Booster Obsolescence and Life Extension (BOLE) for Space Launch System (SLS)

Mark E. Tobias
David R. Griffin
Joshua E. McMillin
Terry D. Haws
Michael E. Fuller
Northrop Grumman Space Systems
P. O. Box 707
Brigham City, UT 84302-0707
Mark.Tobias@ngc.com
David.R.Griffin@ngc.com
Joshua.Mcmillin@ngc.com
Terry.Haws@ngc.com
Mike.Fuller@ngc.com

Abstract – **A human mission to the moon and Mars is the stated space exploration goal of the United States and the international community. To achieve these goals, NASA is developing the Space Launch System (SLS) and the Orion crew capsule as key elements in the architecture for missions to the moon and Mars. As part of the SLS Booster Obsolescence and Life Extension (BOLE) program, Northrop Grumman Space Systems is working to address booster obsolescence issues in design and manufacturing. The upgraded boosters will also provide increased performance that will benefit future lunar campaigns, science missions, and the eventual Mars campaign.**

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1. INTRODUCTION

Northrop Grumman Space Systems is currently working to support NASA in achieving the mission of deep space exploration by providing the booster stage for the Space Launch System (SLS). The selected SLS architecture removed systems necessary for booster recovery and reuse that were employed during NASA's Space Shuttle program. There are eight flight sets of hardware (steel cases, structures, etc.) available for reuse, after which parts and processes will need to be redesigned, requalified, and rebuilt. The SLS Booster Obsolescence and Life Extension (BOLE) program is NASA's plan to continue use of the current SLS system through redesigned hardware that can be produced to support missions for the foreseeable future. As part of the BOLE program, overall architecture and design is being heavily assessed to ensure maximum performance while improving processing.

Human exploration beyond low earth orbit (BEO) has been a long-term goal of the United States and the international community since the end of the Apollo program. The current administration of the United States has further emphasized the importance of BEO missions with Space Policy Directive #1 directing NASA to return to the Moon followed by crewed missions to Mars [1]. To achieve this goal, NASA has been developing the Orion crew capsule and SLS as key elements in the architecture designed to advance human spaceflight from our current capability in low earth orbit (LEO) to eventually landing humans on Mars [2]. This ambitious exploration campaign is being undertaken using an incremental approach, as shown in Figure 1.

As shown, the initial steps have already begun, with research being carried out in LEO at the International Space Station. The next steps push into cislunar space in 2020 with the launch of the first SLS and Orion spacecraft. SLS and Orion enable the delivery of crew, supplies, science equipment, and other payloads to a special lunar orbit called the near rectilinear halo orbit (NRHO), where the Gateway Lunar Orbital Platform will be located. The Gateway will enable research into technologies and procedures for living farther away from Earth. The initial pieces of the Gateway – the power and propulsion element (PPE) and the habitation and logistics outpost (HALO) – are currently in development [3]. Landings on the lunar surface then stage from the Gateway, enabling exploration of multiple locations, as well as refueling and sample processing facilities [4]. These missions provide practice in

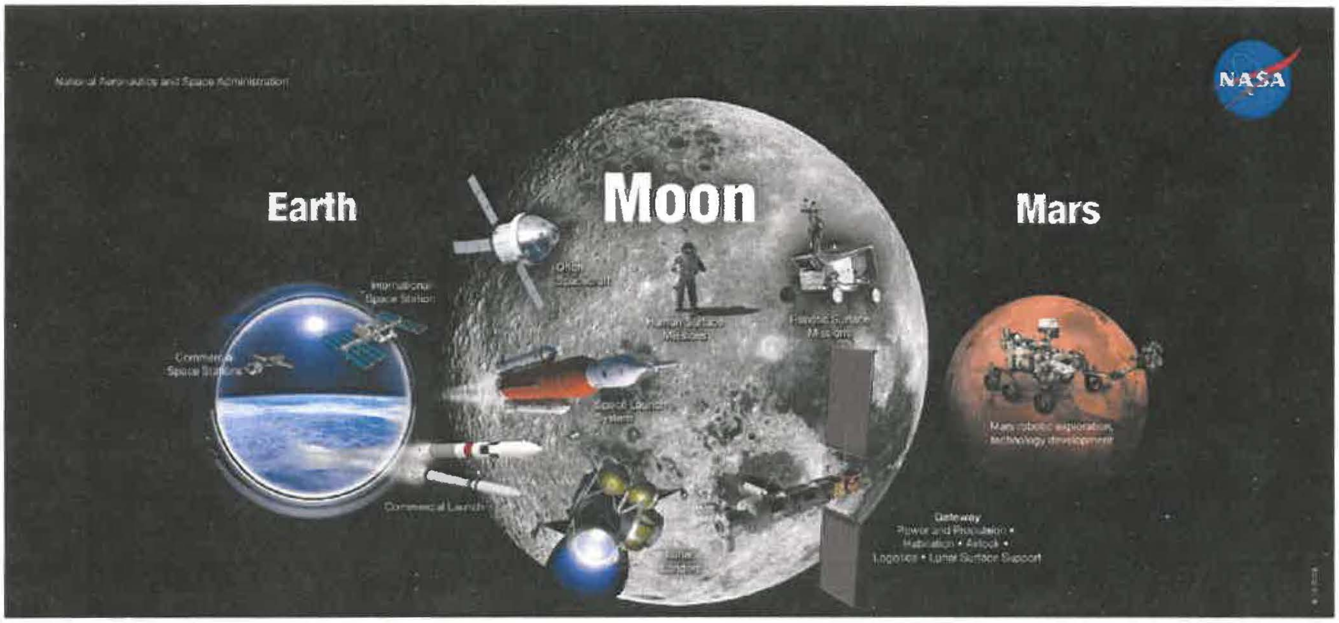

Figure 1. Incremental Approach to Mars Exploration. Source: NASA

living and working on the surface of another body, lessons that will eventually be useful to Mars surface missions.

Building on Gateway and lunar experiences, NASA would finally have the experience to begin initial human forays into the Martian system. The initial mission will be a human orbital mission with attendant systems to allow for direct human exploration of the Martian moon Phobos, as well as the telerobotic exploration of the Martian surface, utilizing either prepositioned robotic assets or assets that are brought along with the crew. Future missions to Mars may involve the establishment and buildup of infrastructure to enable multiyear long human exploration and in-situ resource production.

This approach is made possible by the heavy-lift capability of SLS, necessary to deliver the large components required to live in space, land on the moon, and eventually travel away from Earth's vicinity.

This paper discusses the progress that has been made on BOLE, how BOLE takes advantage of commonality with other Northrop Grumman programs, and how BOLE will improve the capability of SLS to help ensure NASA meets its ambitious goals of sending humans into deep space.

2. SLS Capabilities and Details

SLS is the keystone heavy-lift vehicle for the lunar and Mars campaign. SLS consists of a liquid oxygen/liquid hydrogen powered core with two solid rocket boosters, designed and built by Northrop Grumman Space Systems (formerly Orbital ATK). The SLS boosters are based on the reusable solid rocket motor (RSRM) design built for the Space Shuttle, using many of the same technologies, including the heritage steel cases. The core is powered by the RS-25, initially using remaining Space Shuttle main engines followed by non-reusable versions of that engine. The initial Block 1 configuration includes the Interim Cryogenic Propulsion Stage (ICPS), a liquid oxygen/liquid hydrogen stage powered by a single RL-10 engine based on the Delta IV cryogenic second stage. The vehicle is topped by a 5.4-meter fairing in the cargo configuration.

The first mission of Block 1, labeled Artemis 1, is currently scheduled to launch in late 2020 for an uncrewed test flight around the moon and back [5]. A crewed mission will follow in 2022 [5].

SLS then evolves to the Block 1B configuration with a new, more powerful 8.4 m diameter Exploration Upper Stage (EUS), as shown in Figure 2, powered by four RL-10 engines, which will replace the ICPS. The addition of the EUS gives SLS added payload capability, especially for BEO missions.

The crewed variants of SLS will utilize the Orion crew capsule to transport astronauts to their intended destination. Along with delivering Orion to cislunar destinations, the Block 1B vehicle has additional payload capability. This capability will be utilized to deliver co-manifested payload (co-manifested with Orion) carried inside the payload attachment hardware. Figure 2 shows a cut-away of the top of SLS, including the Orion, with an example of a

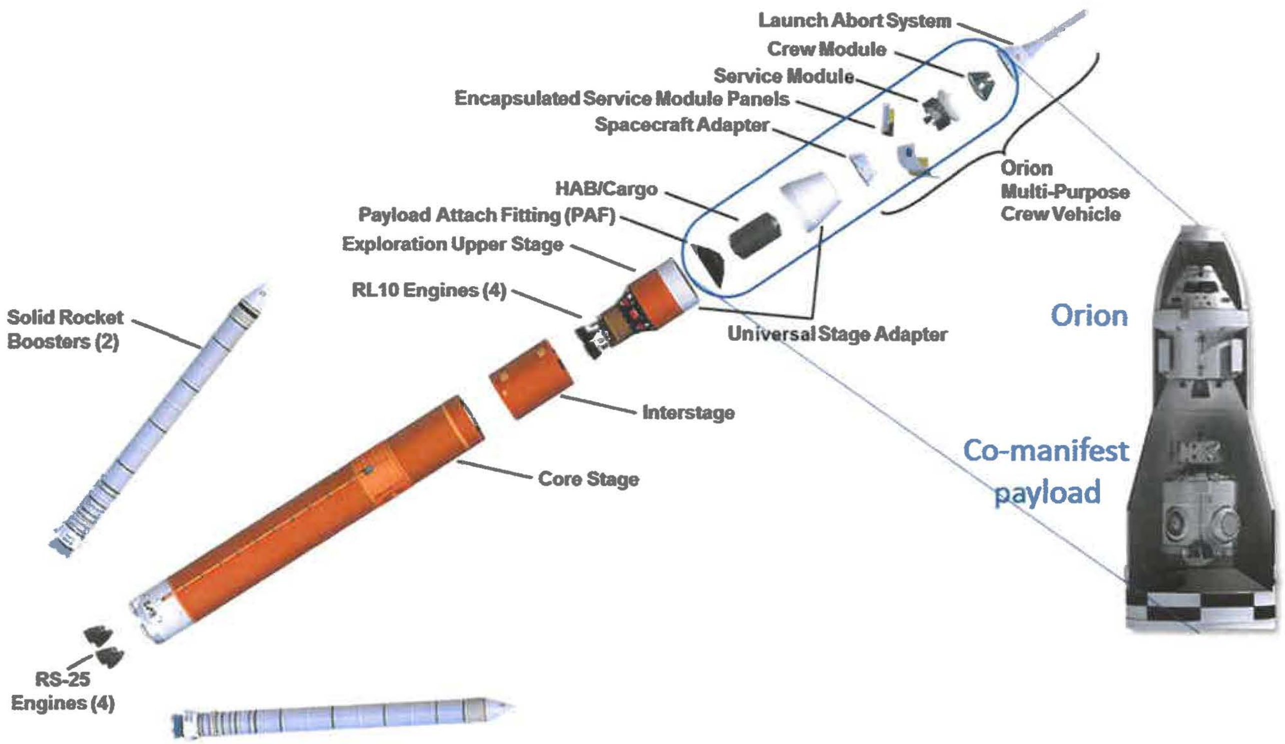

Figure 2. Expanded View of SLS Block 1B, Crew Configuration, and Cutaway Showing Orion and Co-manifest Payload. Source: NASA and Boeing Corporation

co-manifest payload inside the universal stage adapter. Co-manifesting payload with Orion provides additional flexibility in achieving human exploration, operations, and science objectives on any given mission.

For the cargo variant, Block 1B will replace the 5.4 m fairing with a new 8.4 m fairing, with a possibility of evolving to a 10 m fairing if the need arises.

Based on trajectory models, SLS Block 1B configuration can deliver 36.9 mT of payload to NRHO. Of this payload, 27.2 mT is assumed to be Orion, allocating 9.7 mT for co-manifested payload. It is assumed that Orion would provide the ΔV to insert from an initial translunar insertion (TLI) orbit into NRHO.

SLS Block 1B can also deliver 41 mT of cargo-only payload to TLI. As with the crew configuration, the payload is assumed to be responsible for its own orbital insertion burns.

3. BOLE Design Changes

The major BOLE design deltas from current SLS production, shown below in Figure 3, are as follows:

Motor Design Updates

- Composite case with industry-leading composite joint and fiber technology resulting in nearly 30% weight savings and improved joint functionality to replace obsolete steel segments that are no longer cost effective to produce
- Upgraded hydroxyl-terminated polybutadiene (HTPB) propellant – the industry standard – to handle higher strain levels inherent to the composite case and to eliminate reliance on the five-segment reusable solid rocket motor (RSRMV) unique polymer system
- Wound Elastomeric Insulation® (WEI) with newer more cost effective materials to improve processing and compatibility with new propellant
- New nozzle optimized for use with new propellant and enhanced vehicle performance

Improved Booster Structures and Thrust Vector Control (TVC)

- Updated booster structures to address obsolescence, simplify processing, and interface with updated motor design
  - Combined nose cone and frustum
  - Optimized forward skirt with increased structural capability
  - Simplified systems tunnel architecture designed for BOLE systems

Figure 3. BOLE Design Changes Overview

  - Improved booster-to-core attach and in-flight booster separation systems
  - New aft skirt designed for manufacturability and load path efficiency
- Electric thrust vector control (eTVC) system to replace heritage TVC system and reduce use of hazardous materials to simplify ground processing at Kennedy Space Center (KSC) and address obsolescence of legacy technology

These changes address the current obsolescence issues and help streamline production at both Northrop Grumman's facilities and at the KSC launch site – while providing an added benefit of increased performance as compared to the current SLS boosters.

4. Progress on BOLE

Over the past two years, significant progress has been made on the BOLE booster design efforts. One combined SLS vehicle design analysis cycle (DAC) has been performed and the second cycle is currently underway. Multiple trade studies have been completed to solidify the architecture. Component designs are maturing to a point where long-lead procurement efforts have begun. The proposal for the full design, development, test, and engineering contract is underway with the first expected use to be with the ninth launch of NASA's SLS.

Detailed design of the forward booster structures has matured to ensure adequate strength to carry the higher loads associated with the significantly higher thrust levels. Recent testing on the core stage inter-tank structure indicates that the existing core stage design will handle the expected increase in booster loads.

A new cylindrical launch mount has been designed to reduce the mass associated with the aft skirt. The Space Shuttle heritage skirt contained significant structural members to carry the load through four vehicle support posts on the mobile launcher. The cylindrical launch mount distributes that load more uniformly around the booster resulting in a significant improvement in structural mass efficiency for the aft skirt that will fly with the vehicle. Preliminary sizing, loads, and lift-off clearance assessments are complete and discussions on the operations impacts and implementation of the design are underway. Mobile Launcher 2 is being designed such that it can accommodate the Block 1B vehicle with either the heritage aft skirt or the new cylindrical launch mount with minimal reconfiguration efforts.

The ballistic design of the new BOLE booster has gone through significant optimization to ensure NASA objectives of additional payload are met while minimizing overall vehicle impacts. The resultant thrust trace of the new booster is shown in Figure 4. The first full-scale BOLE propellant mix has been completed and detailed material characterization is underway. This propellant is an HTPB with improved energy density relative to the heritage polybutadiene acrylonitrile (PBAN) propellant used on the heritage Space Shuttle and SLS programs. The propellant technology has been successfully fielded in the CASTOR® series motors that have been used for the last three decades.

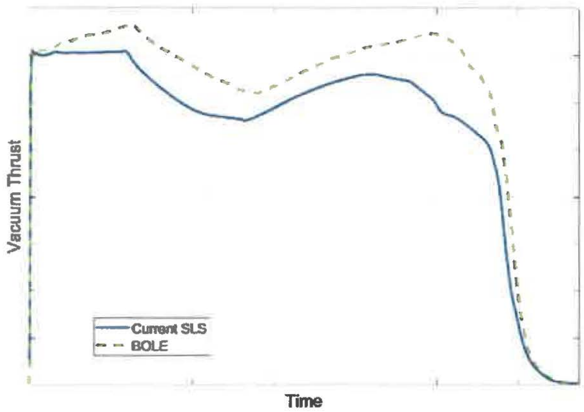

Figure 4. BOLE vs Current SLS Booster Thrust

The BOLE nozzle design has been matured through multiple iterations to ensure success. These designs have been analyzed and indicate acceptable performance, with significant improvements in processing, reduced part count, and reduced gimballing stiffness. The nozzle design analyses have been completed sufficiently that procurement activities of metal forgings has begun. Multiple subscale motor firings have been completed to evaluate ablative performance of several candidate materials for the nozzle liner. Additionally, recent full-scale motor firings are providing valuable information on material performance in full-scale environments.

Significant progress has been made towards creating a state-of-the-art mass efficient pressurized case design. This design has used lessons learned from the first combined SLS vehicle DAC to provide a case that will allow significantly increased internal loads and still minimize loads impacts on the overall vehicle at approximately the same mass as the heritage design. An area of emphasis for the case design has been in seals design, and the team has developed sealing systems that are not only mass efficient, but have sealing capability that is significantly improved over heritage RSRMV designs. Subscale testing on case materials and joint configurations has been highly successful in demonstrating the structural performance of the case design. Procurement of metal forgings has begun. Of particular note, the required forgings have been sized to enable domestic production.

Required modifications to SLS avionics boxes have been defined as well as initial layout configurations for the forward skirt avionics. The aft skirt eTVC system and its associated control boxes and batteries are largely off-the-shelf items that lean heavily on development already completed by our commercial programs. The first demonstration motor for BOLE is expected to use the same thrust vector control hardware already qualified for use in commercial ground tests.

5. BOLE Commonality with OmegA™

During the development of BOLE, Northrup Grumman has been focused on leveraging the investments made in the OmegA vehicle to reduce the long-term program costs and improve technology and manufacturing readiness levels. The investments in the OmegA vehicle have been substantial, and have provided significant learning opportunities for all aspects of design and manufacturing of large rocket motors made using composite fiber technology.

To date, the OmegA has achieved multiple milestones, including:

- Critical design review
- Nine motor segments successfully fabricated through case wind
- Successful structural qualification and burst test of the composite segment design
- Five propellant segment castings – two with inert propellant and three with live propellant
- eTVC system qualification
- Successful ground test of the C600 motor design – May 2019
- Begun launch site integration at KSC

Currently, the program is on track for a ground test of the C300 upper stage design in February 2020. A pictoral display of some of the OmegA program accomplishments is shown in Figure 5.

Learnings from these activities are improving the readiness posture of BOLE as the team progresses towards initial ground test motor fabrication. In addition, the BOLE boosters are built on learnings successfully employed in fielded systems such as Titan Solid Rocket Motor Upgrade, and Graphite-Epoxy Motor (GEM) programs.

Figure 5. OmegA Paving the Way for BOLE

6. BOLE Empowers SLS Missions

As mentioned above, SLS will continue to evolve into a more and more capable vehicle. The evolutionary path is shown in Figure 6. The first mission will launch on the Block 1 configuration. The EUS will be added, increasing the payload capability. The current RS-25 inventory will be expended, and the non-reusable version will offer increased performance. Then the current inventory of steel booster cases will be expended, and BOLE will further empower additional capability. Based on our trajectory models, the BOLE boosters provide at least 3 mT of additional TLI performance. That additional capability will be useful for all NASA missions using SLS going forward.

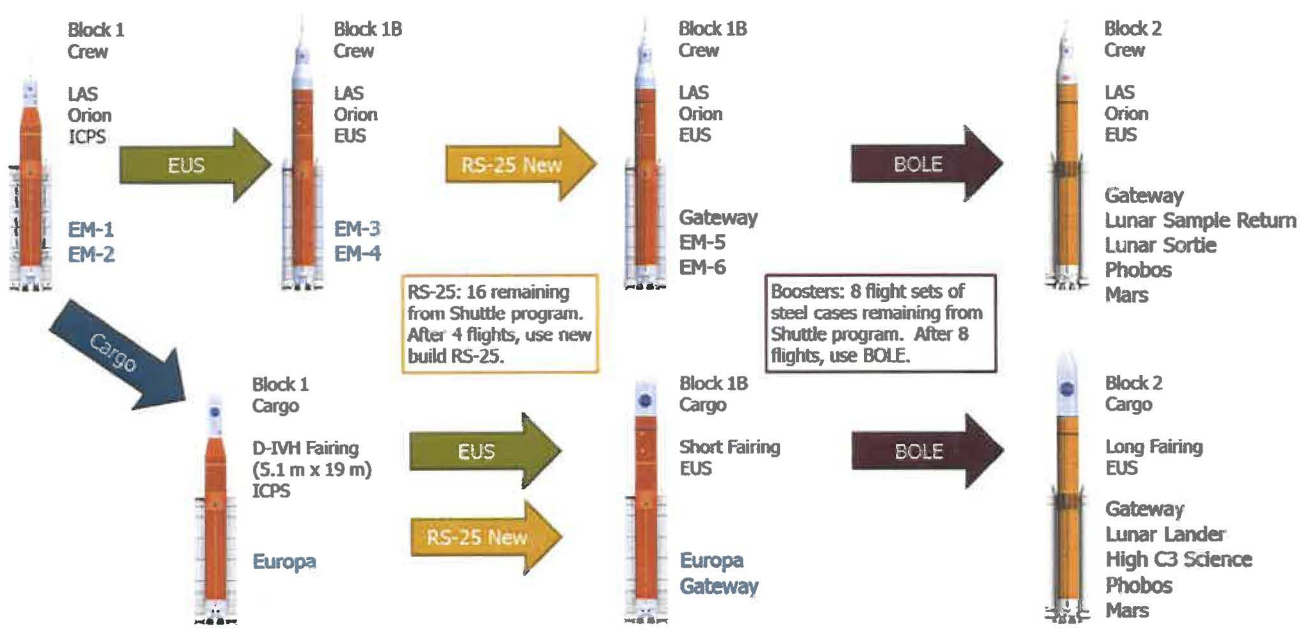

Figure 6. SLS Configuration Evolution

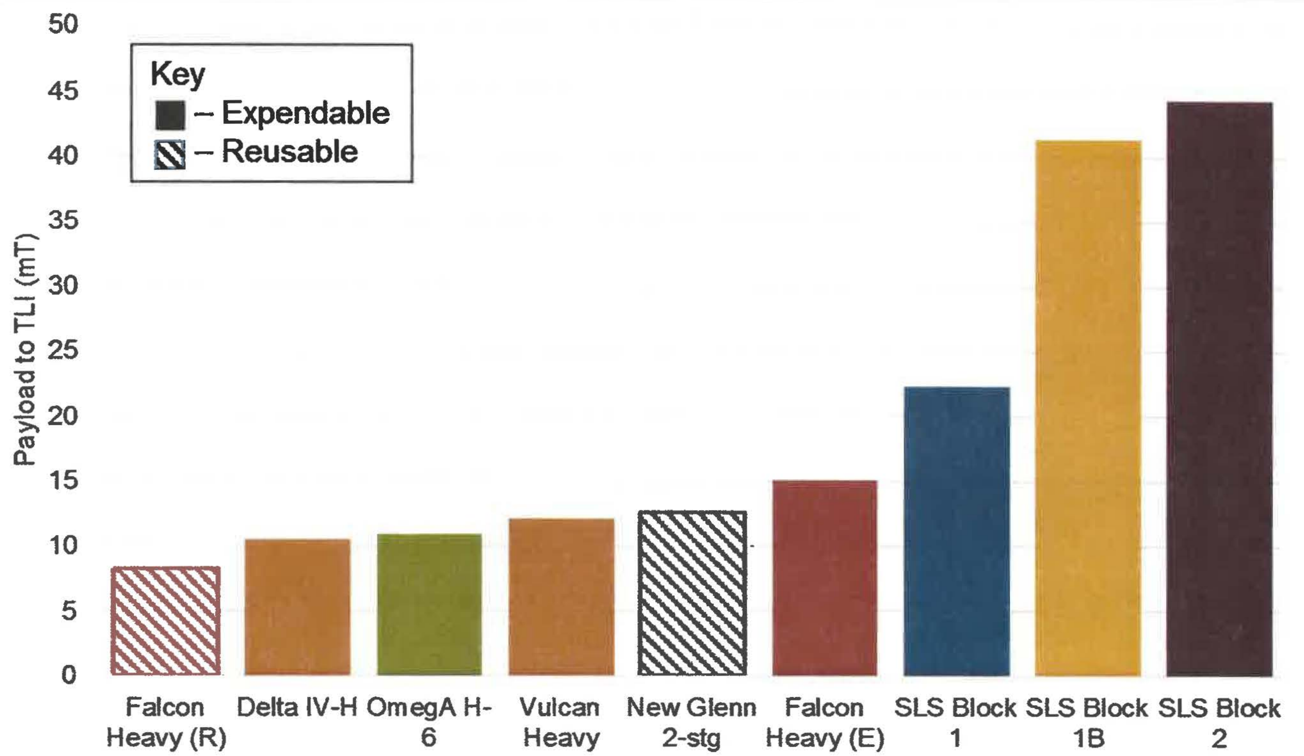

Figure 7. Payload to TLI comparing SLS and Other Heavy Launch Vehicles

Empowering the Lunar Campaign

The evolving SLS capability will support the upcoming lunar campaign. Figure 7 shows the payload to TLI for the SLS cargo configurations, compared to other heavy launch vehicles. SLS Block 1B provides significantly more payload to the moon, and Block 2 improves that capability further. These increased payload values are especially useful for delivering large payloads, including large habitats for the Gateway, large lunar landers, lunar surface habitats, and other lunar architecture.

SLS payload mass capability allows these large payloads to be launched in a single piece. SLS Block 1B also has the advantage of the 8.4 m diameter fairing, allowing for more payload volume. More payload mass and volume leads to fewer in-space assembly and unfolding operations, reducing complexity of component design and operations. SLS is thus the cornerstone of the continuing lunar campaign.

Empowering the Mars Campaign

The Mars campaign will similarly aggregate at the Gateway, meaning that the added payload to TLI provided by BOLE will also greatly benefit the Mars campaign. The initial Mars mission will likely be a Phobos rendezvous mission. While that mission does not require a Mars lander or ascent vehicle – those will come later – it still requires the Deep Space Transport (DST), as well as the Phobos Habitat Module and the fuel and supplies necessary for the three-year mission. The added capability of SLS with BOLE allows for more mass to be available for the mission.

And for eventual follow-on missions to the surface of Mars, SLS with BOLE will be better able to lift the lander and Mars Ascent Vehicle that the crew will need to access the surface and return safely.

Empowering Science Missions

Along with the benefits to the crewed lunar and Mars missions, BOLE also brings benefits to science missions launched on SLS. For example, using SLS allows for direct insertion trajectories for outer planet missions, reducing the time of flight by removing gravity assist flyby maneuvers.

Outer planet missions require significantly more departure energy (C_3) than missions to the moon or Mars, as shown in Table 1. Adding BOLE increases SLS's capability to these high C_3 missions.

Table 1. Destinations and Typical Departure C_3 [6]

Destination	C_3
Moon	-1 km^2/s^2
Mars	+10 km^2/s^2
Jupiter	+85 km^2/s^2
Saturn	+105 km^2/s^2
Uranus	+130 km^2/s^2

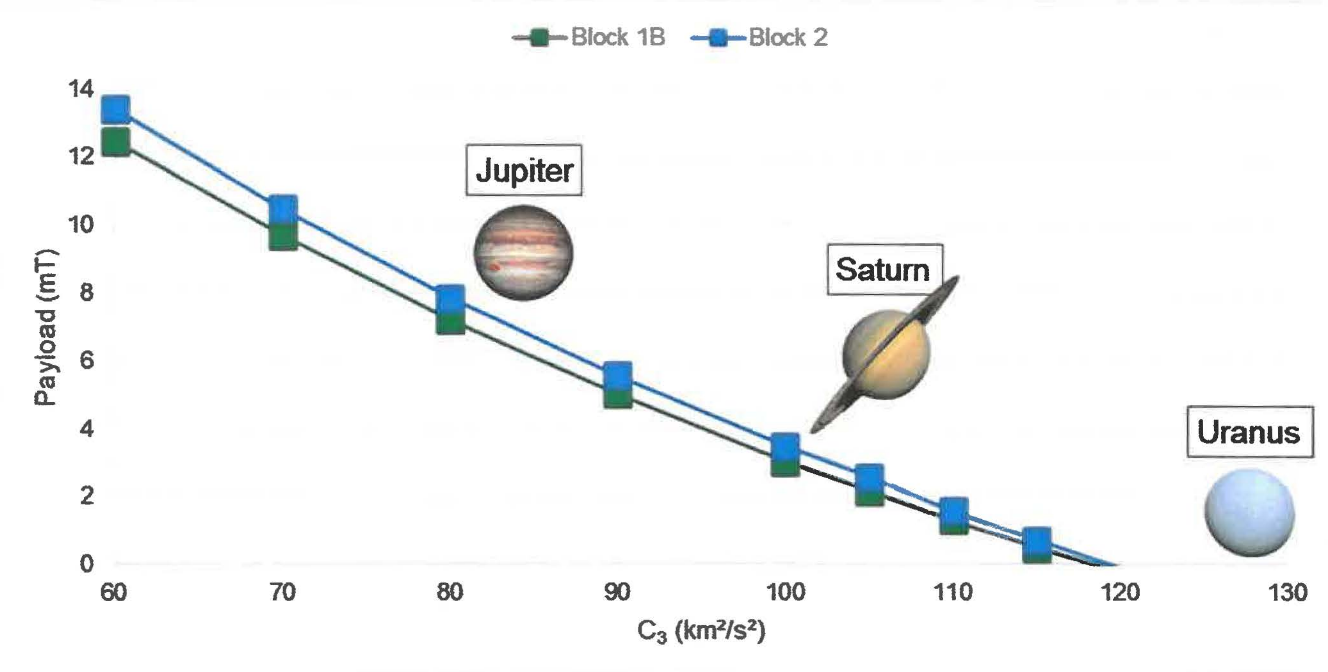

Figure 8. SLS Block 1B and Block 2 Payload Capability to Mission C3 (Planet graphics courtesy NASA [7-9])

Figure 8 shows the payload capability of SLS Block 1B and Block 1B with BOLE to various departure C_3. For a direct departure to Jupiter, adding BOLE improves SLS payload capability by about 10%. To Saturn, the improvement is about 20%. This means more spacecraft mass – either more propellant for longer missions or more scientific instruments or both.

7. Summary

The flexibility of the SLS vehicle to transport crew, cargo, or both facilitates the exploration of cislunar space, the lunar surface, and eventually Mars. BOLE will resolve the obsolescence issues associated with the use of the heritage Space Shuttle hardware. Once the BOLE booster is fully developed, significant new mission space is unlocked for planners to enable lunar and Martian missions as early as 2029. Additionally, BOLE will build off of commercial best practices and materials while utilizing existing infrastructure to produce a booster that will increase the overall capabilities of the SLS launch vehicle. By utilizing standard processes and materials, future obsolescence issues will be minimized. The BOLE booster is one additional step on the SLS evolution path, making it an ever more capable heavy-lift launch vehicle that will propel us to the moon, Mars, and beyond.

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BIOGRAPHIES

Mark E. Tobias *has nearly 30 years experience in a variety of design, analysis, and leadership positions. These positions include assignments in bolted joint design, ignition system design, motor performance grain design and analysis, propellant formulation, systems engineering, post-flight assessment, and testing. His leadership experience includes project engineering, management of frontline engineering groups, Systems Integration Team Chief, and most recently SLS Booster Deputy and Advanced Booster Chief Engineer. He has either been a significant contributor to or leader for several major propulsion system development activities, including ETM-03, Five-Segment Reusable Solid Rocket Motor (RSRMV), Ares I-X, Ares I, Advanced Booster NASA Research Announcement (NRA) and SLS. As SLS Deputy and BOLE Chief Engineer, Mark is responsible for technical execution of the SLS Booster project and development of an evolved booster eliminating future obsolescence challenges. He has also served in a variety of business development and technical proposal lead roles.*

David R. Griffin *received his BS in chemical engineering from Brigham Young University in 2004. He joined Northrop Grumman Space Systems in 2004 working on insulation development for the now retired Space Shuttle booster. His background includes insulation and propellant material development and characterization and rocket motor performance analysis. He has spent the last two years as a principal investigator for Northrop Grumman Space Systems' efforts on BOLE motor design.*

Joshua E. McMillin ***received his BS*** *in mechanical engineering from Purdue University in 2000. He joined Northrup Grumman Space Systems in 2000. He started in the Ballistics and Grain Design Team and has supported the preliminary design of all Northrop Grumman Space Systems' large segmented solid rocket motor designs supporting NASA programs since 2000. He has also served as a science and English educator for grade school students in Maldives. He currently supports the BOLE program as the Chief Booster Architect.*

Terry D. Haws *received his BS and MS in mechanical engineering from Brigham Young University in 1997 and 1999, respectively. He worked for Pratt & Whitney for five years modeling jet engine performance before joining Northrop Grumman Space Systems in 2005. He performs conceptual design and analysis, trajectory modeling, and interplanetary mission modeling and is a licensed professional engineer and a senior member of the American Institute of Aeronautics and Astronautics.*

Michael E. Fuller *received his BS in ceramic engineering and MS in materials science and engineering from the Ohio State University in 1992 and 1995, respectively. He worked for 10 years at a small materials development company prior to joining Northrop Grumman Space Systems in 2005 as a research scientist. He has spent the last four years leading Northrop Grumman Space Systems' efforts with industry partners and NASA on the Journey to Mars. He is currently a Senior Member of the American Institute of Aeronautics and Astronautics.*