket (i.e., through incorporation and modification of proven, heritage systems into the vehicle and ground systems); 2) Implementation of a lean approach to reach-back support of hardware manufacturing, green-run testing, and launch site processing and activities; and 3) Partnering between the vehicle design and operations communities on state-of-the-art predictive operations analysis techniques. An example of innovation is testing the integrated vehicle at the processing facility in parallel, rather than sequentially, saving both time and money. These themes are accomplished under the context of a new cross-program integration model that emphasizes peer-to-peer accountability and collaboration towards a common, shared goal. Utilizing the lessons learned through 50 years of human space flight experience, SLS is assigning the right number of people from appropriate backgrounds, providing them the right tools, and exercising the right processes for the job. The result will be a powerful, versatile, and capable heavy-lift, human-rated asset for the future human and scientific exploration of space.

I. Introduction

NASA's Space Launch System, a heavy lift, human-rated vehicle, will be an important asset for the future of space flight. Following its tenets of safety, affordability, and sustainability, the SLS Program is developing its system for a first flight in December 2017 launching from KSC in Florida. This paper will focus on Program activities through first flight, Exploration Mission 1 (EM-1). In keeping with its affordability goals, the SLS Program is coordinating with the GSDO Program, a "sister" program responsible for developing the spacecraft processing and launch infrastructure throughout the design and manufacturing phases to ensure successful integration and sustainable life-cycle costs across the decades that the system will be operated. The SLS Block 1 vehicle will be composed of an integrated Core Stage, heritage RS-25 engines and Boosters, and an Interim Cryogenic Propulsion Stage (ICPS). The SLS will carry the Orion MPCV, as shown in **Figure 1**. Simultaneously, GSDO designers are developing capabilities that accommodate the SLS rocket evolution strategy, as well as other commercial and government launch vehicles. Its "Clean" launch pad design and Vehicle Assembly Building (VAB) relocate-able platform configuration schema are centerpieces to the single string, yet highly flexible ground architecture that provides a significant increase in system capability while minimizing the required assets from previous human spaceflight program architectures.

The SLS tenet of affordability does not just apply to the vehicle. The Block 1 vehicle, with its 70-t lift capability, is designed to evolve to 105-t and ultimately a 130-t configuration. This evolvable design will enable game changer science missions to travel to destinations such as near-Earth asteroids, Mars, Saturn, and Jupiter. SLS's large payload fairing will reduce experiment design complexity, and its high performance capability will decrease travel time, reducing mission cost and risk. It will also provide a platform for the first Mars sample return mission and the first humans on Mars. Similarly, GSDO leverages five decades of experience in complex launch and test systems – building a spaceport capable of launching the world's largest rocket while reducing the required footprint and operations costs. A key aspect of the GSDO Program's approach to long-term sustainability and affordability is to design – one time – for the evolution of the Space Launch System. Capitalizing on investments from the Constellation Program, GSDO is modifying a Mobile Launcher that will enable integration in a controlled VAB environment in days instead of weeks at the launch pad (**Figure 2**).

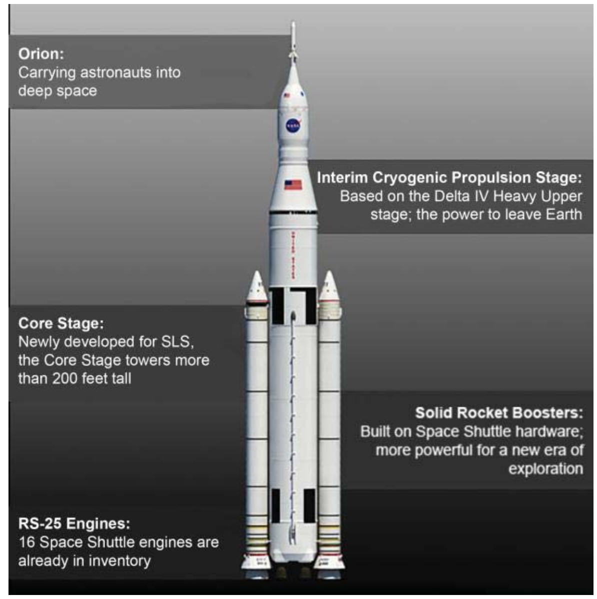
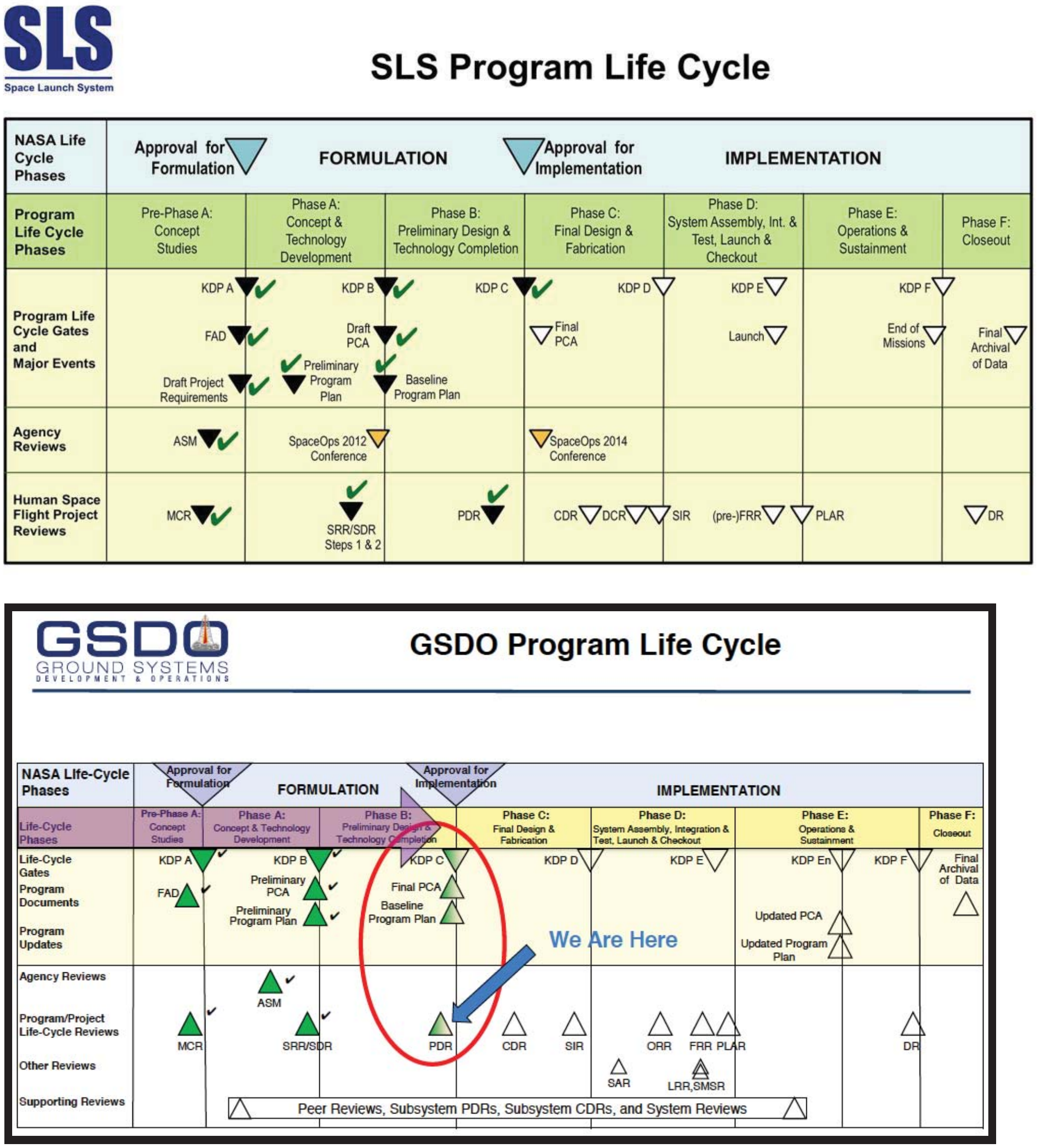


Figure 1. NASA's Space Launch System is comprised of new and heritage hardware.

Since the introduction of the predecessor paper ("NASA Space Launch System Operations Strategy," J. Singer, J. Cook, and C. Singer) at the SpaceOps 2012 conference, the SLS Program has moved from concept to design in just over 2 years, completing its in-depth internal Preliminary Design Review (PDR), where a Standing Review Board also made an independent technical and programmatic assessment of the SLS Program, weighing cost, schedule, performance, and risk. Upon completion of the PDR, the SLS Board and the Standing Review Board recommended the Program proceed to Key Decision Point C – the point where the Program received Agency approval to move from the formulation (preliminary design) phase into the implementation (final design and fabrication) phase of the program life cycle. The Program's next step is to work towards Critical Design Review (CDR) in 2015. Likewise, GSDO plans to complete its PDR and subsequent Standing Review Board assessment during the spring of 2014, and then move from this important design phase into implementation, with its CDR also planned in 2015 (**Figure 3**).

Figure 2. Key GSDO Program assets.



Legend

ASM: Acquisition Strategy Meeting
CDR: Critical Design Review
DR: Decommissioning Review
DRR: Decommissioning Review 2
FAD: Formulation Authorization Document
FRR: Flight Readiness Review
KDP: Key Decision Point
PCA: Program Commitment Agreement
PLAR: Post-Launch Assessment Review
SIR: System Integration Review

Figure 3. SLS (top) and GSDO (bottom) are moving from formulation into implementation.

Reducing the life–cycle costs for NASA's space transportation flagship maximizes the exploration and scientific discovery return on the taxpayer's investment. Accordingly, NASA is taking action during development that will pay dividends once the systems are operational. NASA has leveraged heritage hardware and systems from the Space Shuttle and Constellation Programs, while dramatically reducing the launch and production infrastructure needed for the respective SLS and GSDO Programs. This approach reduces near term development costs, schedule, and risk, while also lowering fixed infrastructure costs through the life cycle of the respective Programs. NASA is also implementing a smart, flexible workforce approach where launch site engineers participate in key system production and test activities, and a cadre of design engineers engage on-site in processing operations. This workforce approach provides important opportunities for learning early in the hardware production flow, increases sharing of best practices, and enhances resolution of hardware and software challenges encountered during the campaign. NASA is using state-of-the-art predictive operations analysis tools to identify opportunities to streamline the processing flow and evaluate design and development decisions from an operability perspective. From a management perspective, NASA is employing an innovative cross-program approach that emphasizes collaboration between the launch site and space system development programs, enhancing accountability and reducing integration overhead.

II. Implementation of Affordability Strategies

From its inception, the SLS Program has implemented safe, affordable principles into the design of the evolvable vehicle while ensuring sustainability throughout its life cycle. This strategy involves the use of heritage hardware and infrastructure where sensible, and includes leveraging an experienced workforce from previous NASA programs. The SLS Program, in coordination with its prime contractors, has adopted lean management and manufacturing techniques to increase efficiencies and reduce cost and production timelines. This approach has allowed the Program to plan to a streamlined development schedule.

Figure 4. Sixteen RS-25 engines were transferred from the Shuttle Program for use on SLS.

Given the flat budget profile in today's fiscally-focused environment, the use of heritage hardware has been critical to meeting schedule goals while remaining affordable. The SLS Program obtained ample existing hardware and infrastructure from the Space Shuttle, Constellation, and Evolved Expendable Launch Vehicle (EELV) Programs. At the conclusion of the Space Shuttle Program, 16 RS-25 reusable engines remained in stock and were available assets for use by the Program (**Figure 4)**. The value of these assets exceeds one billion dollars, a significant cost savings to the SLS Program. However, because these engines will be flown in new environments, the Program is thoroughly testing the hardware for these new conditions to ensure safety and reliability. The SLS Program is also employing a vehicle architecture that includes the use of two 5-segment solid rocket boosters that were in the development stage under the Constellation Program and are derivatives of the Space Shuttle four-segment Boosters[1]. For its upper stage, the SLS Program will employ the design of modified Delta Cryogenic Second Stage (DCSS) engines used for the Delta IV EELV Program. The DCSS engines have completed over 20 flights[1]. Another holdover of the Constellation Program is the J-2X engine. While the J-2X engine is not currently planned to be used in the initial SLS vehicle design, its development has served as a test bed for analyzing 3D printing of less expensive rocket components, and resulted in a new common engine controller which is being adapted for use with the RS-25 engines[1].

A significant aspect of the SLS design is leveraging existing infrastructure to reduce cost and schedule. The Program is using manufacturing facilities, test stands, and other facilities from prior programs to design, manufacture, and conduct qualification tests to verify and validate the design of the vehicle. The SLS Core Stage structure will be the same diameter as the Space Shuttle External Tank, allowing the SLS Program to leverage much of the manufacturing infrastructure already in place at the Michoud Assembly Facility (MAF) in New Orleans, Louisiana. During design, the Program was limited on vehicle height based upon the size of the existing Vertical Assembly Building at KSC, shown in **Figure 5**, where integration of the launch vehicle upon the mobile launcher will occur before rollout to the pad. The Program is also using the System Integration Test Facility at MSFC to develop, test, and verify the integrated vehicle avionics system. NASA will also harness existing facilities for the integration of hardware and activities associated with pre-launch preparations, launch, and post-launch analysis. SLS requires state-of-the-art tooling that will include some modifications and the restoration of the one-of-a-kind A-1 and B-2 test stands at Stennis Space Center. The use of existing facility infrastructure from prior programs allows the SLS Program to focus its limited resources to remain within budget and stay on course for first flight in 2017[2].

Figure 5. Integrated SLS/Orion Vehicle Rolling Out Of The VAB *(artist's concept)*.

Consistent with the affordability theme to optimize design and manufacturing efforts and minimize Program costs for the SLS launch vehicle, the Program is also executing lean manufacturing techniques at the production sites to increase efficiency and reduce unneeded infrastructure, ultimately reducing production timelines. The execution of value stream mapping (VSM) techniques, as first introduced in the 2012 SpaceOps paper, are already in place in the manufacturing of Booster Qualification motor 1 (QM-1) hardware[3], shown in **Figure 6**. On-going VSM efforts being implemented for Core Stage development activities will be addressed later in this paper.

Figure 6. Booster QM-1 Segment

Another successful affordability strategy implemented by the Program included the manufacturing process for the MPCV Spacecraft Adapter (MSA) under the direction of the SLS Spacecraft Payload and Integration Office (SPIO). The MSA (**Figure 7**), combined with a diaphragm manufactured by NASA's Langley Research Center, will integrate the SLS vehicle to the Orion crew vehicle. In 28 months, SPIO completed the design and manufacture of the MSA in time to support the Exploration Flight Test-1 (EFT-1) slated for launch later in 2014. This same MSA design will be used for EM-1 in 2017. The "design once, use many times" philosophy contributes to the vehicle's overall affordability initiative. The MSA design will support both crew missions and cargo applications such as flagship science payloads. In addition to providing a standard interface adapter between the SLS and its primary payload, the MSA is designed for up to 11 cubesat-class secondary payloads. This further enhances the utility of the SLS vehicle and provides unprecedented access to deep space for a broad range of stakeholders.

Figure 7. MPCV Spacecraft Adapter

With the goal of multi-mission flexibility, the Kennedy Space Center is currently undergoing an unprecedented transformation, evolving from a government-only launch complex into the spaceport of the future as the embarkation point for the SLS and Orion, as well as commercial launch vehicles and spacecraft. The GSDO Program is responsible for meeting multiple challenges related to designing and developing the ground systems, launch pads, integration facilities, processing areas, and launch and recovery ranges to support this vision.

To achieve this goal, GSDO developed a rigorous Architecture Refinement Cycle (ARC) process to enable major programmatic decisions regarding the architecture of NASA's assets. This process enables GSDO to quickly respond, in a quantitative manner, to internal and external requests for use of the broad range of facilities available at Kennedy Space Center. Currently, nine cycles have been completed, each addressing a wide array of questions from "Where should we launch?" to "How do we evolve to enable future exploration missions?" Each cycle begins by documenting current GSDO capabilities that meet both SLS and multiple user needs. Trade studies are initiated to help define the decisions that would optimize the architectures to meet requirements while minimizing life-cycle costs. A nominal architecture refinement cycle lasts 90 days to avoid costly delays associated with indecision. During this time period, a concept of operations is developed for a specific area in question. An operational assessment is then conducted to assess cost, schedule, and technical merits for the proposed option space and potential risk to the system. In many cases, advanced modeling and simulation techniques are applied to quantify GSDO's ability to meet requirements with minimal assets. Figures of Merit (FOM) are agreed to at the beginning of each cycle for specific trades, and then the trades are analyzed against them for the optimal outcome. The final recommended solution then goes through a rigorous control review forum and once approved becomes part of the Program baseline. **Figure 8** outlines the flow process for how these iterative steps provide a closed loop solution for optimizing the architectures through each ARC.

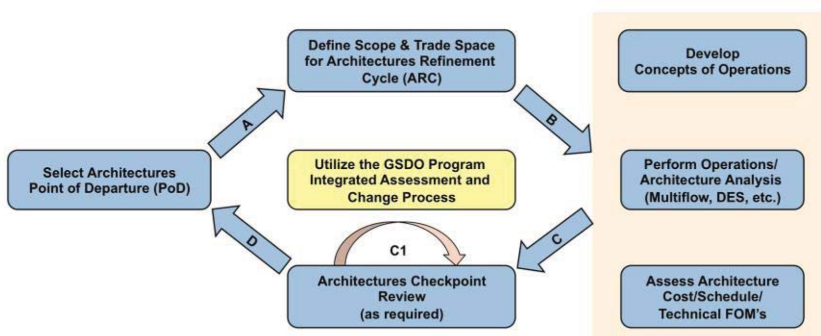


Figure 8. GSDO architectures assessment process.

To reduce the cost of space launch operations for multiple customers, the GSDO Program broke down institutional barriers and provided multiple users with access to NASA experts possessing decades of experience and to a well-established launch infrastructure. An example of decisions made through the ARC process include establishment of a multi-use launch pad. This mandated implementation lead to a clean pad concept, which is revolutionary in human space flight. The clean pad concept leverages a mobile launch platform that is specific to customer needs and interfaces while eliminating costly and unnecessary launch pad infrastructure. In addition, servicing activities have been pushed to offline facilities whenever feasible to reduce time and infrastructure in major integration areas (i.e., Vehicle Assembly Building, launch pad).

Throughout the ARC process a primary tenet was established that GSDO must support SLS and Orion with the most efficient architecture possible. In this process, GSDO decided to move to what is called a "single-string architecture" which means that the Program only has a single launch pad, integration cell, and mobile launcher. When compared with human-rated programs (Apollo and Space Shuttle) this is an impressive reduction from the two launch pads, three mobile launchers, and multiple integration cells. These decisions were not made lightly, but were instead done by carefully analyzing requirements and quantifying risk from historical failure rates. This approach allows GSDO to maintain the nominal capability to process one SLS and Orion every two years, with the surge capability for three launches in a single year for strategic missions, within an affordable budget[4].

Both SLS and GSDO Programs recognized that the most cost effective time period to impact flight and ground systems designs is early in the development process. To do this, both Programs developed a common understanding of how the vehicle will be processed at the launch site. The Ground Operations Planning Database (GOPD) allows SLS and GSDO to identify drivers and efficiency opportunities early in the development process when design changes are least costly to implement. The GOPD is web based and accessible by both Programs, providing unprecedented insight into future ground operations while using a common data set. The GOPD allows multiple authors and ensures that all stakeholders are utilizing the same data source. The database captures operations planning sequences, timelines, resources, services, Ground Support Equipment (GSE), hazards, contingencies, and any other information that is relevant to planning and executing ground operations. Ultimately this becomes a detailed concept of operations that serves as the framework for procedure and requirements development once flight and ground designs have reached the appropriate maturity. An equally important function of the GOPD is that it serves as a tool to establish relationships and communication paths between flight and ground system designers regarding planned operations. In addition, the data captured within the GOPD will be utilized to verify by analysis the NASA requirements such as flight rate and contingency durations.

The GOPD has been developed in an evolutionary manner, maturing along with the vehicle and ground designs. For example, as processing concepts became clearer, capability was added to the database to capture GSE and its associated model numbers. This path allows GSDO to accurately assess demand and ensure excess capacity is not unnecessarily built into the system. In addition, the GOPD is being used to identify support services that will be required from external entities for operations. This approach will allow the GSDO Program to have a comprehensive view of the agreements that need to be in place prior to flight hardware arrival at the launch site.

III. Lean Cross-Program "Reach-Back" Strategies

The SLS and GSDO Programs are implementing cross-pollination strategies for streamlined hardware development and ground processing activities prior to the EM-1 launch. This three-prong approach includes: 1) establishing cross-Program liaisons early in the respective Program life cycles; 2) sending KSC personnel "upstream" to the SLS design centers to engage in production/integration testing support to gain familiarity with the flight hardware prior to delivery at KSC; and 3) establishing SLS design center support at KSC in preparation for the ground processing of flight hardware. Design center support will include a small cadre of experts residing at the launch site to provide reach-back for sustainment support and assistance in resolving unique anomalies detected during the KSC pre-flight preparations.

The GSDO Program utilizes liaisons within its launch vehicle organization to ensure continuous open communications during the concurrent development of flight and ground systems. These GSDO liaisons bring forward operational considerations into the flight system design process and maintain close ties with the SLS hardware elements to help ensure that technical issues or disconnects surface and are resolved early in development, serving to minimize costly redesigns and rework. In addition to the GSDO liaisons role within the GSDO Program, the SLS Program has established a Ground Operations Liaison Office (GOLO) equipped with personnel at the MSFC resident office at KSC, and personnel located with the SLS Program at MSFC, who are steeped with Shuttle ground processing experience. GOLO personnel complement and interact with the GSDO liaisons to maintain the flow of communication between the two Programs to minimize "surprises" impacting the other Program's programmatic planning efforts.

To mitigate risks associated with the timely processing of flight hardware at KSC, the SLS and GSDO Programs are instituting an on-site manufacturing support (OMS) strategy that engages GSDO personnel at the respective design centers (i.e. ATK facility in Utah and MAF in Louisiana) during key flight hardware manufacturing phases prior to delivery at KSC (**Figure 9**). GSDO personnel participation in the manufacturing phases enhances information exchange between the Programs, facilitates additional ground resources, supplements SLS personnel, and provides an opportunity to develop common procedures and integration processes. This strategy has been implemented on previous NASA Programs and has proven to help build strong cross-Program teams in preparation for ground processing at KSC.

Complementing the OMS strategy of GSDO "reach-back" expertise at the design centers during manufacturing, a cadre of key SLS personnel will reside at the launch site during ground processing to provide design center expertise and engage reach-back support as appropriate. Design center support at KSC during the Shuttle era proved to be an effective way to address ground processing issues in a timely fashion. For EM-1, design center support at KSC will build on the cross-Program relationships established during the earlier design and manufacturing phases of ground and flight hardware, and will ultimately produce a lean, close-knit cross-Program team that will be needed to address and resolve non-conformance conditions at KSC in a timely and effective manner. This lean on-site support approach optimizes opportunities for launching the EM-1 mission in a safe, affordable, and timely manner.

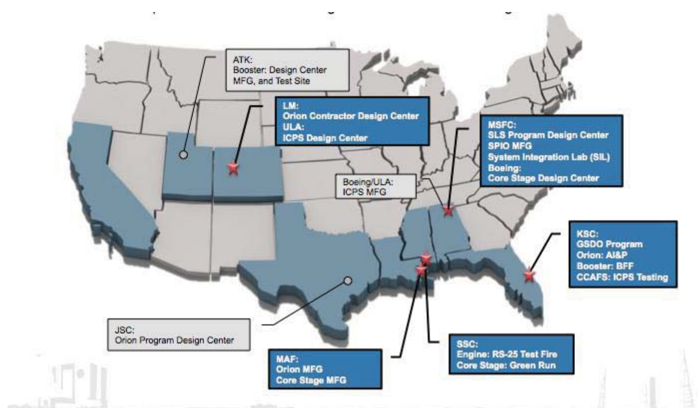


Figure 9. Proposed GSDO OMS at SLS design center locations.

IV. Implementation of Cross-Program Predictive Operations Analysis Techniques

The establishment of the GOPD and a common operations concept between vehicle and ground has enabled the use of state-of-the-art predictive operations analysis techniques to reduce life-cycle costs and ensure mission needs will be met. Discrete Event Simulation (DES) is one of several analytical approaches GSDO and SLS are employing for planning operations, improving operability, comparing system design alternatives, and verifying requirements. DES is a computer-based statistical sampling method that helps the programs make more informed decisions regarding ground operations planning.

A common criticism of Shuttle operations was its inability to meet the cost and utility goals initially outlined. The original projected turnaround time for a vehicle was 160 hours. Ultimately the turnaround time ended up being significantly longer, on an order of months. Many factors played into this reality (**Figure 10**), and lessons learned from 30 years of operating the Space Shuttle provide an apt foundation for a new era of space exploration operations.

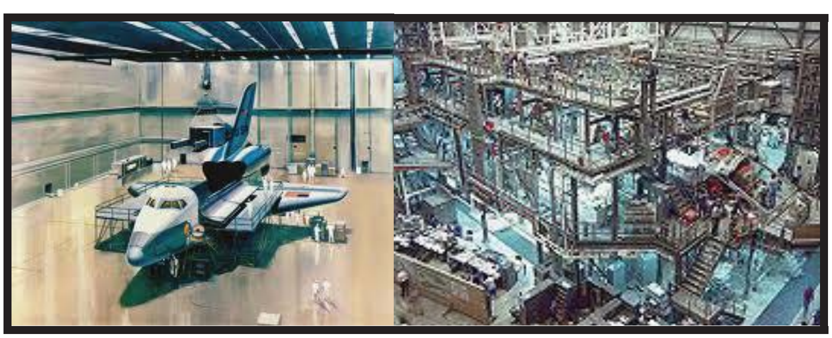


Figure 10. Shuttle Turn-Around Time Concept versus Reality

The GSDO Program has utilized DES to forecast realistic processing timelines which include risks such as common cause variability, historical processing delays, and learning curves. By quantifying risks, GSDO can make informed decisions about levels of funding that will be required to process the SLS and Orion. The DES models leverage heavily off historical NASA processing documentation as well as industry standards to create a holistic image of ground processing capabilities and expected processing issues. The data generated have been directly leveraged in creating budget estimates as well as schedules.

DES is also being used to perform requirements verification that would otherwise be too costly to execute through testing. Some examples of requirements that will be closed using DES analysis include launch to launch spacing capability, rollout to launch duration, time to roll back from the pad in the event of a contingency, and pad turnaround time. These are all areas where it is critical that GSDO set operations requirements for the design community, but would have issues with performing full scale testing with flight hardware due to risk and cost. Through using the data developed under the common framework of the GOPD, analysts have generated high quality models that allow GSDO to verify the requirements. In addition, these models were developed early in the program life cycle allowing feedback to be provided to the designers continuously to ensure they will meet their requirements[5].

Missions to deep-space destinations offer unique challenges from a launch reliability perspective. Missions to interplanetary destinations must be launched in time to meet tight departure windows where a missed opportunity could delay a mission by a year or more. Crewed missions to deep space could require multiple launches for a set departure window, with a portion of the mission complement holding at a rendezvous point awaiting launch of the remainder of the mission complement[6]. As the Space Launch System's primary mission is deep-space exploration, the ability to reliably launch the vehicle at specified departure times is important. At the same time, development funds are limited and NASA must choose wisely where to make investments in systems reliability. NASA uses a quantitative Reliability, Maintainability, and Availability (RMA) approach, first developed under the Constellation Program[7], to assess predicted system launch availability and to drive system design decisions. The results are Technical Performance Measures (TPMs) which provide, for example, the probability of launching the integrated vehicle over a 30 day launch window within a specified confidence level. The TPMs are decomposed into a set of reliability targets that each GSDO subsystem must be designed to meet. For example, the launch pad's liquid hydrogen storage and loading subsystem must meet a reliability target for the initial launch attempt. A small team of reliability experts work with the subsystem design teams to construct a statistical reliability model using reliability block diagrams. At each major subsystem design milestone, the reliability team provides a reliability estimate for the subsystem, identifies the major subsystem reliability drivers, and provides suggestions for improving the reliability of the system. In many instances, the reliability of subsystems can be improved by an order of magnitude or more with smart design and component selection decisions. The subsystem level reliability models are then rolled up into mission level launch availability models to verify the system designs are on track to meet the overall mission objectives. Progress toward meeting the enterprise launch availability targets is statused regularly to the Program Managers and the Exploration Systems Director via a set of TPMs.

GSDO is also implementing design visualization to perform interference analysis, analyze operations concepts, support trade studies, and develop GOPD sequences. Through directly importing engineering models and laser scanning major existing assets, such as the launch pad, GSDO is able to accurately model operations in a three-dimensional environment well before new hardware goes into fabrication (**Figure 11**). This is an important tool in providing feedback early in the design process to ensure that the Program will be able to meet its operational objectives and avoid paying exponentially more for changes late in the life cycle. The Program even instituted checkpoints where major designs are integrated virtually and feedback provided on potential issues. Operators have also been able to ensure designs will meet the human factors requirements of technicians performing tasks and that access is adequate for contingency operations.

Figure 11. GSDO Design Visualization 3D Engineering models.

During the SLS vehicle design process, analysis performed by SLS vehicle operations personnel provides valuable insight into the operations and supportability characteristics of the launch vehicle. These analyses form a report, produced at the end of each Design Analysis Cycle (DAC), which provides observations regarding how well the SLS vehicle design is expected to meet the total life-cycle mission needs within the planned operations and support environment. This report also provides recommendations to improve supportability and operability while maintaining an affordable system.

A prime focus of the report is on vehicle servicing, assembly, and maintenance demands for time, manpower, consumables, and equipment resources. Steps to reduce the need for these can improve Assembly and Integration (A&I) process efficiency while reducing operations costs. The analyses are performed in lieu of specifying requirements that can be hard to verify, costly to implement, and of potentially little benefit. By taking incremental looks at the ramifications of the current state of the SLS design on the support infrastructure, issues can be identified and used to enable balanced and practical management decisions before costs and problems are locked in. These analyses include a forecast of SLS system readiness, launch availability, and maintenance down time based on data from the GOPD for nominal processing, select weather events, off-nominal processing, and SLS vehicle reliability factors. SLS manufacturing, transportation, A&I, launch pad, and ascent environments are provided to parts and component vendors who must prove acceptable product performance and reliability data through evidence of a rigorous qualification program or appropriate heritage application. Using reliability of SLS system components to identify likely failures, maintainability prediction data are compiled for primary SLS components and subassemblies. This strategy allows identification of the most likely failures and designation of critical Line Replaceable Units (LRU) and system redundancy. Some SLS LRUs identified address 60% of all failures in the ground environment. The SLS design layout process ensures that these LRUs are accessible for change out during the A&I process. The philosophy of building in maintainability ensures a reasonable balance between the ability to repair at the launch site and the levying of costly reliability requirements on components. Overall, these analyses help SLS and GSDO decision makers improve risk management activities, resource planning, scheduling, and integrated SLS to launch site infrastructure performance as a single system.

Production efficiencies from the SLS Core Stage Element have benefitted from Value Stream Mapping (VSM) studies that have eliminated redundant and unnecessary steps in the production flow. VSM results focused on the processes required within each Production Area at MAF, as well as the movement of equipment and Core Stage subassemblies between Production Areas. A Production Area is where a primary subassembly of SLS is manufactured or where a production activity for several subassemblies is carried out due to use of common tooling. A detailed scanning of MAF ceilings, walls, and support structure provided up to date and accurate information regarding the facility's floor space, ceiling height, room geometry, wiring, plumbing, heating, cooling, data lines, and lighting. The resulting scans provided accurate facility information factoring into the overall layout of the production flow at MAF and the selection of the Production Areas.

MAF flow capacity is planned for one Core Stage per 12 month period and with two core stages in the flow at any one time. Similar to the GSDO design visualization techniques being implemented for ground processing planning, SLS design visualization techniques are being used to design the production processes and assess planned production feasibility; the accurate facility data was incorporated digitally into a virtual simulation of each Production Area within the Dassault Systems' Digital Enterprise Lean Manufacturing Interactive Application (DELMIA). The virtual simulation uses vehicle design data from the Computer Aided Three-dimensional Interactive Application (CATIA), along with the facility scan data, to provide an accurate visual of the product flow and production steps taking place within the Production Area. **Figure 12** is a DELMIA rendering of the SLS integrated core stage (forward skirt, intertank, and engine section) on the Rotation Assembly Transportation Tool in the MAF final assembly area. These dynamic simulations accurately account for the kinematics and address clearance and tolerance issues in a virtual environment before implementation. This approach avoids the need for manual testing of each production configuration via mockups and walkthroughs. The end result is a highly efficient production process subject to the constraints of using a heritage facility and the limitations of the manufacturing tools and allocated production costs.

Figure 12. DELMIA rendering of the SLS Integrated Core Stage.

V. Implementation of Cross-Program Technical Integration Model

Historically, NASA has used a systems engineering and integration (SE&I) model to execute technical integration across projects or programs (often geographically dispersed). This model has historically been executed through the establishment of a separate SE&I organization, often a third-party contractor, to manage the integration of the flight and ground systems being developed. This third party held responsibility for managing the interfaces between the individual flight elements as well as the ground elements. These interfaces often include complex loads and environments, functional and performance parameters for commodities and data which pass across the interfaces, as well as design and construction standards that must be compatible for the resulting systems to perform as intended when they finally come together for the first time at the launch site. The newly proposed cross-program technical integration model removes the third party integrator. Instead, this model relies on self-integration (**Figure 13**). This approach's driving rationale is that SE&I technical expertise is resident within the Programs and the resources required to stand up a third party SE&I organization goes against the affordability tenet of the Programs.

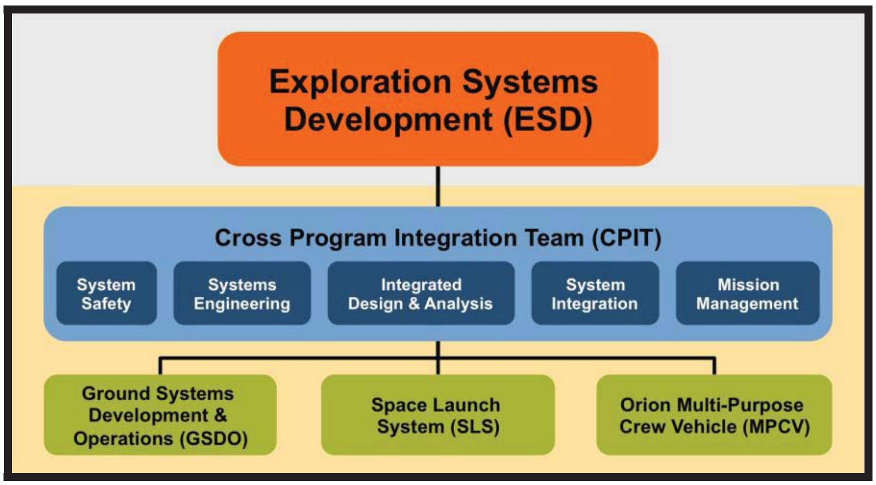
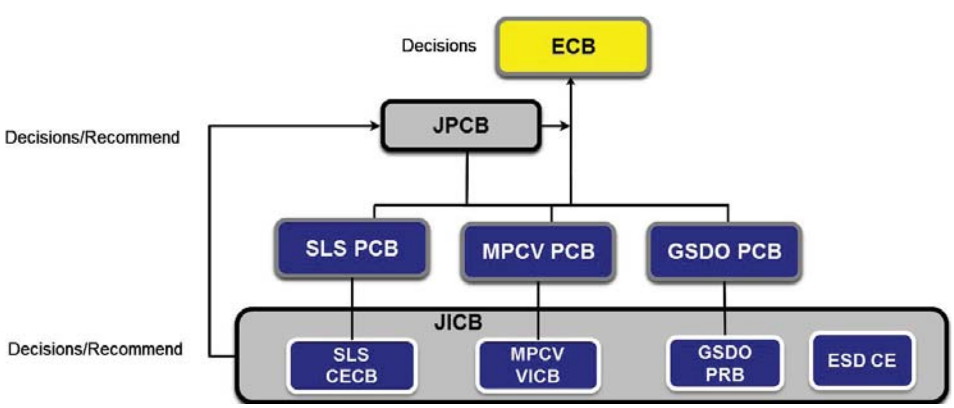


Figure 13. ESD Cross Program Integration Framework

The decision-making governance structure (**Figure 14**) has been established to use joint-program integration boards (technical) and joint program control boards (budget and schedule), enabling the three Programs to resolve technical issues in a structured, rigorous manner. The programs themselves are motivated to resolve the issues since there is no third party to "hand off" the problems to for resolution. Given that the budget is capped, the single shared pool of resources is also a driving consideration to find the lowest cost, best technical solution. For example, simply shifting the problem from one program to another does not "save" any money, since the shared pool gets reduced to deal with the issue regardless of which program must fund it.



Legend

CECB: Chief Engineer's Control Board

ECB: Engineer's Control Board

ESD CE: Exploration Systems Directorate Chief Engineer

JPCB: Joint Program Control Board

PCB: Program Control Board

PRB: Program Review Board

VICB: Vehicle Integration Control Board

Figure 14. ESD Cross Program Integration Framework

Conclusion

Figure 15. SLS 70t launching from the pad at KSC.

Only 3 years have passed since NASA established the SLS Program and chose a vehicle concept in September 2011, in parallel with the GSDO Program's efforts to modify and streamline their ground processing infrastructure. During that time, the use of heritage hardware and infrastructure; the experience of Shuttle and Constellation personnel participating in preliminary design efforts; the introduction of lean design, analysis, and manufacturing techniques; and the communication, coordination, and collaboration between the SLS and GSDO Programs have resulted in a vehicle design and ground operations on the verge of transitioning into the implementation phase of their respective program life cycles. Both the SLS and GSDO Programs are on schedule to complete their Critical Design Reviews in 2015. Hardware building and testing have begun. The coordinated efforts of the Programs will ensure that as hardware is designed, built, tested, and integrated for flight, the right people are involved in each step of the process to ensure success. Challenges that arise will be addressed by personnel from their respective Programs accustomed to working together so that solutions do not lead to surprise impacts in other related areas. All of this progress has been accomplished to date within a fiscally-conscious budget that ensures maximum value for the taxpayer dollars for the respective life cycles of both the vehicle and ground systems. Future SpaceOps papers will provide progress on this evolving endeavor.

In only a few years the SLS Program hardware will begin arriving at the Kennedy Space Center. Ground processing of flight hardware will start back up in the VAB in anticipation of the dawn of deep-space human exploration, depicted in **Figure 15**. Opinions vary widely on which missions and destinations the SLS should embark upon. Fortunately, the SLS capabilities, in concert with updated GSDO ground infrastructure, will allow the evolvable vehicle to complete a wide variety of human and science exploration missions. Thanks to the careful consideration of cost, both during the development and for operation of the vehicle, the only considerations need be which missions provide the greatest return of knowledge and scientific/technological advancements to improve our way of life, as well as understand the universe and our place within it.

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