SSME to RS-25: Challenges of Adapting a Heritage Engine to a New Vehicle Architecture

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Abstract

A key constituent of the NASA Space Launch System (SLS) architecture is the RS-25 engine, also known as the Space Shuttle Main Engine (SSME). This engine was selected largely due to the maturity and extensive experience gained through 30-plus years of service. However, while the RS-25 is a highly mature system, simply unbolting it from the Space Shuttle and mounting it on the new SLS vehicle is not a “plug-and-play” operation. In addition to numerous technical integration and operational details, there were also hardware upgrades needed. While the magnitude of effort is less than that needed to develop a new clean-sheet engine system, this paper describes some of the expected and unexpected challenges encountered to date on the path to the first flight of SLS.

1. Introduction

Following the cancellation of the Constellation program and retirement of the Space Shuttle in 2010-11, NASA initiated the Space Launch System (SLS) program to provide next-generation heavy lift cargo and crew access to space. A key constituent of the SLS architecture is the RS-25 engine, also known as the Space Shuttle Main Engine (SSME). The RS-25 was selected to serve as the main propulsion system for the SLS core stage in conjunction with the 5-segment solid rocket boosters, also based on Shuttle hardware. This selection of the RS-25 was largely based on the maturity and extensive experience gained through 135 missions, almost 3,000 ground tests, and over 1 million seconds total accumulated hot-fire time. In addition, there were also 16 flight engines and 2 development engines remaining from the Space Shuttle program that could be leveraged to support the first four flights.

During the length of its 30-year service, the RS-25 has been evolved through periodic block upgrades to improve its performance, reliability and safety. However, while the RS-25 is a highly mature system, simply unbolting it from the Space Shuttle boat-tail and installing it on the new SLS vehicle is not a “plug-and-play” operation. In addition to numerous technical integration details involving changes to significant areas such as the environments, interface conditions, technical performance requirements, operational constraints and so on, there were other challenges to be overcome in the area of replacing the obsolete engine control system (ECS) and executing the testing program. While the magnitude of accomplishing this effort was less than that needed to develop and field a new clean-sheet engine system, the path to the first flight of SLS has not been without unexpected challenges.

1.1 SSME Legacy

The RS-25 is pump-fed staged-combustion rocket engine burning liquid oxygen (LOX) and liquid hydrogen (LH_2) to produce 2279 kN of vacuum thrust. Primary components involve two low-pressure turbopumps feeding into two high-pressure turbopumps supplying propellants to the combustion devices, including two preburners , the main combustion chamber and nozzle. The preburners are independently controlled to provide variable thust and mixture ratio. In addition, the system was designed to be reusable, providing a certified service life of 55 starts and 27,000 seconds. The fuel-rich staged combustion cycle provides high performance, making it an attractive candidate in many vehicle trades for the SLS and prior conceptual vehicle studies. Figure 1 shows an oblique view of the RS-25 and major components.

Development of the RS-25 (aka SSME) was started by Rocketdyne in 1972 and first flown on the STS-1 Space Shuttle mission in 1981. The Space Transportation System (STS) shipset involved three RS-25s installed in the boat-tail of the orbiter. During the STS program, Rocketdyne operated 74 development engines and 83 flight engines to accomplish an extensive flight and test record. Its history has been extensively documented[1], and the behavior of the engine system is thoroughly understood, repeatable, and predictable. Its legacy is valued as a key contribution to the rapid development of the SLS system toward flight certification and operation.

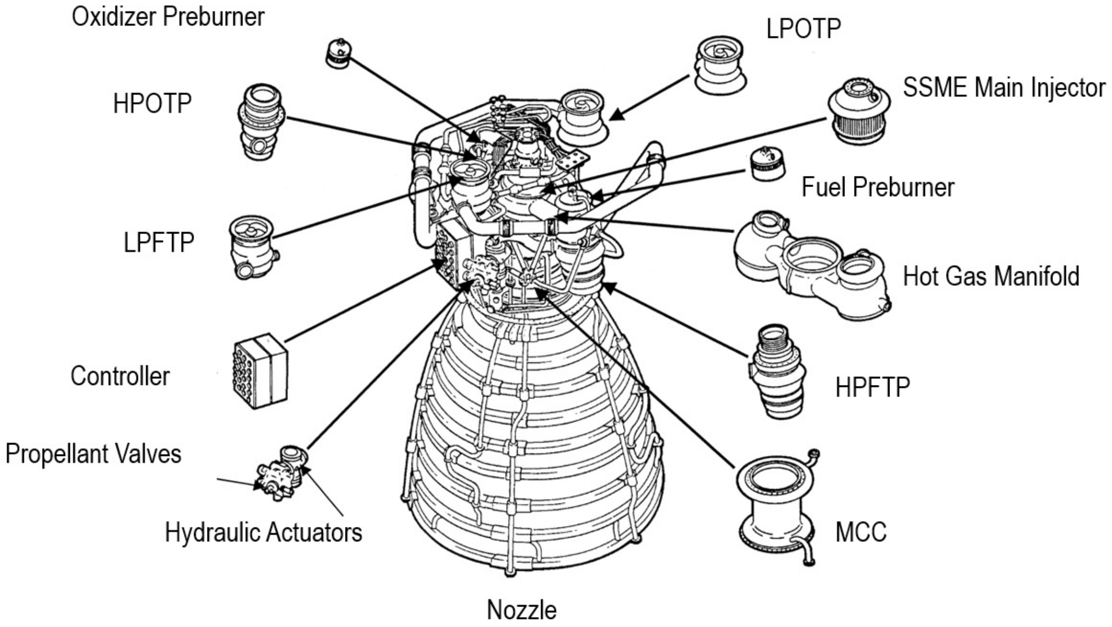

Figure 1: RS-25 Components

1.2 Genesis of SLS

Coincident with the cancellation of the Constellation program and retirement of the Space Shuttle program, the SLS program was initiated to replace the launch functionality of the Shuttle in terms of heavy-lift and crewed access to space. In particular, SLS was envisioned as an “exploration class” capability to support mutiple human and robotic missions into deep space. The SLS program is one of three collaborative NASA programs supporting crewed space exploration, the others being the Orion Multi-Purpose Crew Vehicle (MPCV) program and the Ground Systems Development & Operations (GSDO) program. Each program is responsible for key functional elements needed to enable the access to space objectives, and their respective management was disseminated across the three NASA centers responsible for space flight: SLS is managed at the Marshall Space Flight Center, MPCV is managed at the Johnson Space Center, and GSDO is the launch infrastructure managed at the Kennedy Space Center. Effective integration of these programs into an operational enterprise requires a high level of coordination and communication. This is especially important to ensure that the decisions of one program does not unintentionally impact the others and that the collective enterprise can evolve into an effective operational organization.

The organization of the SLS program office is partitioned into several Elements, including:

- The Liquid Engines Office (LEO), responsible for all aspects of the RS-25 core stage engine and upper stage engine.
- The Stages element office, responsible for the Core Stage (CS) and Exploration Upper Stage (EUS).
- The Boosters element office, responsible for the solid rocket boosters.
- The Spacecraft/Payload Integration and Evolution Office (SPIE), responsible for the Interim Cryogenic Propulsion Stage (ICPS) and advanced development activities to evolve the initial SLS Block 1 vehicle (70t payload capability) to higher performance configurations with up to Block 1B and 2B (130t payload capability to low Earth orbit) vehicle configurations.
- The Ground Operations Liason Office (GOLO), responsible for coordinating integration activities between SLS and GSDO.

The LEO element coordinates the integration function primarily with the Stages element due to the engine interface with the core stage main propulsion system (MPS) lines, structural attachments, power supply and command and data handling (C&DH) connections. In addition, vehicle integration efforts also involve engagement with program-level systems engineering and integration (SE&I) and the GSDO organizations.

2. Adapting the Heritage SSME for SLS

One of the cornerstones of the foundation enabling the SLS program to move out quickly was the selection of the RS-25 as the main engine for the core stage. Development of an all-new engine would have been both time- and cost-prohibitive. The propulsion system is typically the most challenging task of any new launch vehicle development. Not only did using the RS-25 system bring a wealth of performance capability and technical experience, recovering the residual hardware assets of Shuttle program produced fourteen operational flight units and the components for two more engines required for the first four SLS flights. In addition, two non-flight engines were immediately available to provide a functional platform for development, verification and Engine Controller Unit (ECU) certification testing.

It is an important note that utilization of the heritage assets had immediate advantages and liabilities:

- Rapid availability of hardware for tests. Manufacture of an RS-25 takes approximately 5 years and is generally the longest-lead item in a development program. In this case, the engines were largely ready, requiring only modification of the Stennis Space Center (SSC) A-1 test stand and completion of the new RS-25 ECU before testing could begin.
- Limited development engines and schedule available for system development and verification tests. Even though the two non-flight engines needed replacement ECUs, the established date for the first SLS flight allowed a limited span of time to perform all the system tests needed to accomplish all the objectives for characterizing engine operation under new SLS conditions, certifying the replacement ECU, and verifying new or modified requirements. Also, the limited hardware and time available for system testing did not allow development of a broad statistical sampling of data from which well-validated test-to-test and unit-to-unit dispersions to be generated.
- Limited life remaining flight assets. Given that the heritage flight assets had already flown on the STS program, some of the components had service life limitations that needed to be accounted for in planning any tests prior to flight. This included being used on the green run test of the first core stage to be performed at the B complex at the SSC. Taking in account the service life remaining on the flight assets required careful allocation to flight vehicles.
- Minimal useful hardware spares inventory – The quantity of available engine hardware allowed no room for error in handling or use.

When the Constellation program transitioned into the SLS program, the LEO organization modified the J-2X contract with Aerojet Rocketdyne to include the adaptation effort for the RS-25 as a separate contract line item. This contract was to run through the end of GFY 2016 and was to focus on adapting the heritage assets for use on the first four SLS vehicles. After the Adaptation contract was completed, follow-on efforts would be needed to 1) evolve the RS-25 into an affordable engine that could be produced more rapidly, and 2) begin production of the evolved RS-25 system. However, for the present, the primary focus areas for adapting the heritage SSME configuration involved the following:

- Compliance with allocated SLS vehicle and program requirements, including loads and environments
- Replacing the obsolete engine controller with a modern system.

2.1 SLS Requirements and Environments

In selecting the RS-25 system for service on the SLS vehicle, it was granted that the certification of the engine for STS could be applicable to SLS so long as any changes in the system operation and environments were taken into account. Any new SLS requirements allocated to the RS-25 were analyzed by the LEO team to determine if compliance produced any impacts, and whether it affected budget, schedule or the technical baseline of the engine. Given that there were over a dozen engines already flight-certified and accepted, it was important to avoid generating any requirements that drove a design change or operated the engines off their nominal regimes.

The approach defined for complying with the new SLS requirements allocated to the engine involved a process for validating engine compliance with the requirement without significant impact to budget or the heritage baseline. A majority of the allocated program and vehicle requirements were incorporated, but assessment of the required design and construction (D&C) standards was needed to be performed in comparison to the D&C standards previously established for the heritage SSME system. The established approach for accounting for and demonstrating compliance with the SLS D&C standard was called the “Heritage Exemption”, which meant that the heritage D&C

standards used for hardware manufactured under the STS program met the intent of the SLS D&C standards. However, the Heritage Exemption was not applicable to new hardware produced under the Adaptation effort and compliance with the SLS D&C standards would then be required.

At the onset of the Adaptation effort, it was a baseline assumption that, unless proven otherwise, the vehicle-induced environments and engine interface conditions interacting with the SLS vehicle would be enveloped, or less severe, than those encountered on the STS vehicle. The SSME-Orbiter Interface Control Document (ICD) from the STS program was utilized as a point of departure for the design of the core stage interface with the RS-25. Other heritage documents leveraged for SLS included the SSME Operations and Maintenance Requirements and Specifications Document (OMRSD) to provide guidance for ground operations and the SSME Launch Commit Criteria (LCC) to provide guidance for pre-launch operations.

Using the heritage OMRSD and LCC provided another area of requirements adjustment in operations and supportability. This was primarily driven by changes in operational norms in terms of roles and responsibilties as defined in the program operations concept. A lot of the operational procedures established to support the STS program would need to be revised to reflect operations that had either changed or been disconcontinued following the retirement of the Shuttle.

In the area of vehicle integration, even though the RS-25 was effectively a fixed design, the engine system still needed to be integrated into a vehicle that involved requirements, loads, environments and operations that differed from its prior use on the Shuttle. In the course of performing the vehicle integration function, a number of issues were encountered that required focused attention:

- High LOX inlet pressure – The additional engine used on the SLS vehicle produced an increased propellant load which resulted in a significantly increased length beyond that of the integrated STS vehicle. As shown in Figure 2, the increased tank lengths required the length of the oxidizer feedlines to be increased to the extent that the increased head generated elevated oxidizer inlet pressures to a level above the nominal regime. This posed a risk to the engine startup sequence, which might cause a damaging mixture ratio excursion in the preburners. In addition, the vehicle acceleration during flight would produce a progressive increase in the inlet pressure that posed a risk at main engine cut-off (MECO) for the shut-down transient and subsequent waterhammer surge propagating back up the feedline.

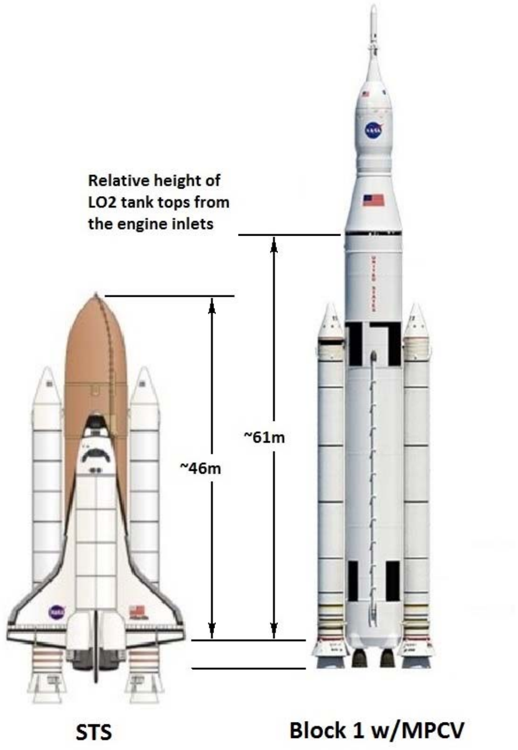

Figure 2: STS and SLS Block 1 Vehicles

- Low LOX inlet temperature – Coincident with the high LOX inlet pressure, the inlet temperature is a concern to the engine start transient that is being mitigated by the addition of electric heaters to the inlet feedlines.
- Induced thermal environments – On the Shuttle, the exit plane of the engine nozzles were located approximately 4 meters above the exit planes for the Solid Rocket Boosters (SRBs). However, on the SLS vehicle, the internal thrust structure configuration resulted in the exit planes for both to be roughly in alignment with each other. This resulted in an increased radiant thermal load induced on the engine nozzles from the SRB plume, requiring the development and application of an injection-molded ablative insulation on the affected section of nozzle facing the SRBs.
- BSM exhaust impingement – In addition to the radiant heat loads induced from the SRB plume, the Booster Separation Motors (BSMs) mounted on the aft skirt of the SRB posed a risk of plume impingement and debris impact from the BSM nozzle covers. This is mitigated by ensuring the configuration of the ablative insulation provides protection from plume impingement and the BSM nozzle covers are being designed with retention features to prevent them being ejected.
- CAPU exhaust impingement – On the Space Shuttle, the hydraulic systems moving key actuators were powered by hydrazine-fueled auxiliary power units (APUs). However, NASA is emphasizing a minimal use of toxic propellants, so hydrazine systems are to be avoided. Instead, the SLS will use hydrogen tapped from the RS-25 propellant tank repress flow to power Core APUs (CAPUs) on the core stage for the hydraulic power. After passing through the CAPU, the hydrogen exhaust is dumped through several nozzles located at the aft bulkhead of the core stage near the engines. The risk of the hydrogen lighting off and impinging on the RS-25 nozzles required the ablative insulation be configured to mitigate this.
- Cold aft compartment thermal environments – Thermal modeling of the vehicle aft compartment revealed unexpectedly cold bulk temperatures that risk affecting engine sensor accuracies and the fluid properties of the hydraulic systems. Further analysis showed the primary contributor to the cold temperature to be the oxidizer feedlines running through the compartment to the engines. The addition of a heated gaseous nitrogen (GN2) purge is being considered as a mitigation. The option of adding insulation to the oxidizer feedlines was also considered, although it conflicted with the heater mitigation of the cold LOX inlet temperature. Although current analytical results show an acceptable bulk temperature without insulation, ground-powered electric heaters will be needed for sections of the hydraulic lines.
- Prelaunch fuel bleed flow conditions – Prior to launch, bleed flows are required on both the fuel and oxidizer systems in order to thermally condition the engine. The fluid conditions and durations required by the engines were well established as a result of experience from the STS program. However, the capabilities of the ground systems were not compatible with the increased fuel flow requirements resulting from the additional engine on the SLS vehicle. This necessitated coordinating the engine fuel bleed flow requirements with upgrades to the affected ground support systems.

2.2 RS-25 Engine Controller

The only significant hardware component of the engine that required upgrade for the Adaptation activity was the ECU, shown below in Figure 3. The functions of the ECU include:

- Receive and respond to commands from the vehicle.
- Provide closed-loop thrust and mixture ratio control of the engine during mainstage operation through position control of variable position propellant valves to the separate preburners.
- Manage engine state (i.e., start enable, start, mainstage, shutdown, etc.) transitions and timing of effectors used during the different states. This includes the control of numerous purges and bleed flows.
- Continuously monitor engine health.
- Provide data and health status to the vehicle flight controllers.
- Provide electrical power to all engine control elements, sensors and effectors.

The heritage ECU was technologically obsolete and incompatible with the SLS vehicle power and data architecture. In addition, many of the parts using in the heritage ECUs were no longer available. However, a new ECU design originally developed for the J-2X upper stage engine during NASA’s Constellation Program could be leveraged and expanded to provide a replacement for the heritage controller. This allowed a significant savings in time and resources to expand the functionality of the J-2X controller to that of the SSME controller. Using the J-2X ECU design as a starting point offered programmatic advantages in terms of cost and schedule versus a “clean sheet” design but posed additional challenges in adapting the J-2X control system to the more complex RS-25, as well as, the cost of specialized electrical, electronic and electromechanical (EEE) parts was underestimated.

The engine team also chose to develop non-flight Engineering Model (EM) controllers that were to be functionally equivalent to the flight units but able to be produced faster than flight units to allow development testing to start earlier. In addition to system testing of the engines at SSC, the EM controllers could also integrated with engine actuators, sensors, wiring harnesses, etc. for testing at the MSFC Hardware-In-the-Loop (HIL) Lab

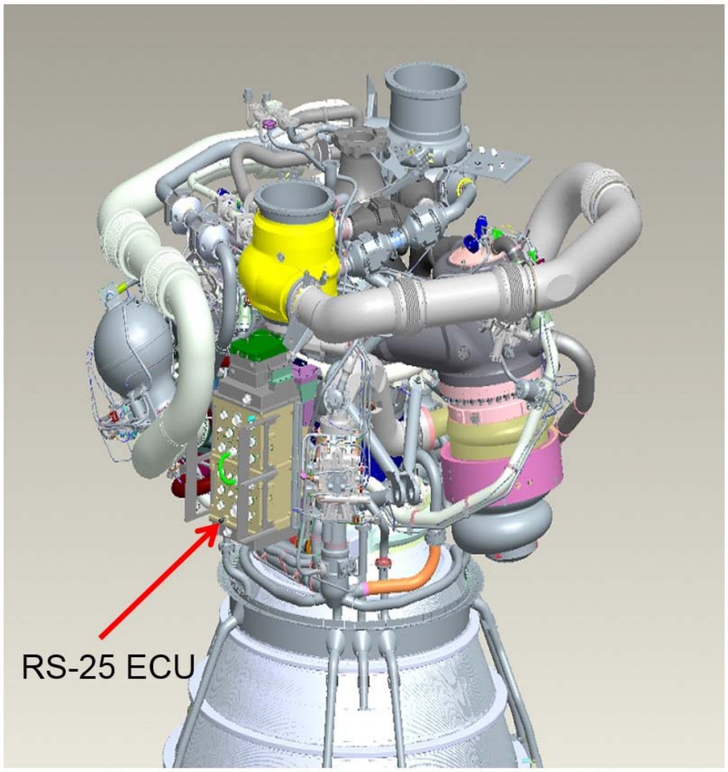

Figure 3: RS-25 ECU

2.3 Other Technical and Programmatic Challenges

The RS-25 team encountered additional challenges in rennovating the A-1 test stand to support RS-25 testing. Originally built to test engines for the Saturn launch vehicles, the stand was modified to support Space Shuttle Main Engine testing. The last SSME test on A-1 was September 2006, and it was subsequently modifed for J-2X engine testing unrelated to engine design and integrationIn addition to working issues with the engine and its integration to the SLS vehicle, other challenges have arisen and been resolved by the NASA SLS RS-25 team. These include some events that were addressed at SSC:

- <u>Contamination in the facility oxidizer feedline</u> [2] – Following the installation of development engine 0525 in the A-1 test stand, borescope inspections of the facility feedlines revealed fiber contamination in the oxidizer feedline. Efforts to remove the fibers revealed additional metallic particulate contamination residual from the feedline machining process. This required the engine to be removed in order to remove the feedline to be cleaned.
- <u>Contaminated hydraulic system</u> – The compromised function of a filter in the facility hydraulic supply to the engine was discovered to allow the bypass of the filter under certain flow conditions and allow the introduction of particulate contaminants.

3. Plans Beyond Adapting Heritage Engines

Taking into account that an RS-25 takes about five years to produce, it is important to develop plans for the continued supply of engines after the first four SLS flights have expended the sixteen engines being adapted from the STS program. In addition, it is also important to evolve the RS-25 system to be more affordable as an expendable engine. It is recognized that there are definite structural advantages to be leveraged from lowering the service life of the engine from the current 55 starts and 27,000 seconds. The current plans to provide a continued affordable supply of RS-25 engines include two contract regimes:

- Recertification – indentify and incorporate targeted affordability options for modifying the RS-25 system as a block change and recertifying the upgraded system for continued service on the SLS vehicle.
- Production Restart – Initiate new production of the RS-25 system with the affordability changes.

4. Summary

In summary, the RS-25 was selected for SLS as a mature, proven propulsion system for the ambitious performance requirements of what will be the world's most capable launch vehicle. In addition to the extensive knowledge base, it also provided the SLS Program with 16 available flight engines and 2 development engines to support SLS adaptation testing and the first 4 operational SLS missions. The SLS Liquid Engines team has encountered and overcome both anticipated and unanticipated challenges in helping NASA open a new era of exploration and discovery by leveraging the best of this nation's investment in space technology. Hotfire testing planned for 2015 and 2016 will demonstrate the soundness of the design and its adaptation to the SLS in preparation for the first launch planned for 2018.

References

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[2] Bergin, C. 2014. SLS Engine Testing Delayed Due to Test Stand Contamination. NASA Spaceflight.com.