SPACE LAUNCH SYSTEM

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

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Overview

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.

- **16 flight engines and 2 development engines were recovered from the Space Shuttle program to support the first four flights.**
  - The recovered flight SSMEs were adapted to replace the obsolete engine controller unit (ECU) with a modern system and certify the engine to the new SLS vehicle loads and environments.
- **The adapted engines are sufficient to support the first four missions**
  - Beyond these initial SLS flights, NASA must have a renewed supply of engines that reflect program affordability imperatives as well as technical requirements imposed by the SLS Block-1B vehicle.
  - Activities are underway to update and restart RS-25 production using modern materials and fabrication technologies, but also by innovations in systems engineering and integration (SE&I) practices.

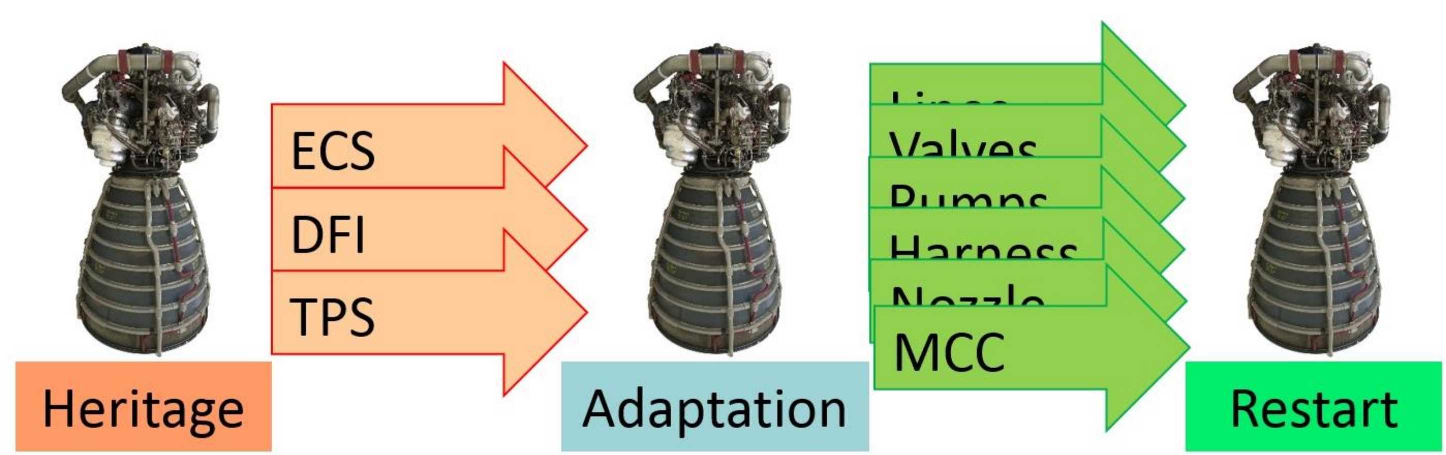
RS-25 Evolution for SLS

The SLS Core Stage Engine (CSE):

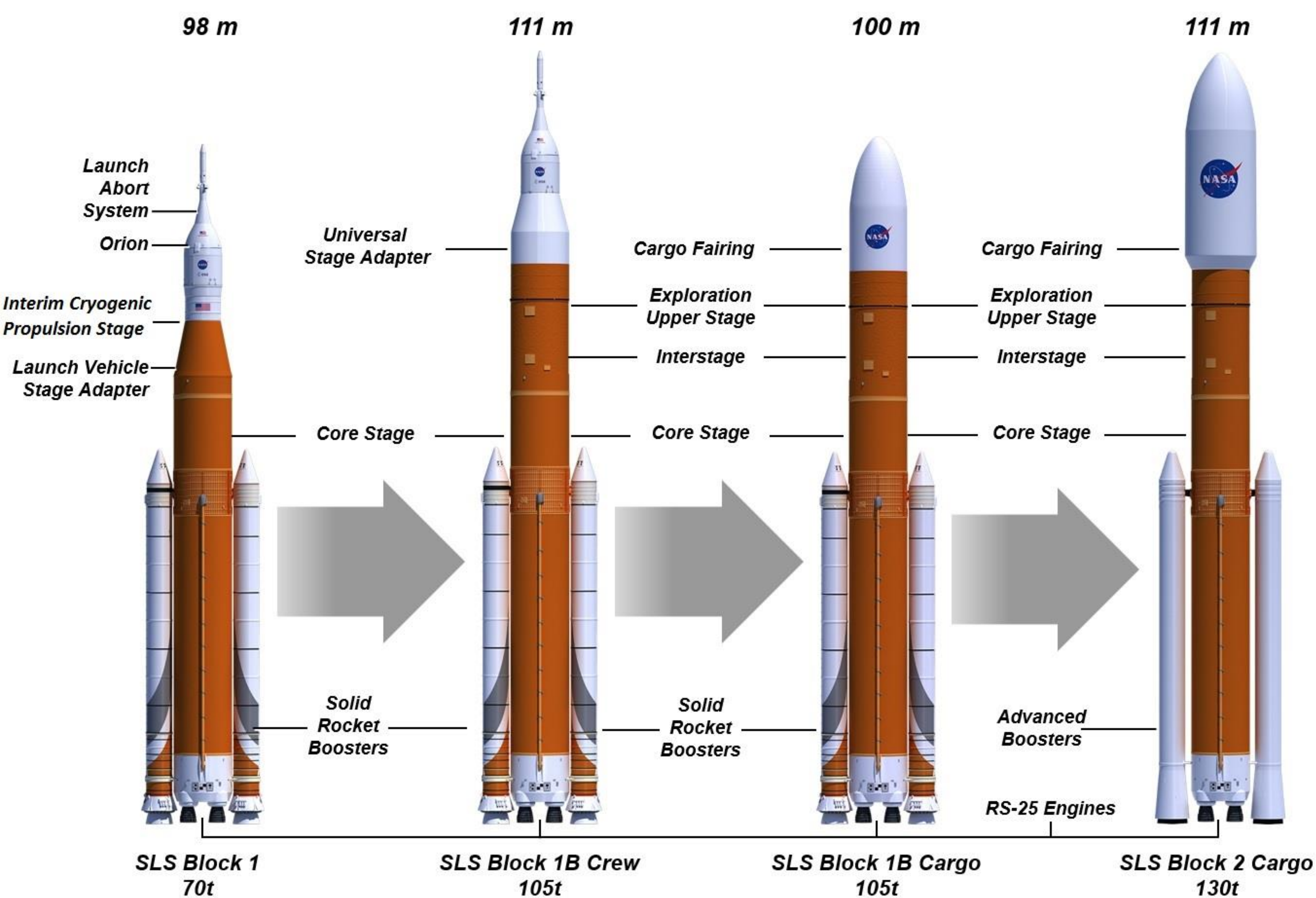
- Aerojet-Rocketdyne (AR) RS-25
- Demonstrated high performance, high reliability staged-combustion cycle LOX / LH_2 engine
- Flight certified in 1979, first flown in 1981

- 405 engine missions
- >3000 ground hot-fire tests
- >1 million secs hot-fire time

Configuration	Heritage (SSME)	Adaptation	Restart
Thrust (kN, vacuum)	2188 (104.5% RPL)	2281 (109% RPL)	2321 (111% RPL)
Isp (secs, vacuum)	450.2	450.7	450.8
Service Life (starts/secs)	55 / 27000	6 / 2500	4 / 1700



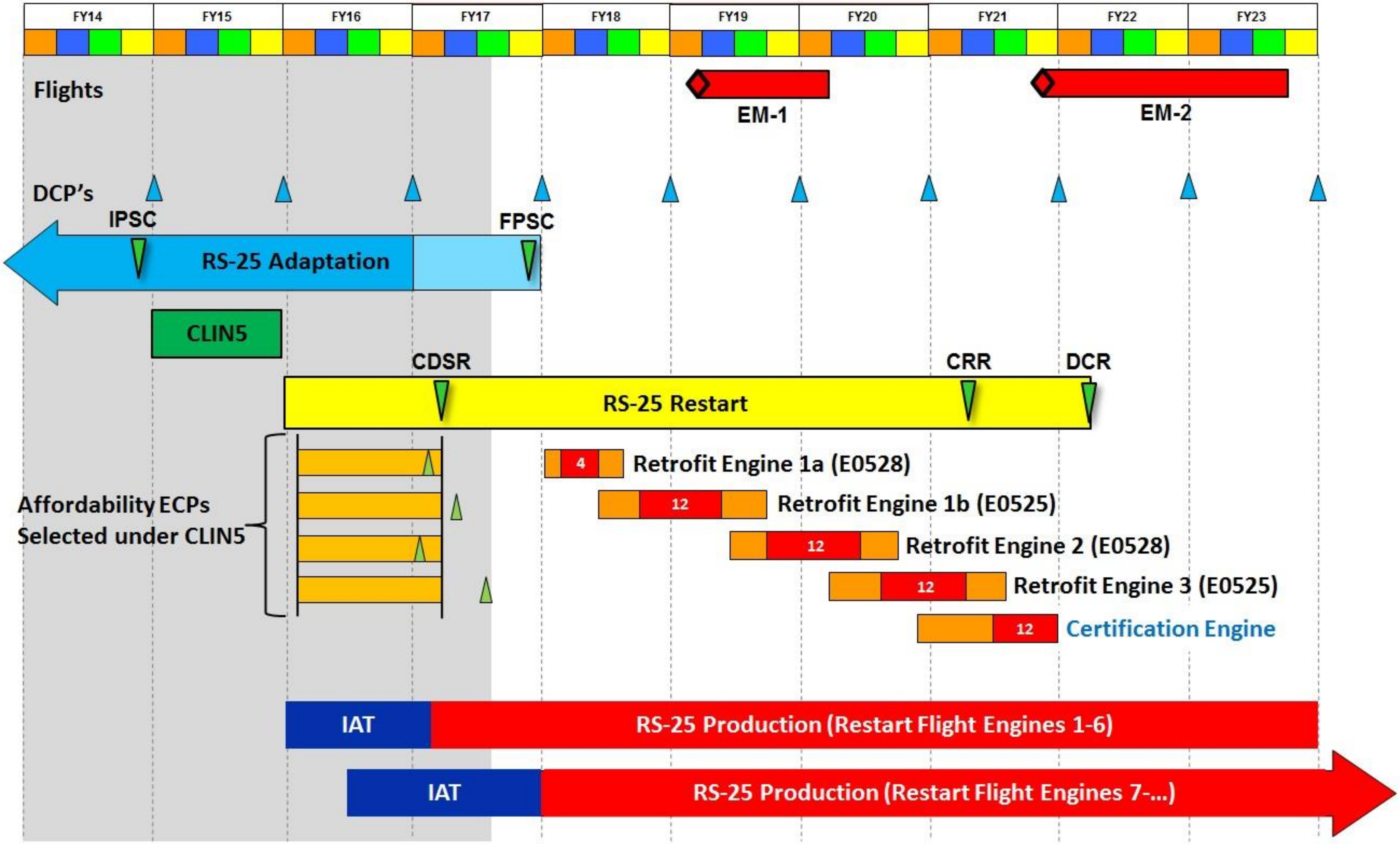
SLS Vehicle Block Evolution



Transitioning to RS-25 Production Restart

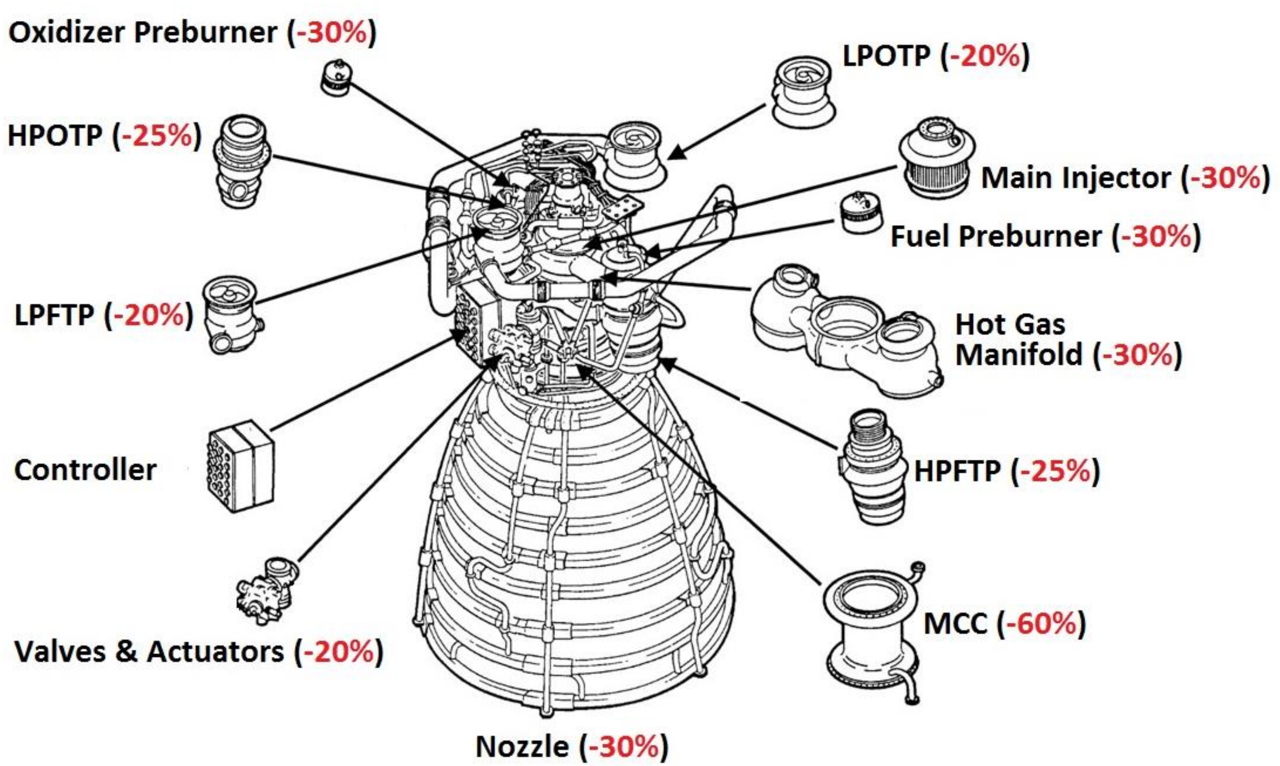
- While the inventory of Adaptation engines would support the first 4 SLS missions, the long lead times for engine production emphasized the need for a renewed flow of RS-25 engines.
- Before committing to re-opening the RS-25 production line, it was recognized as vital to update the engine design baseline to reflect SLS programmatic imperatives and technical requirements.
  - Emphasis on affordability and sustainability to support projected long-term mission launch rate.
    - Deliver up to 4 engines per year at an affordable unit cost by compressing long-lead times and using state-of-the-art materials and fabrication technologies.
  - Evolution of the RS-25 design baseline from Adaptation to Restart required a thorough trade evaluation of SLS-unique technical requirements versus time/cost versus available enabling technologies.
  - Working these trades allowed a development path to be defined with flexibility to respond to unforeseen risks and opportunities.
- The development path for the Restart engine also needed to be phased in parallel to the ongoing Adaptation activity

RS-25 Development Phasing



Setting the Stage

- In order to initiate the Restart development activity, an interim contractual line item (CLIN-5) was authorized for AR to evaluate and identify near-term candidates for development into the RS-25 engine design.
  - Candidates were assessed against the Technology Readiness Level (TRL) involved in pursuing the design change. The minimum allowable TRL was 5.
  - Selection was based on budget, available time and level of technical risk
- The CLIN-5 activity identified a number of design initiatives that could result in reducing production costs across the entire RS-25 engine.
- The goal was to reduce the unit cost of the engine by one third (33%).



NASA Techology Readiness Levels (TRLs)

Basic Research

- **TRL 1** Basic Principles Observed and Reported
  Components and subsystems are possible with basic principles selected; electrical vs pneumatic, etc.
- **TRL 2** Technology Concept and/or Application Formulated
  Basic concepts for the selected component or subsystem are conceived and defined as to preliminary concept layout, etc.

Feasibility Research

- **TRL 3** Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept
  Selected concept and implementation methodology are analyzed, modeled, simulated, etc. such that a preliminary system characterization is completed and understood.
  Examples: Subcomponent and materials testing and/or preliminary design analysis of critical design features to demonstrate proof-of -concept.

Technology Development

- **TRL 4** Component and/or Breadboard Validation in Laboratory Environment
  Breadboard type hardware is designed, fabricated, and subjected to developmental testing to experimentally demonstrate concept validity, characterize individual component and subsystem operational characteristics, and provide data for product improvement.
  Examples: Component test such as subscale thrust chamber/injector or turbopump subcomponent testing such as bearing and seals, turbine air test rigs, thermal shock testing of turbine blades.

Technology Demonstration

- **TRL 5** Component and/or Breadboard Demonstration in Relevant Environment
  Breadboard hardware is subjected to informal environmental testing; shock, vibration, thermal, life, etc., such that additional proof-of-concept data is obtained as well as operational characteristics under expected operational conditions.
  Examples: Full scale component test such as thrust chamber/injector or turbopump performance testing to demonstrate component functional characteristics that can be simulated independent of total system.

System/Systems Development

- **TRL 6** System/Subsystem Validation Model or Prototype Demonstrated in Relevant Environment (Ground or Space)
  Testing or integrated systems and/or individual components in a static firing test environment to finalize ground test exposure prior to full scale development for flight. This could also involve testing in a system level simulation
  facility for operation of components and systems in anticipated environments including loads.
  Examples: Full scale engine system test to demonstrate component interactions May be workhorse (no flight weight) system or prototype (flight weight) system.

Systems Test, Launch and Operations

- **TRL 7** System Prototype Demonstrated in Space Environment
- **TRL 8** Actual System Completed and “Flight Qualified” Through Test and Demonstration (Ground or Flight)
- **TRL 9** Actual System “Flight Proven” Through Successful Mission Operations

Ground Laboratories (TRL 1 – TRL 6)

Space (TRL 6 – TRL 9)

Managing the Restart Development Path

- **Once the CLIN-5 activity defined a portfolio of Restart design candidates, the management of the portfolio was taken over by the LEO Affordability/Obsolescence Review Board (AORB).**
  - The AORB 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.
    - Example: Offramp to replace the fuel flowmeter
- **As the design changes are completed and verified, they will be documented as a series of Engineering Change Proposals (ECPs) to modify the Adaptation design baseline.**
  - The ECPs will be used to establish the Restart design baseline at the completion of the Restart Design Certification Review (DCR).

Milestone Reviews

- **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 (no PDR or CDR), 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.**
  - Critical Design Summary Review (CDSR)
  - Certification Readiness Review (CRR)
  - Design Certification Review (DCR)
  - Development Checkpoints (DCPs)

Affordability Enablers

- **Achieving the affordability goals for the Restart baseline will be enabled by the two key focus areas:**
  - 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.
  - Business practices - this is largely influenced on how AR operates in performing its business processes and depends on optimizing and evolving lean practices.

- **Achieving the affordability goals for the Restart RS-25 cannot be attained exclusively by selective redesign of the engine hardware.**
  - A thorough examination of all areas and organizations involved in producing the engine have been made, starting with raw materials and vendor components arriving at the AR facility, and ending with engine delivery at the NASA Michoud Assembly Facility (MAF).

Technical Focus Areas

- Increased minimum power level requirement to eliminate the need for an engine test stand equipped with a diffuser for throttle testing
- Making the RS-25 expendable allowed reduced structural margins and simplified operational maintenance requirements/tests
- 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 (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

Institutional Focus Areas

- 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

It is understood that the items listed above are largely philosophical common-sense mantras, it is important to note that they can and should be applicable to both AR <u>and NASA</u>.

Pursuing technical perfection and affordability are not generally compatible and will rely on contractor and customer coordination to establish the necessary balance.

Challenges and Opportunities

- **(Challenge) Lack of vehicle integration engagement requiring designing the engine to integrate into a vehicle core stage that does not yet exist.**
  - The prime contractor for the SLS core stage is not on contract to support vehicle integration of the Restart engine with the Block-1B vehicle.
    - The difference is power levels between Adaptation and Restart (i.e., 109% RPL vs. 111% RPL) poses a design gap in integrated coupled loads between the engine and vehicle.
- **(Opportunity) Immediate availability of development engines to provide a platform for hotfire testing.**
  - Rapid prototyping enabled by AM technology allows Restart design initiatives to be tested quickly.

Over the Horizon – RS-25 Block-IV

- **The CLIN-5 assessment activity limited the scope of affordability candidates to those that could be implemented with minimal technology development (TRL ≥ 5).**
  - Selected candidates are being developed as part of the RS-25 Restart design activity.
- **In addition, NASA and AR are working on a "Block-IV Upgrade" study 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.**
  - The Block-IV study looks at low-TRL, higher risk, higher payoff candidates deferred by the Restart initiative.

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.