

NASA Space Rocket Logistics Challenges

James R. Neeley¹,
Jacobs ESSSA Group, Huntsville, AL, 35806

James V. Jones²,
Logistics Management Associates, Irvine, CA, 92620

Dr. Michael D. Watson³, Christopher J. Bramon⁴, Sharon K. Inman⁵,
NASA Marshall Space Flight Center, Huntsville, AL 35812

and

Lorraine Tuttle⁶
NASA Kennedy Space Center, FL 32899

The Space Launch System (SLS) is the new NASA heavy lift launch vehicle and is scheduled for its first mission in 2017. The goal of the first mission, which will be uncrewed, is to demonstrate the integrated system performance of the SLS rocket and spacecraft before a crewed flight in 2021. SLS has many of the same logistics challenges as any other large scale program. Common logistics concerns for SLS include integration of discreet programs geographically separated, multiple prime contractors with distinct and different goals, schedule pressures and funding constraints. However, SLS also faces unique challenges. The new program is a confluence of new hardware and heritage, with heritage hardware constituting seventy-five percent of the program. This unique approach to design makes logistics concerns such as commonality especially problematic. Additionally, a very low manifest rate of one flight every four years makes logistics comparatively expensive. That, along with the SLS architecture being developed using a block upgrade evolutionary approach, exacerbates long-range planning for supportability considerations. These common and unique logistics challenges must be clearly identified and tackled to allow SLS to have a successful program. This paper will address the common and unique challenges facing the SLS programs, along with the analysis and decisions the NASA Logistics engineers are making to mitigate the threats posed by each.

I. SLS Design Architecture

NASA's Space Launch System Program (SLSP) is the latest initiative in human space exploration and this ambitious program is challenged to meet significant innovative technical objectives in the midst of a national austere funding environment. The SLS vehicle concept utilizes an innovative "melding" of technologies, key concepts from the family of Saturn launch vehicles used during the Apollo Program, as well as designs and technologies from the more recent Space Shuttle and Constellation Programs. Figure 1 illustrates the SLS planned evolving architecture and Figure 2 shows the initial Block 1 configuration. While the SLSP design solution will evolve by incorporating the latest technology for propulsion, the first flights will make extensive use of heritage hardware to shorten development time and reduce the design cost. The SLS Elements consist of the Stages, Liquid Engines, Booster, Advanced Development, Spacecraft and Payload Integration, and Ground Operations Liaison.

¹ Supportability Engineering/ILS Lead, MSFC Mission Operations Laboratory, Operations Engineering/EO40.

² President, Logistics Management Associates, 19 Woodlawn, Irvine, CA, 92620.

³ System Engineer, System Engineering Management Office, Chief Engineers Office.

⁴ Operations Discipline Lead Engineer, MSFC Mission Operations Laboratory/EO04.

⁵ Integrated Logistics Support Technical Lead, MSFC Mission Operations Laboratory/EO40.

⁶ Logistics Technical Integration Manager, Logistics Development and Integration Branch/GP-L1.

One of the key measures of success for the SLSP is remaining within the overall budget established by Congress while meeting the baselined launch date. NASA has long recognized that the concepts and processes of Integrated Logistics Support (ILS) and Logistics Support Analysis (LSA) provide a significant opportunity to minimize cost of ownership. NASA has established policy mandating program life-cycle logistics support through applicable phases and inclusion of supportability as part of the system's design characteristics to assist in ensuring system availability and affordability.¹

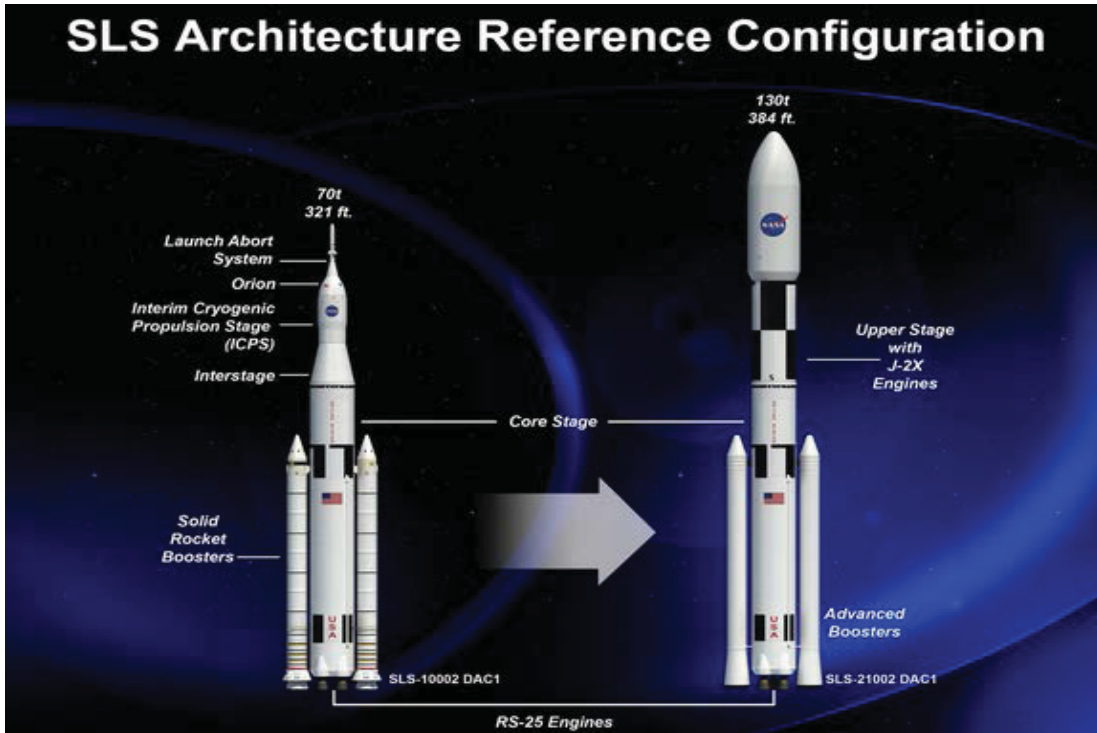


Figure 1. SLS Architecture Evolution.

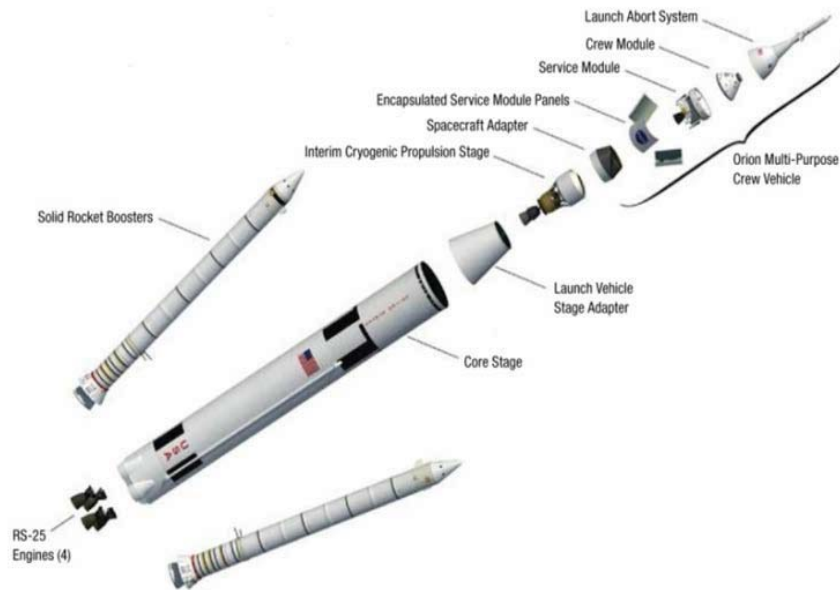


Figure 2. SLS 70 metric-ton Initial Block 1 Configuration, 321 feet tall.

II. Traditional ILS Application

Traditional application of ILS during the design, development, test, and evaluation (DDT&E) of a system typically consists of two different but highly related processes, designing a supportable system and then developing a reasonable, responsive and cost effective support solution for the system.² This approach to ILS has been proven innumerable times by the US Department of Defense (DoD) as being effective and extremely beneficial through reduction of support infrastructures and increases in system operational availability.

Figure 3 illustrates how the expected application of ILS during system DDT&E consists of supportability engineering within the systems engineering process to assure that the system design defined for operation, when used within the mission profile and environmental limitations, will produce a design that required the lowest possible in-service support solution. Then maintenance task analysis (MTA) provides the foundation for development of the physical support resource package necessary to sustain the system over its possibly 30-50 year operational life. One of the basic premises of ILS is that a higher quality system will require far less support when in-service. Increasing system reliability, maintainability and testability, which can increase cost during development, can reasonably result in a much lower cost of ownership by reducing the logistics footprint, i.e. personnel, spares, facilities and other cost drivers, during in-service operation and support.

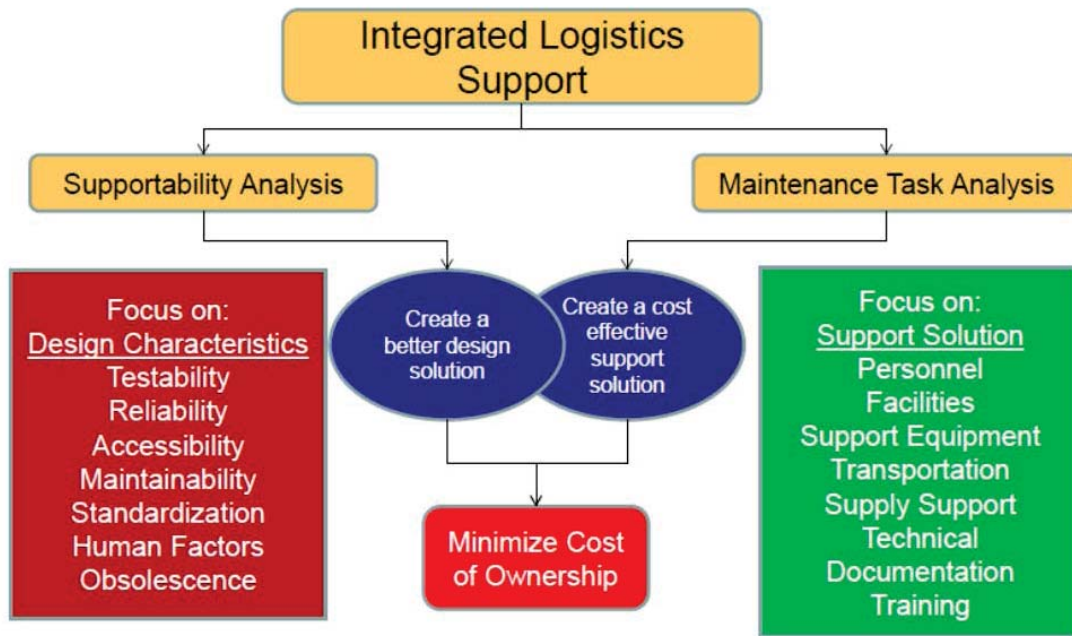


Figure 3. Integrated Logistics Support During System Development.

The specific application techniques and schemes for traditional ILS vary by technology, industry and organization; however, normally the functions shown at Fig. 4 are typically contained in all participants. Supportability engineering normally consists of LSA, human factors integration (HFI) and reliability and maintainability (R&M) in a coordinated approach to design improvement that includes bottoms-up estimates for life cycle cost (LCC). The traditional Logistics Products include; technical manuals or publications (TM/P); initial provisioning of spares and other materials required for maintenance (IP); support equipment, test equipment and tools (S&TE) required for operation and maintenance support; training (TNG) for all associated personnel in operation, support and maintenance; packaging, handling, storage and transportability (PHST) of the system and all support resources; and all facilities (FAC) required for operation, support, maintenance, training or storage. Resultant data is captured and managed in an LSA Record (LSAR) database. The consolidation of all these logistics products results in the logistics footprint required to operate and sustain the system throughout its operational life. The success of this process is measured in terms of operational availability.

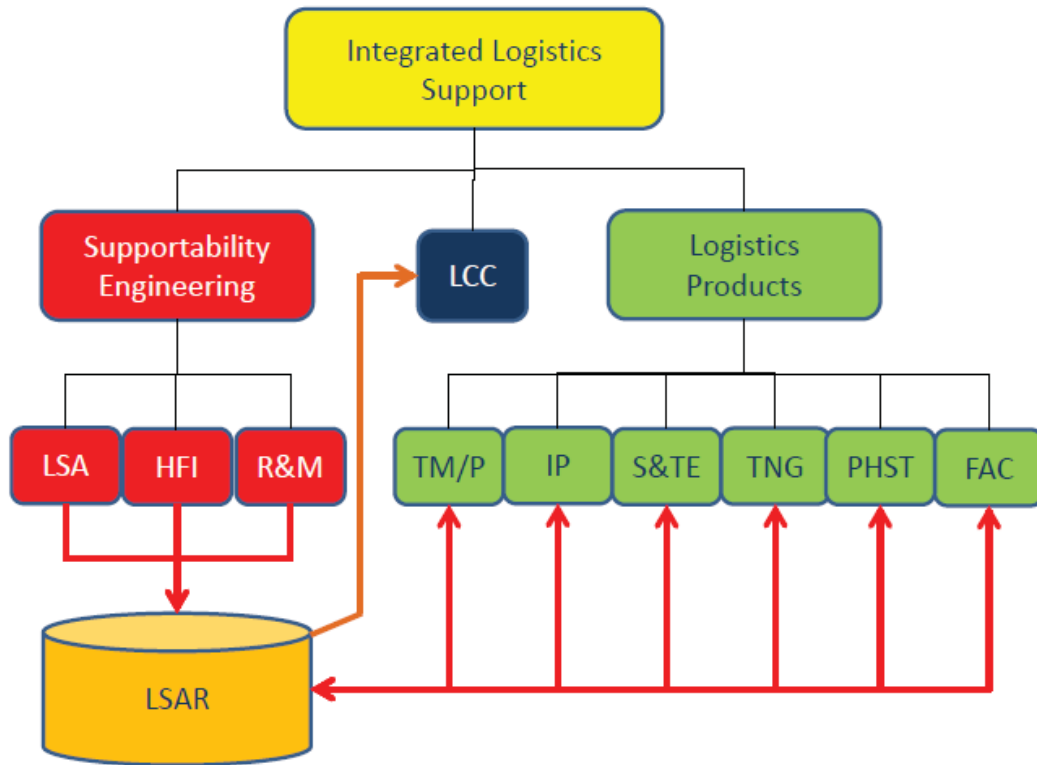


Figure 4. Typical Integrated Logistics Support Functions and Interrelated Processes.

A simple comparison of traditional ILS concepts and processes with the unique circumstances of the SLSP indicates that application must be drastically different to be effective. The SLSP DDT&E phase will have one launch every four years, and each SLS vehicle will have significantly different technology baselines and physical hardware configurations. A large, costly logistics support infrastructure would be impractical and unaffordable. So, the SLSP application of ILS has been adapted to select and maximize those processes that will contribute to the program goals while at the same time taking a significantly different approach to meeting potential physical logistics support requirements. SLSP is performing a comprehensive, but non-traditional ILS program. The remainder of this paper provides specific details of the unique application techniques of ILS on the SLSP to meet the challenges.

III. SLS Challenges and Threats

Space launch vehicle logistics have a complicated flow involving many vendors delivering parts and supplies to manufacturing sites and launch sites. This supply chain is complex and involves several 100 vendors. Saturn V, for example, had over 280 major subcontractors (not counting lower level subcontractors) with over 1000 vendors supplying approximately 3,000,000 parts. Some of these vendors supported more than one stage, delivering components to multiple manufacturing sites.³ Over 100,000 logistical events were estimated for the fabrication of the Saturn V.⁴ This supply chain ultimately relates to many sources to a single site, different from many commercial supply chain models. From the perspective of vendors that support multiple stages, this can appear as a one site to many site support. Mapping all of these relationships leads to a very complex interconnection diagram. This can be simplified by viewing the supply chain as two tiers: vendor to manufacturing site, and manufacturing site to launch site. Figure 5 provides a simple illustration of this complex interconnection.

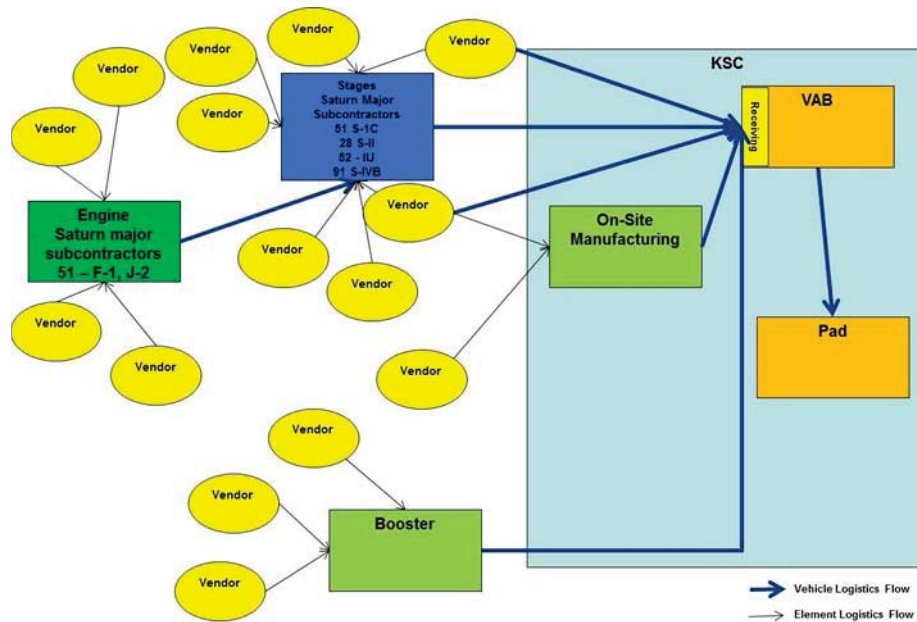


Figure 5. Two Phase Supply Chain.

The first tier of the supply chain is the manufacturing sites, where thousands of parts are assembled and integrated into a vehicle stage or booster. A large portion of vendors support the manufacturing sites directly and the supply chain for each of these sites is large and complex. In some cases one manufacturing site will feed to another. This is the case for engines which feed the stage manufacturing site. Some stage or booster manufacturing can also occur at the launch site. Once the stage or booster has been produced, it is transferred to the launch site. This second tier is less complex than the first tier feeding the manufacturing sites. This tier can also have vendors delivering directly to the launch site for line replaceable unit (LRU) spares and consumables used in the assembly of the vehicle.

There are 3 types of delivery sources to the launch site: external manufacturing sites, internal (to the launch site) manufacturing sites, and vendors. Regardless of the source, each must follow the same property delivery procedures to maintain control of materials and supplies transferred to the launch site facilities.

Tables 1 and 2 list the common and unique challenges and associated threats.

Table 1. Common Challenges and Threats.

Challenge	Threat
Integration of multiple geographically separated programs	Stakeholder communication, conflicting schedules, lack of commonality, gaps in requirements and funding
Integration of multiple geographically separated projects within a program and multiple contactors	Stakeholder communication, conflicting & complex schedules, lack of commonality, gaps in requirements, different goals, lack of flowed down requirements
Funding constraints	Increased risk

Table 2. Unique Challenges and Threats.

Challenge	Threat
Low manifest rates and frequencies (Up to four years apart)	Costly logistics solutions, increased risk for availability of skilled personnel resources
Architecture Block upgrade approach	Delay for operational phase, increased cost for changing support solutions: LSA, resources, sparing philosophy
Mixed new and heritage hardware	Obsolescence, parts marking, commonality
Multiple projects (elements) with individual milestone reviews	Limited personnel resources, design interface issues
Dictated flat funding constraints, no inflation allowed	Increased risk for adequate logistics support

IV. Logistics Support Analysis, Lessons Learned, and Initiatives

LSA and ILS activities have been initiated to mitigate each threat and are contained in Tables 3 and 4 followed by the analysis approach for the evolving vehicle configuration. A tailored set of logistics data requirements was established by the SLSP and allocated to the Elements for results of analyses performed to identify maintenance significant items to include LRUs and associated logistics and maintenance resources required to maintain the flight and ground hardware in serviceable and flight ready condition. The SLSP ILS Team will use this data to identify logistics risks and develop an affordable and cost-effective integrated support solution. Various initiatives and lessons learned are also discussed in this section.

A. Analysis and Activities

Table 3. Common Threats and Analysis/Activities.

Threat	Analysis/Activities
Multiple Programs: Stakeholder communication, conflicting schedules, lack of commonality, gaps in funding.	Cross-Program Logistics Integration Team (LIT) established to provide communication and work concerns/issues
Multiple Projects: Stakeholder communication, conflicting schedules, lack of commonality.	SLSP ILS Team established for integration of projects' schedules, data, and analysis.
Multiple prime contractors: Different goals, lack of flowed down requirements.	Contractors included in SLSP ILS Team activities, tailored Data Requirements Descriptions (DRDs) implemented.
Schedules: Conflicts, complexity.	SLS Integrated Master Schedule (IMS) established with inter-relationships. Logistics Support Date (LSD) concept implemented.
Funding: Increased risk.	Implemented engineering bottoms-up life cycle cost (LCC) and identified program risks for mitigation.

Table 4. Unique Threats and Analysis/Activities.

Threat	Analysis/Activities
Low manifest rates: Costly logistics solutions, increased risk for availability of skilled personnel resources.	Minimal approach for first two flights (2017 & 2021). Phased approach for 30-year life cycle integrated logistics.
Block upgrade approach: Delay for operational phase, increased cost for changing support solutions: LSA, resources, sparing philosophy.	Risk assessments.
Hardware: Obsolescence, parts marking, commonality.	Materials assessment, sustaining engineering planning.
Milestone reviews: Individual project element reviews, limited personnel resources, design interface issues.	Integrated reviews. Element supportability reviews.
Funding: Increased risk for adequate logistics support.	Identification of budget risks.

The SLSP ILS team is conducting LSA for the integrated Block 1 configuration and will document the results in an SLSP LSA Report and related data will be captured in the SLSP LSA Record (LSAR) database. Logistics analyses is tailored to focus on the hardware that is the same across the blocks as depicted in Fig. 6. Analyses of common hardware across the three configurations will provide the greatest opportunity to maximize affordability.

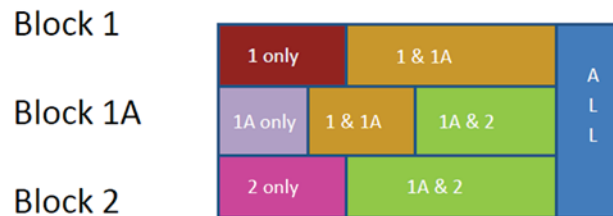


Figure 6. Depiction of Common Hardware Across SLS Configurations

Tailoring of the supportability analyses and logistics engineering efforts should address the specific requirements for each block configuration. Any item that will only be utilized in the Block 1 configuration, which will be for flights EM-1 and EM-2, should address support resource requirements. Maximum use should be made of existing data generated during the original design and development of heritage hardware. The results of this analysis should be a complete identification of all resources that will be required for support of the test flights. The resources will then be assessed to determine the specific items that must be purchased and pre-positioned to reduce risk of non-availability when required. It is envisioned that the items that appear in only Block 1 should be minimally supported with little residual materials for disposition after the second test flight.

The Block 1A configuration will perform the majority of the currently planned operational SLS flights. Heritage hardware will be replaced with new design hardware. Therefore, analyses should focus on investing in the support requirements from Block 1A implementation and beyond. Analyses should initially address design attributes and characteristics that have the potential to improve supportability and lower cost of ownership. Any item that will be in the Block 1A configuration should be subjected to the full range of analyses with intent to improve the design and reduce cost due to support requirements. Full application and documentation of supportability engineering should provide evidence of results and serve as the basis for long term support development and investment.

The Block 2 configuration will perform the last few operational flights starting after Block 1A is completed. Items should be assessed for obsolescence and life time sustainment. New technology insertion and functional upgrades will require these items to be fully documented for sustainment and obsolescence management. These items should be subjected to the same depth of analysis as items appearing in Block 1A integrated task analysis.

A tailored set of logistics data requirements was established by the SLSP and allocated to the Elements for results of analyses performed to identify maintenance significant items to include LRUs and associated logistics and maintenance resources required to maintain the flight and ground hardware in serviceable and flight ready condition.⁵ The SLSP will use this data to identify logistics risks and develop an affordable and cost-effective integrated support solution.

B. Lessons Learned

Lessons learned from recent space programs have been studied for application to the SLSP and progress has been made to apply several lessons learned from the NASA Space Shuttle Program, Space Station Program, Constellation Program, and Ares/Ares 1-X Projects. The Ares I rocket is the most recent similar vehicle to the current SLS, and Ares was the first new design to emerge from NASA in 30 years and was envisioned to be the workhorse of the NASA Constellation Program, which was established to replace the aging fleet of Space Shuttles. Ares I-X was the first design concept demonstrator in the program and was successfully launched on October 28, 2009.

The major logistics focus of the Ares I-X test flight was large element transportation and supplying material and tools to Ground Processing Operations. The development timeline was severely limited, and since Ares I-X was a test flight, in many cases, logistics considerations were not infused into the design.⁶ Maintainability, supportability, commonality, standardization, testability, reliability, and availability were not considered. Operational access and transportability were considered. Most of the “ilities” are not necessarily applicable to a test program since long term sustainment is not an issue, but designers need to be sensitized to materials costs versus application for test programs. For example: Were satellite qualified, radiation hardened tie wraps really necessary for a sub-orbital flight?

There were also numerous supply chain issues because the contractual supply chain responsibilities were not clear. In some cases flight hardware procurements were not compliant with NASA directives. Waivers had to be processed for the flight hardware that did not meet the stringent procurement and quality requirements. Logistics supply support requirements should be defined prior to initiating contracts. The contractual responsibilities should be clearly defined and a logistics support plan should be developed prior to contract initiation.

Real time demands for flight material were constant since material quantities were uncertain because “As Required” quantity designation was used on drawings and parts lists. These shortages caused delays during vehicle processing because ground operations expected to receive the material they needed in minutes or hours, not weeks. In addition to this situation, the procurement representatives experienced conflicting resource requirements once the vehicle was transferred to Kennedy Space Center (KSC) for launch processing. Processes were not established to allow the transfer of material, so the Space Shuttle Program developed a Hardware Transfer Request process to enable transfer of Shuttle material to Ares I-X. The ground operations contractor should have the responsibility to provide real time supply support and material from qualified suppliers for vehicle launch site integration processing and processes and procedures should be established for material transfer between programs and contracts.

Inventory management for material and Ground Support Equipment (GSE) was time consuming and resource intensive. Tracking material location required extensive manual effort. Researching availability of material for each flight element had to be done manually because the inventory information was in separate databases. There was no indication of who was accountable for the parts and, for excess parts, where they should be returned. A comprehensive inventory tracking system is required to provide visibility into inventory location. A web based system and application of automatic identification technology using radio-frequency identification (RFID) should be considered.

Following are summaries of progress for application of lessons learned.

1. *Implemented NASA Agency “Program and Project Life-Cycle Logistics Support Policy”, NASA Policy Directive (NPD) 7500.1C and includes Supportability, ILS and LSA.*
2. *SLSP established an engineering bottoms-up Life Cycle Cost estimating capability.*
3. *SLSP established an ILS Team that includes Program, Elements, contractors, and collaboration with the launch site.*
4. *A Cross-Program Logistics Integration Team (LIT) was established and includes the three NASA Exploration Programs.*
5. *Reliability, Availability, Maintainability, Supportability, Cost, and Testability considered in SLS vehicle design.*
6. *Analysis is being accomplished to consider LRU remove and replace (R&R) steps and required supporting materials, tools and equipment.*

7. *Collaboration is on-going with the launch site for streamlined shipping and receiving processes, marking techniques to ease identification of items, use of a common warehouse, and improved inventory management.*
8. *Flight and ground hardware transfer points, processes, and procedures being addressed.*
9. *Launch processing requirements for materials, fluids, and consumables being worked, to include plans to fund the launch site to provide these common items.*
10. *SLSP is clarifying Supply Chain Management (SCM) which includes the Elements and a subject matter expert study is in-progress.*
11. *Commonality (Standardization) is included as an evolving consideration for materials and parts.*
12. *Supportability Engineering exists as a discipline of Systems Engineering at Program level.*
13. *SLSP Sustaining Engineering is part of early planning.*
14. *Supportability metrics include Launch Availability (LA) and Maintenance Down Time (MDT).*

C. Initiatives

Several initiatives have been implemented to assist in systems engineering and integration of design and development efforts, as well as planning for affordable operations. Following are summary examples.

15. *The SLS ILS Team provides a forum for technical interchange and includes Program and Element supportability and logistics engineers, as well as contractor representatives. The ILS Team focus is on designing an affordable ILS footprint that achieves long term program goals (beyond block 1). SLSP ILS activities integrate and analyze element and vehicle logistics data for ground processing activities at KSC for hardware maintenance and supportability planning.*
16. *SLSP supportability assessments of the SLS Core Stage and Booster Elements' support concepts and maintenance planning have been conducted to determine the extent to which supportability characteristics have been considered and incorporated in the system design, review tasks on potential high maintenance/supply support drivers, recommend ground process improvements for maintenance tasks, and discuss supply support activities and concerns. These assessments are an on-going activity for all SLS Elements.*
17. *A common LSAR database, PowerLOG-J, has been established with the SLSP and the launch site to allow transfer, integration, and report generation of logistics data. SLSP has developed and is implementing a tailored LSAR Database Style Guide, to include use of logistics control numbers (LCNs). The LSAR Style Guide enables consistency and commonality in logistics data being developed independently by various organizations that will ultimately be integrated into a single SLSP support knowledge base.*
18. *An existing water barge is undergoing modification for use as the primary transport mode for large flight and ground hardware which initially is the Core Stage.*
19. *Supportability design considerations and operational support planning are being applied with equal importance to both Ground Support Equipment (GSE) and flight hardware.*
20. *The current SLS integrated vehicle fault management (IVFM) model is being developed to provide extensive failure mode detection capability against the established launch commit criteria (LCC) and planning efforts are underway that propose to evolve the model to include fault isolation to a reasonable ambiguity group of 4-5 LRUs to enable performance of off-nominal repair during test or pre-launch activities at the launch site.*
21. *Established the Logistics Support Date (LSD) as a management approach and tool to assure that all physical support resources and the support infrastructure required to support a system are in place and ready to provide any support prior to actual arrival of the system to be supported. After assessment of delivery schedules to the launch site for SLS flight and ground hardware based on the September 15, 2013 integrated master schedule, April 15, 2017 is determined to be the current LSD for the overall SLSP. Each Element of the SLSP has differing LSD dates based on individual schedule and contractual requirements. The guidance for estimating a LSD is delivery date minus 90 days for flight hardware and delivery date minus 60 days for ground hardware.*

V. Decisions

Decisions to determine the application of traditional ILS technologies and methodologies are driven by NASA policy and SLSP implementation of policies for management and control, goals and objectives, cost constraints, and mission launch schedules. Primary influencing factors include seeking to maximize use of contractor best practices with limited program-imposed management and control plans, recurring DDT&E phases for architecture block upgrades, flat budget with no inflation allowance, heritage hardware, and employing a risk-based approach for Element and contractor insight/oversight in an SE&I environment. Following are major decision points.

A. Tailor Traditional ILS Approach

1. *Ensure the vehicle support infrastructure is adequate, has everything we need....nothing we don't.*
2. *Ensure the design is successful within cost constraints.*
3. *Integrate ILS efforts across the Elements for support of vehicle assembly and integration activities.*
4. *Perform Logistics Support Analysis (LSA) for the integrated launch vehicle.*
5. *Implement supportability engineering and integrate reliability, maintainability, testability, affordability, safety, commonality, human factors, and availability.*
6. *Establish ILS within the SE&I Operations Discipline Lead Engineering (ODLE) organization.*

B. Implement Life-Cycle Logistics Support

C. SLSP LSD for Initial Flight is April 15, 2017

D. Identify and Mitigate Supportability Risks for Block 1

Conclusion

The SLSP has taken a measured approach in applying both traditional and innovative concepts of supportability and logistics engineering. As indicated in this paper, the ILS Team has had the foresight to assess applicability, study past experiences, and develop unique solutions where necessary. The SLSP is proving to be a clear example where traditional logistics ideas can be molded, modified, and adapted to fit a totally different situation and still be expected to provide the same benefits of increased operational availability for a lowered cost of ownership.

References

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- ¹ NASA Logistics Management Division, NASA Policy Directive (NPD) 7500.1C, "Program and Project Life-Cycle Logistics Support Policy", Washington, D.C., 2012, pp. 1.
 - ² US Department of Defense, Assistant Secretary of Defense for Logistics and Material Readiness, "Product Support Manager Guidebook", Washington, D.C., 2011, pp. 10, 37-38.
 - ³ Bilstein, Roger E.; "Stages to Saturn", NASA SP-4206. 1996, pg. 288.
 - ⁴ Bilstein, Roger E.; "Stages to Saturn", NASA SP-4206. 1996, pg. 297.
 - ⁵ NASA Space Launch System Program (SLSP), "SLSP Data Requirements List", SLS-RQMT-018, Data Requirements Description (DRD) 1406OP-032, "Element Logistics Support Data", Marshall Space Flight Center, Huntsville, AL, 2013.
 - ⁶ NASA Ground Operations Integrated Product Team, Logistics Integration Team, "Ares 1-X Logistics Lessons Learned", Kennedy Space Center, FL, 2012.