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Next-Generation RS-25 Engines for the NASA Space Launch System

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Abstract

Use of heritage RS-25 engines, also known as the Space Shuttle Main Engine (SSME), has enabled rapid progress in the development and certification of the NASA Space Launch System (SLS) toward flight status. 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. Beyond these initial SLS flights, NASA must have a renewed supply of engines that reflecting program affordability imperatives as well as technical requirements imposed by the SLS Block-1B vehicle. Toward this objective, design activities are underway using modern materials and fabrication technologies, but also by innovations in systems engineering and integration (SE&I) practices.

1. Introduction

With the first flight of the SLS vehicle approaching a reality in the 2019 timeframe, inaugurating flight status of the SLS architecture will invigorate mission planning for a number of flagship missions extending into the foreseeable future. The current schedule of SLS missions will allow the existing supply of modified heritage RS-25 engines to last long enough to permit the development and certification of a new RS-25 design baseline that is more aligned with long-term SLS program objectives. The design upgrade will preserve the recognized strengths of the proven SSME/RS-25 system in the areas of performance and reliability, and pursue additional enhancements of reduced production costs, fabrication times and operational requirements.

1.1 SLS Overview

NASA's Space Launch System (SLS) was initiated to replace the launch functionality of the Space 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. All three programs are under the aegis of the Exploration Systems Development (ESD) organization and each program is responsible for key functional elements needed to enable "access to space" objectives. The management of each program is 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. In order to insure effective integration of these programs into an operational enterprise, a high level of cross-program coordination and communication is required so that the decisions of one program does not unintentionally impact the others and the collective enterprise can evolve into an effective operational organization.

Figure 1 shows how the SLS vehicle is planned to follow an evolution-based approach to achieve operational status followed by progressive upgrades. The first SLS vehicle configuration is called the Block-1 and leverages modified RS-25 and solid rocket booster heritage hardware recovered from the Shuttle program to support a first flight goal in 2019. It will carry an uncrewed MPCV using an Interim Cryogenic Propulsion Stage (ICPS) powered by a single RL10 engine. The next SLS vehicle configuration is called the Block-1B and will provide support crewed and cargo missions in time for the second SLS launch in the 2021-2023 timeframe. The Block-1B vehicle will be capable of performing crewed and cargo missions by replacing the ICPS with a higher-performing Exploration Upper Stage (EUS) using four RL10C-3 engines. The Block-1B vehicle will eventually be supported by the addition of the Block-2

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configuration, which will provide improved payload capability through the use of advanced boosters using solid or liquid propellants.

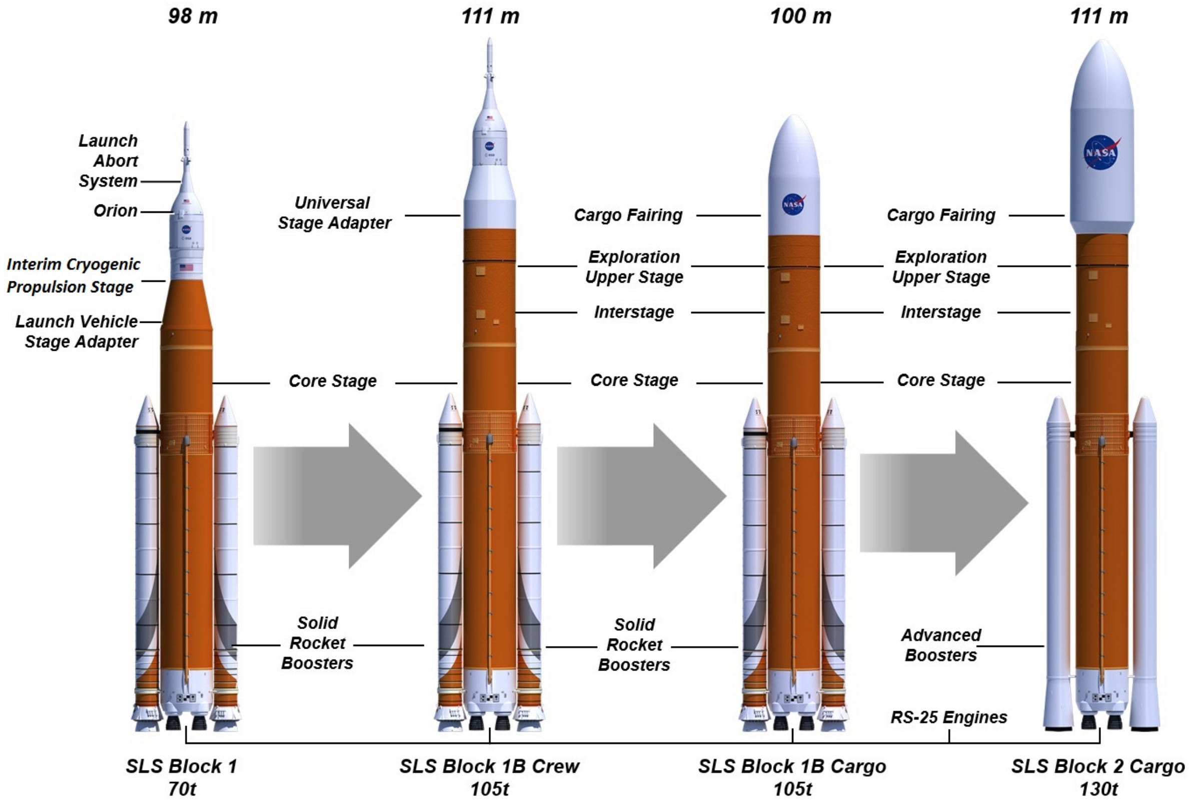

Figure 1: SLS Vehicle Block Evolution

In each vehicle configuration, the core stage will use four RS-25 engines, the first missions using modified Heritage RS-25s until they are expended, and eventually replaced by modern RS-25 engines developed specifically to support SLS missions. These new engines will be developed to selectively trade reusability in exchange for affordability and improved performance.

1.2 SSME Overview & Brief History

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 2 shows an oblique view of the RS-25 and major components with affordability objectives for cost reduction.

Development of the RS-25 (aka SSME) was started by Aerojet-Rocketdyne (AR), then the Rocketdyne division of Rockwell International, 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, AR 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.

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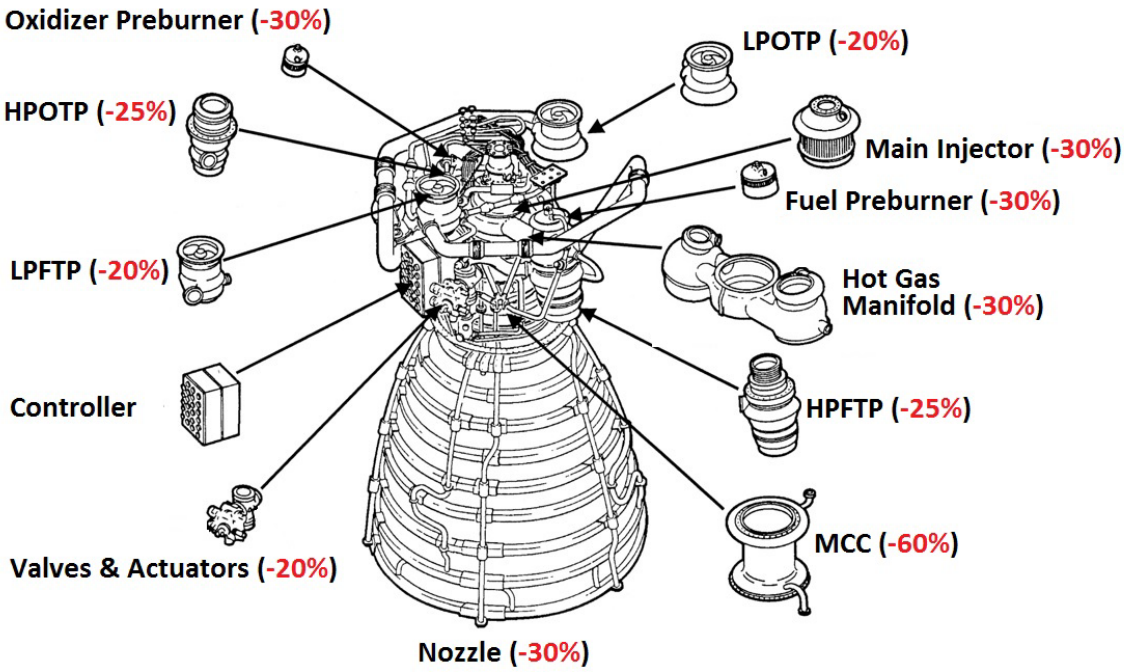

Figure 2: RS-25 Components (and cost reduction objectives)

When the heritage SSMEs were recovered from the retired Space Shuttle program, they were effectively free flight-certified hardware with exhaustive supporting documentation and experience backing them. Care was taken to preserve that status as much as possible while modifying them for operational use on the SLS vehicle, and also establish a solid foundation to enable further improvements for follow-on engine production. Figure 3 shows the planned evolution of RS-25 design baselines, starting with the Heritage design baseline of the SSMEs recovered from the Shuttle program, then establishing the Adaptation design baseline through the incorporation of a new Engine Control System (ECS), an SLS-specific suite of Development Flight Instrumentation (DFI) and Thermal Protection System (TPS) for the nozzle. The Restart design baseline is planned to reduce the recurring and non-recurring costs of the RS-25 by a third in order to provide long-term affordability and sustainability of propulsion elements for SLS.

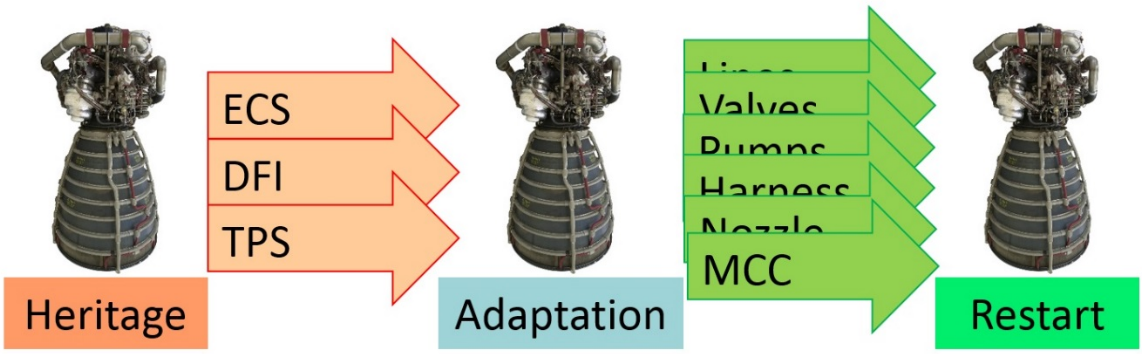

Figure 3: RS-25 Evolution from STS to SLS

2. Next-Generation RS-25

Understanding that with four engines expended per SLS mission, the current supply of sixteen Adaptation engines will be exhausted after four missions. Anticipating the long lead time required to revive a production line for a complex system that has some parts which haven't been manufactured in decades, planning was established to begin work immediately. The RS-25 Production Restart Program focused on enabling the restart of manufacturing and production of RS-25 engines with emphasis on improving RS-25 system affordability and sustainability in order to provide

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extended service toward SLS mission needs. The new engines will leverage innovations in low-cost manufacturing technologies, materials, and design practices acceptable for expendable engines.

In addition to systemic efforts to reduce cost, the following changes are some of those being incorporated into the Restart design baseline:

- Increased maximum thrust from 109% rated power level (RPL) to 111% RPL
- Reduced service life to reflect engine expendability – the engine service life requirement will be reduced to enable nominal acceptance testing, mission operations and a moderate additional contingency.
- Updated integrated loads with the SLS vehicle

2.1 Phasing Integration of RS-25 Production Restart Development

It was recognized that in order to pursue the objective of making the next generation of RS-25 engines a reality, it had to be conducted partially in parallel with the completion of adapting the heritage RS-25 engines for the initial SLS missions. This required that additional attention be paid to phasing and coordination of programmatic and technical activities, as well as be responsive to unanticipated events and development challenges. Figure 3 shows the overall layout of RS-25 contract phasing with respect to the Adaptation and Restart activities.

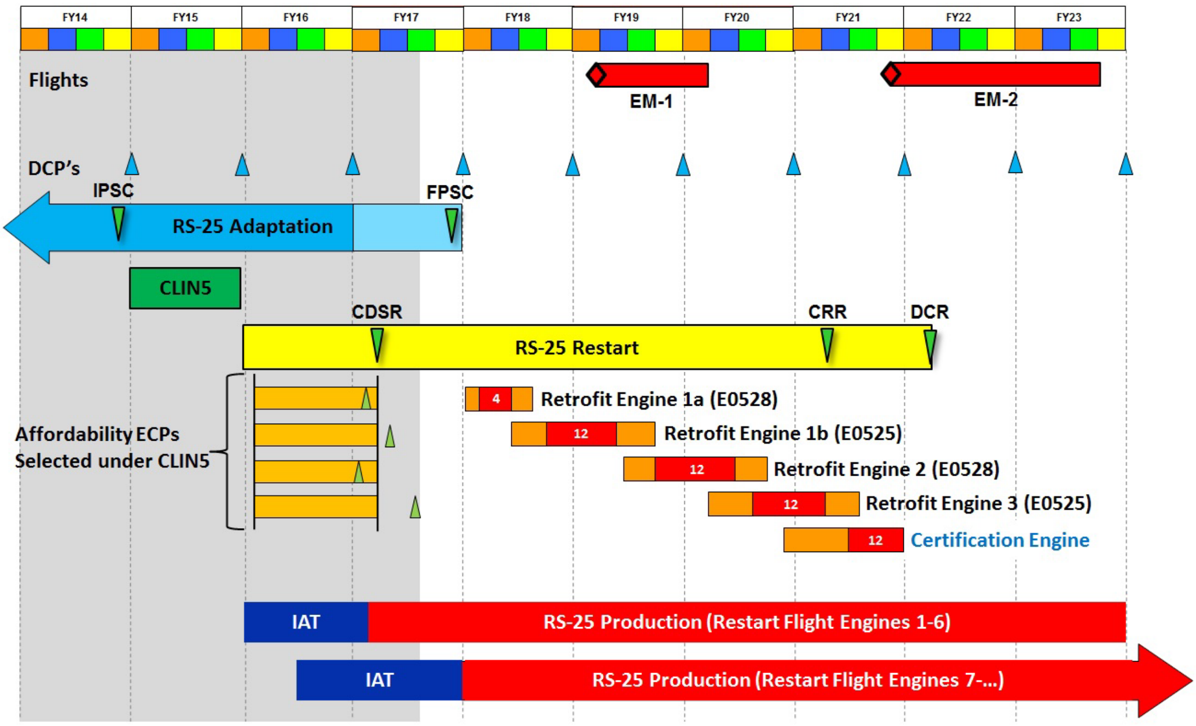

Figure 3: RS-25 Block Development Phasing

An interim activity was contracted with AR to prepare for the imminent Restart development activity by trading and evaluating candidate design initiatives with emphasis on reducing cost without sacrificing reliability or performance. The interim effort was contracted as an indefinite delivery/indefinite quantity (IDIQ) activity called contract line item number 5 (CLIN-5) appended to the AR contract. Affordability candidates were assessed against the Technology Readiness Level (TRL) involved in pursuing the design change, and their selection was based on budget, available time and level of risk. In order to set a boundary for the limit of acceptable technical risk, the minimum TRL limit for candidates was set at 5 (i.e., component and/or breadboard demonstrated in a relevant environment). Also, an exhaustive assessment was performed across the overall continuum involved in the RS-25 life cycle using advanced process improvement tools and techniques such as Value Stream Mapping (VSM) and Kaizen exercises. At the end of the CLIN-5 period of performance, all validated design candidates were carried forward into the Restart contract for further development.

The RS-25 Production Restart Program commenced in October 2015 with a portfolio of validated design candidates to be pursued as part of establishing the Restart design baseline. This being conducted in parallel with the final stages

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of the activity to establish the RS-25 Adaptation design baseline. Also in parallel with the Restart activity, long-lead procurements are planned to be conducted for use on the new flight engines using the Restart design baseline.

2.2 Control Boards & Milestone Reviews

Following the selection of RS-25 design initiatives identified during the CLIN-5 activity, the continued management of Restart activities was performed under the auspices of the Affordability/Obsolescence Review Board (AORB). The AORB was established to review and disposition all Restart design initiatives and is responsible for monitoring the progress of each design activity to insure that the expected programmatic benefit in terms of cost reduction is realized. The development path of each design initiative is laid out with key decision points and potential "off-ramps" that can be triggered by the AORB if the affordability benefit is reduced or threatened. An example of this occurred when an initiative to eliminate the expensive fuel flowmeter with an alternate flow-measuring approach could not provide sufficient accuracy to meet the required mixture ratio control precision. As a result, after all reasonable options were examined, it was elected to off-ramp the flowmeter elimination initiative and return to the Adaptation flowmeter design until an acceptable flow-measuring approach was identified.

A change management process was established to 1) ensure proper coordination and assessment of changes with all relevant stakeholder organizations (i.e., program management, engineering, safety & reliability), 2) disposition changes at the appropriate level, and 3) ensure change incorporation planning, verification closeout, and reporting. As they are completed, the design initiatives will be documented as part of a series of Engineering Change Proposals (ECPs) to modify the Adaptation baseline. The ECPs will provide formal detailed documentation needed to establish the Restart baseline at the completion of the Restart DCR.

Periodic milestone reviews are a useful tool for providing an independent review of development work in progress and also to demonstrate to other stakeholders that useful work is being effectively pursued and the risk portfolio is being successfully managed. Like the milestone reviews executed for the Adaptation effort, the Restart activity took credit for the established operational record of the RS-25 and defined a set of milestone reviews to provide a composite assessment of work underway at particular points in the Restart development cycle. These include:

- Critical Design Summary Review (CDSR) – a milestone providing a system-level roll-up of all subsystem- and component-level design activities that have completed a detailed design level of maturity commensurate with a Critical Design Review (CDR). The timing of the CDSR is planned to be at a point where most of the Restart design efforts will have completed their respective CDRs, and the CDSR is intended to insure that the aggregate system-level effects of the proposed design changes are adequately captured and understood. The CDSR is also intended to assess alignment of the Restart development activity with programmatic imperatives of affordability and sustainability.
- Certification Readiness Review (CRR) – a milestone preceding the initiation of system certification testing as a risk mitigation activity to assess readiness for design certification culminating in DCR. The CRR will also examine the results of the prior development work and evaluate the maturity of the hardware design going into the certification test phase.
- Design Certification Review (DCR) – a NASA-led milestone planned to be in compliance with a conventional DCR in order to formalize the establishment of the Restart design baseline when all verification and certification activity is completed.
- Development Checkpoint (DCP) – a recurring annual event performed at the end of each fiscal year to provide a "year in review" synopsis and also review and assess readiness to continue work underway. It has been shown to be an effective supplement to the Monthly Performance Reviews (MPRs) and provide a useful extension to the information compiled for the CDSR. Like the CDSR, the annual DCP provides customer insight to insure that design work performed at the component- or subsystem-level is accurately reflected at the system level.

In addition, AR was responsible for internal reviews as needed (i.e., chief engineer reviews, technical interchange meetings, component- or subsystem-level design reviews) to assure effective NASA insight and oversight into all Restart activities.

2.3 Affordability Enablers

The results generated by the CLIN-5 studies showed that achieving the affordability goals for the Restart baseline will be enabled through the following key focus areas:

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- Hardware definition – this includes not only exploitation of modern fabrication techniques such as Additive Manufacturing (AM), but easing design and operational sensitivities imposed by reusability / supportability requirements. This area can have the most tangible and easily measured savings in terms of per-unit cost.
- Business practices – this is largely influenced on how AR operates in performing its business processes, but the cost savings of optimizing and evolving lean practices will also result in lower programmatic costs incurred by NASA.

The key focus areas described above illuminate the fact that achieving the affordability goals for the Restart RS-25 cannot be attained exclusively by selective redesign of the engine hardware. It emphasizes a "deep dive" examination into all areas and organizations involved in producing the engine, starting with raw materials and vendor components arriving at the AR facility, and ending with engine delivery at the NASA Michoud Assembly Facility (MAF). The work currently being undertaken in the Restart activity is guided by the following imperatives and objectives:

Institutional

- Challenge entrenched paradigms and "sacred cows", allow freedom to innovate and adapt
- Seek and prosecute inefficiencies
- Encourage fresh perspectives, opinions, ideas
- Establish guidance on risk tolerance (i.e., perfection is unnecessary when "good enough" is acceptable)
- Seek new technologies for evaluation and exploitation
- Leverage documented lessons-learned and nonconformances (e.g., Unsatisfactory Condition Reports (UCRs), Material Reviews (MRs)) to identify preemptive corrective actions that can be implemented in the design, processes, or operations
- Establish a methodical approach to affordability with quantifiable tracking, including development of a business case for each change that trades development cost and risk against run-out cost savings
- Grant credit for the long history of the RS-25 system (40+ years), AR experience, and NASA insight skills

Technical

- Increased minimum power level requirement to eliminate the need for an engine test stand equipped with a diffuser for throttle testing
- Reduced gimbal angle requirement to enable the use of flex hoses instead of flex ducts – reduced hardware complexity reducing fabrication costs
- Selected use of Additive Manufacturing (AM) technologies, including Selective Laser Melting (SLM), Near-Net Shape forgings
- Leverage design and manufacturing experience and lessons-learned from recent J-2X engine development [3] (e.g., replace MCC plated liner with hot isostatic pressed (HIP) manufacture; AM valve housings).
- Reduce sub-assembly parts and welds
- Eliminate nonconformance drivers for manufacturing rejects and assembly reworks
- Selective use of Manufacturing Technology Demonstrators (MTDs) to validate affordability approach
- Eliminate unnecessary instrumentation and supporting bosses, sense lines and harnesses
- Eliminate outdated inspection and maintenance operations
- Eliminate or mitigate failure modes that drive maintenance-intensive hazard controls
- Push for reductions in touch labor and fabrication cycle times
- Push for innovations in supplier selection and management
- Incorporate lean manufacturing practices to optimize scheduling and factory flows for fabrication machinery/tooling

While it can be said that the Institutional items listed above are largely philosophical common-sense mantras, it is important to note that they can and should be applicable to both AR and NASA. Pursing technical perfection and affordability are not generally compatible and will rely on contractor and customer coordination to establish the necessary balance.

2.4 System Testing

In addition to selected component-level testing, two development engines will serve as platforms for initial system-level tests of design changes managed by the AORB. These tests will be conducted on a series of progressive "retrofit" configurations to allow performance characterization of each modified component and their interaction with the system to determine if further adjustments to the design change is needed. The tests performed on the retrofit engines will

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also contribute toward certification of system service life by accumulating starts and run duration on selected components.

After completion of the development test program on the retrofit engines, the CRR milestone review will be conducted as a gate to proceed into the system-level certification test series. The certification tests will be performed on a RS-25 engine reflecting the expendable Restart design baseline.

Spanning the period between the CRR and DCR milestones, the system test program is expected to take 4 years and includes 40 hotfire tests on the development engines, 12 tests on the certification engine, and 4 tests as contingency options.

2.5 Over the Horizon – Block-IV RS-25

While the CLIN-5 work was focused on identifying near-term upgrades to the RS-25 design to address affordability and obsolescence concerns, it was constrained against using low-TRL, higher-risk candidates. Understanding that the NASA and the aerospace industry will promote the advancement of promising material and manufacturing technologies as their merits became more apparent and exploitable, a longer-term study is being performed to identify and assess the benefits of those design candidates that were not selected to be incorporated into the Restart design activity. Referred to as the "Block-IV Upgrade" study, AR is working with NASA to conduct engineering studies to enable the development of a longer-term strategic plan to possibly pursue more aggressive affordability options for the RS-25 engine beyond the Restart configuration.

3. Summary

Evolving the RS-25 into the next generation design baseline will be challenging in order to accommodate the numerous programmatic and technical imperatives imposed by the SLS program. Work completed to date by AR and the SLS Liquid Engines team shows good progress and rapid response to overcome both anticipated and unanticipated challenges. The path ahead for making the RS-25 Restart Production a reality is focused on helping NASA open a new era of exploration and discovery by leveraging the best of this nation's investment in space technology.

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