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CORE STAGE TVC SYSTEMS ENGINEERING CHALLENGES IN REUSING HERITAGE HARWARE

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The Space Launch System (SLS) Core Stage (CS) Thrust Vector Control (TVC) system is comprised of 8 mechanical feedback Shuttle heritage Type III TVC actuators and four RS-25 engines, each attached to a Shuttle heritage gimbal block/bearing. Two actuators are used to move each engine in two planes perpendicular to one another (i.e., pitch and yaw). The TVC system design leverages hardware from the Space Shuttle program as well as new hardware designed specifically for the Core Stage. The Space Shuttle heritage hardware directly reused on SLS includes the Orbiter TVC hydraulic servo-actuators (with two slight design modifications), the Orbiter hydraulic circulation pumps, the Orbiter gimbal block/bearing, and the Solid Rocket Booster hydraulic pumps. The Core Auxiliary Power Unit (CAPU) is derived from the Orbiter Auxiliary Power Unit (APU). The Orbiter and Solid Rocket Booster APU turbines are powered by hot gas produced by catalyzed hydrazine decomposition. On the SLS Core Stage, the CAPU turbine is spun using cold gas tapped-off from the RS-25 to CS liquid hydrogen autogenous pressurization line. While direct reuse or slight modification of existing hardware may seem to be a triple-win for a program in cost, schedule, and technical risk mitigation, those benefits can only be realized when its degree of application in a new system is carefully and thoughtfully managed. The heritage hardware reuse should be prescribed within the heritage design capability and reuse environments must lie within the envelope of heritage qualification testing. Despite the significant test and flight experience of the Shuttle heritage hardware components, successful integration with the newly designed CS TVC components and incorporation into the stage design proved to be a challenge which required re-qualification of the heritage hardware as well as thorough integrated testing to support flight certification. Examples of the challenges that were overcome include: re-qualifying heritage hardware to survive new shock and vibration environments, certifying performance of extensively modified heritage hardware, regenerating design insight due to lack of available heritage vendor data, showing compliance to modern structural design standards, translation of heritage requirements for analog avionics to modern digital avionics, and interfacing heritage mechanical hardware with newly designed avionics. This paper is the second installment in a seven-paper series surveying the design, engineering, test validation, and flight performance of the Core Stage Thrust Vector Control system. This paper will discuss several engineering challenges encountered during the

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development process for SLS CS TVC and how they were successfully overcome to reach flight readiness.

INTRODUCTION

The Space Launch System (SLS) Core Stage (CS) Thrust Vector Control (TVC)) System provides the capability to position the SLS RS-25 Core Stage Engines (CSEs) thrust vector as well as provide hydraulic power to the CSE hydraulic actuation system (HAS) propellant control valves.

The CS TVC system consists of four main assemblies: the TVC actuators and controllers which provide thrust vector control, the Core Auxiliary Power Units (CAPUs) and controllers which provide hydraulic power, the hydraulic system components which support the operation of the TVC system, and the pre-launch thermal conditioning components which maintain acceptable hydraulic fluid temperature prior to launch.

There are two thrust vector control actuators for each of the four RS-25 engines, one located in the pitch axis, and one located in the yaw axis. The actuators provide the force and control capability to position the engine nozzles for vehicle steering. All eight actuators communicate to four actuator controllers. The hydraulic power assembly includes a single CAPU and single CAPU controller, and the hydraulic main pump. The hydraulic system components consist of a reservoir, filter module, supply accumulator, return accumulator, quick disconnects, flex hoses (gas and hydraulic), exhaust gas heat exchanger, exhaust flex duct, and check valves. The pre-launch thermal components include a circulation pump and line wrap heaters. The CS TVC system is designed to be single fault tolerant at the system level, although select sub-components require additional redundancy as defined within the component specifications.

The TVC system design leverages hardware from the Space Shuttle program as well as new hardware designed specifically for the Core Stage. The Space Shuttle heritage hardware directly reused on SLS includes the Orbiter Type III TVC hydraulic mechanical feedback servo-actuators (with two slight design modifications), the Orbiter hydraulic circulation pumps, the Orbiter gimbal block/bearing, and the Solid Rocket Booster hydraulic pumps. The Core Auxiliary Power Unit (CAPU) is derived from the Orbiter Auxiliary Power Unit (APU). The Orbiter and Solid Rocket Booster APU turbines are powered by hot gas produced by catalyzed hydrazine decomposition. On the SLS Core Stage, the CAPU turbine is spun using cold gas tapped-off from the RS-25 to CS liquid hydrogen autogenous pressurization line. This paper will focus on the challenges of integrating the heritage hardware into the new design and the efforts to overcome those challenges. It is not intended to be an exhaustive listing of all the challenges encountered along the almost decade long journey to the first SLS launch.

REQUIREMENTS CHALLENGES

There were several challenges that the SLS TVC team faced regarding requirements. First, for many of the components used from the Space Shuttle on SLS the predicted environments were greater than those to which the components were originally qualified. This meant that the heritage components would have to undergo testing and/or analysis to show that the components would survive and perform in these higher environments. This put the heritage hardware at risk of component failures during qualification testing which had the potential to drive cost and schedule impacts. For example, the circulation pump environments were higher, but the pump was only active during ground operations which provided relief for the pump having to operate during the high vibration environment. On the CAPU a vibration isolating platform was designed to mitigate the higher vibration environments from impacting the CAPU and Main Pump (which is mounted to the CAPU). However, with the actuator, it was noticed during development testing that the mechanical feedback linkage internal to the actuator which mechanically communicated the achieved actuator position to the four servo-valves on the actuator had a resonance at one of the higher magnitude portions of the vibration environment. This resonance caused the actuator position to shift randomly by a small amount while the actuator was experiencing the environment. This finding led to a series of activities including the exploration of potentially substantial design changes. The result of a more involved development test program for the actuator was a minimal design change to increase the spring rate of preloading springs in the mechanical feedback mechanism. This improved the robustness of the actuator design to perform in the vibration environments. A side benefit of the vibration testing on the SLS actuators is that it confirmed the known resonance frequencies of the actuator internal modes associated with the position feedback mechanism. The piston position sensor data from this vibration test were later important to illustrate the need for specific anti-aliasing filters prior down sampling for telemetry.

The design and construction standards levied on the SLS program were different than the practices used during the development of the Space Shuttle hardware. This required an assessment of the heritage hardware design standards compared to the SLS requirements. This assessment resulted in some of the SLS standards being waived for the heritage hardware and replaced with the standards used in the original hardware development. This process required a significant time investment for the responsible engineers and systems engineering and insight to review and manage these waivers through the process. As an example, the proof and burst factors for heritage components had to be reassessed but Environmental Correction Factors (ECF) were not part of the original assessment for the main pump and actuators. This error was caught after the main pump proof test had been completed. Applying the environmental correction factor would have increased the pressure applied during the test. Ultimately waivers were processed for both the main pump and actuator exempting both components from the environmental correction factor. Adding waivers for specific components and assessing heritage standards compared to the modern versions expended valuable engineering resources whereas a blanket acceptance of the heritage hardware could have mitigated this effort.

There were also issues with translating heritage requirements for analog avionics to modern digital avionics. Even an experienced engineer when tasked with migrating heritage requirements to a new hardware specification, can introduce unforeseen issues. Design intent is not always conveyed accurately through requirements. Requirements can often be open to interpretation when not clearly stated. An example of this occurred with the TVC Actuator Controller (TAC) development. The TAC is not heritage hardware but was designed by utilizing the same requirements that developed the heritage Space Shuttle avionics box called the Ascent Thrust Vector Controller (ATVC). The ATVC performed multiple functions for all the Shuttle thrust vector control hardware and the TAC performed most of the same function for the SLS CS TVC system. Duplicating this functionality in the TAC, and converting from an all-analog device to a digital device with some analog features proved challenging. The digital anti-aliasing filters for telemetered data were missed in the initial creation of the requirement set for the TAC. Furthermore, the use of the heritage specs to design the TAC rather than ensuring consistent performance with the heritage ATVC led to some unintentionally degraded behavior, observed after the TAC design was integrated to flight hardware. The behavior, discussed in companion paper [5], was an amplitude dependent scale factor nonlinearity in the servo amplifier circuitry that needed to be accounted in the evaluation of TVC response data in the lab and at the Green Run test campaign. A unique feature of the heritage actuators is the servo-channel delta pressure equalization and bypass functionality whereby the ATVC and for SLS, the TACs, would acquire the servo-channel delta pressure for each of the four servo-valves, and if that channel were to exceed a certain threshold, would apply current to the valve in the opposing direction. This would effectively slow down a servo-valve moving to a hard-over condition until that delta pressure exceeded a higher threshold, after which the channel would be bypassed. This fault detection logic was initially incorporated incorrectly into the TAC and the algorithm had to be restructured to achieve the desired fault detection performance. This further emphasized the importance of understanding the design intent, as well as the full requirements set for heritage hardware.

These requirements challenges and others occurred throughout the design cycles were all driven by the incorporation of the heritage hardware. That is not to say that an all-new design would have been free from issues or challenges, but rather to point out the ones that surfaced with the reuse of heritage hardware in a non-heritage way.

SYSTEM DESIGN CHALLENGES

There were several design challenges that were the direct result of the chosen TVC system architecture on SLS Core Stage which deviated in a few distinct ways from the heritage systems on both the Space Shuttle Orbiter and SRB. The APU power source was changed from hot gas decomposed from liquid Hydrazine flowed over a catalyst bed to cold gaseous Helium from the ground supply (prior to engine start) and Hydrogen gas from the autogenous pressurization line from the RS-25 Engine (following engine start). The hydraulic reservoir type was changed from a bootstrap design to a gas pre-charged metal bellows and the hydraulic fluid volume was reduced from the Orbiter design. The hydraulic circulation pump was used directly from the Space Shuttle Orbiter, but it was plumbed into the hydraulic system on SLS differently than on Orbiter.

At first glance, the removal of hydrazine from the Core Stage seems like a good design practice since the liquid propellant is known to be a carcinogen and requires special handling procedures for fuel loading, storage, and decontamination of hardware. Additionally, opting to use the high-pressure hydrogen gas coming from the RS-25 tank pressurization line as the working fluid to spin the CAPU turbine is essentially a “free” power source as it would either be used to pressurize the liquid hydrogen tank or vented overboard. This change to the Orbiter and SRB APU architecture precipitated additional changes and many challenges that the SLS TVC had to overcome along the way. The Space Shuttle Program had performed a series of tests in the early 2000’s timeframe related to potential upgrades for the SRB APU that would eliminate hydrazine from the system. Several upgrade options were tested, but the only option that was able to perform without a reduction of requirements was the gaseous helium spun APU. During the Constellation Program the Ares Upper Stage had conducted development testing of a Delta IV turbine assembly that could potentially do the same job but was plagued with turbine bearing failures during development testing. The failures were related to bearing lubrication. Further discussion of the CAPU challenges will be detailed in the performance challenges section below.

The particular issue with proof and burst testing on the main pump referenced above in the requirements challenges section was exacerbated by the fact that the hydraulic system return pressure for SLS Core Stage was significantly higher than both Orbiter and SRB systems. The higher return pressure was the result of changes to the overall hydraulic system design from Orbiter and SRB, particularly the inclusion of a gas pre-charged metal bellows type reservoir on the Core Stage as opposed to the bootstrap reservoirs on Orbiter and SRB. The bellows reservoir retained warm hydraulic fluid after the system was shutdown which caused the return pressure to increase as the bellows volume increased. The resulting return pressure for SLS was almost double the heritage return pressure. As stated previously, a proof and burst test were performed on the main pump at these higher pressures and there was data from the Space Shuttle Program that indicated the pump would withstand these pressures, but the lack of ECF inclusion still resulted in the need for a waiver.

The circulation pumps are electric motor drive dual output gear pumps used to circulate hydraulic fluid in the TVC systems to maintain the hydraulic temperature above a specific level to keep the hydraulic fluid from freezing when the Core Stage propellant tanks are filled with cryogenic liquid hydrogen. The RS-25 engine has hydraulically actuated throttle valves referred to as the Hydraulic Actuator System (HAS). The fluid routed to those valves must be kept warm enough to allow the valves to operate when the RS-25 engines are started. On Orbiter there was a high flow and a low flow output that were plumbed separately for different functions. On SLS those two outputs were tied together and the needed flow rate to circulate hydraulic fluid was somewhat less than the pump capability. The circulation pump vendor was no longer available to consult on this change in operation for the circulation pump, so a series of development tests was devised to understand the capability of the pump to sufficiently heat the hydraulic fluid. Also, due to the lack of vendor involvement, a test stand was constructed to perform the development testing as well as the acceptance testing for the flight hardware.

These system design challenges serve to illustrate that combining heritage hardware from different systems, reusing components in different configurations, and using hardware with scarce original design insight remaining can introduce unforeseen issues into the design and development phases of a rocket program.

PERFORMANCE CHALLENGES

Some of the most difficult challenges for Core Stage TVC were related to the CAPU which transformed from heritage hardware to extensively modified heritage hardware over the course of the development of the Core Stage TVC system. Initially the main CAPU modification was the change in working media for the turbine as described previously. To achieve the necessary gas flow rates into the turbine, larger flow rate control valves were required. These larger valves which had been direct acting solenoids on the SRB and Orbiter APUs now required pilot stages to work properly. The valves incorporated were based on a Commercial off the Shelf (COTS) valve design widely used in industry. After development testing was underway those valves required some redesign and the results of the testing ultimately led to moving from a 2-valve control scheme, which was used on SRB and Orbiter with a primary and redundant valve, to a single valve scheme. This moved the redundancy management to the vehicle level rather than holding it at the CAPU level. Whereas on SRB and Orbiter, if a primary control valve failed open, the APU controller would move the system to use the secondary valve for control, now the Core Stage would command the CAPU with a stuck open valve to shut down causing further redundancy management actions. The CAPU originally used a bang-bang control scheme, just like SRB and Orbiter APU, but with a more energetic propellant, came higher than expected induced loads. The original design for the gas inlet tubing into the CAPU allowed for an “accumulator” effect which drove a failure of the inlet filter due to an unanticipated reversing gas flow condition. This was corrected by shifting to a single inlet for both hydrogen and helium instead of separate inlets as the system was originally designed.

These challenges were eventually all overcome, and a successful qualification program was completed. The CAPUs all performed as expected through integrated subsystem testing, Core Stage Green Run Testing, Artemis 1 Wet Dress Rehearsal, and Artemis 1 Flight. Utilizing the heritage APU was originally intended to be a wise use of heritage assets that ended up as a significant challenge to overcome.

The other performance challenges associated with the TVC command response are covered in the companion papers [1-5]. Despite the use of heritage gimbal bearing, RS-25 engine, and heritage actuators, the newly designed core stage and thrust structure was different than on the Shuttle.

Furthermore, application of extended frequency testing and nozzle/engine position instrumentation revealed some new behaviors not revealed during the Shuttle program. This additional testing, largely conducted during the Green Run test campaign, was critical to uncover key behaviors relevant to the SLS core stage system response and provided confident flight rationale for the highly successful flight of Artemis 1.

OPERATIONAL CHALLENGES

There were several operational challenges the team faced in getting the Core Stage TVC System ready for launch on Artemis 1. The CAPU vendor changed the lube oil de-servicing procedure from how it was performed on Shuttle, a new ground hydraulics system was developed for use on the Mobile Launcher (ML), and the circulation pumps were powered by a new electrical power system.

The CAPU gearbox is lubricated with oil. If there is too much oil in the gearbox the gears will drag in the oil and the oil will overheat. A long-standing oil removal or de-servicing procedure was updated. The oil was removed at the vendor following acceptance testing prior to shipping. The update allowed oil to be removed, but not accurately tracked, and residual oil was left in the gearbox. The flight CAPUs were shipped with residual oil and then subsequently filled with the appropriate amount of oil leaving the gearboxes overfilled with an unknown quantity of oil. This error was realized when another CAPU showed signs of an overfilled gearbox during a test. Once the error was noted and a corrective action devised, the CAPUs already installed on the vehicle had to be de-serviced and re-serviced with oil to ensure the correct amount to avoid the possibility of an issue during the Core Stage Green Run testing.

A new ground hydraulic servicing system was developed for the mobile launcher which was designed to maintain a certain return pressure on the systems using back-pressure regulators, but only when hydraulic fluid was flowing above a certain rate. Due to the vehicle being located well above the servicing system in the Mobile Launcher base, this allowed the return pressure to drop to vacuum levels during testing while a valve configuration was being changed. This was an unexpected occurrence that happened during the first time the ground hydraulics were used with the system. This condition had to be evaluated to ensure no damage was done to the flight hardware, particularly the heritage main pump. It was determined that no damage occurred, and operational adjustments and procedural updates were made to ensure this issue did not recur. The damage assessment was further complicated by the improper orientation of a drain port on the main pump. This port was oriented in such a way to make routing the vehicle plumbing simpler, but it prevented the cavity between the CAPU and main pump to be drained. The performance of the main pump and CAPU during Green Run and Wet Dress Rehearsal were used to show that no lasting impact from the event had been incurred.

The circulation pump power issue was related to high in-rush current and resultant over-voltage protection issues on SLS. The Orbiter powered the pumps directly from the on-board power busses, with comparatively short power cable runs to the pumps. SLS powers the pumps via power supplies located on the ML, and has much longer cable runs from the power supplies, across the length of the umbilical arms, through the umbilical plates, and over to the pumps in the Core Stage Engine Section. This exacerbated the effects of in-rush current at start up, and reduced the available margin on over-voltage protection, such that a very narrow window of power supply settings was required to achieve circulation pump start-up. The issue first appeared at MAF during engine section checkouts, a second time at Stennis during the Green Run test campaign, and a third time at KSC during the first Wet Dress Rehearsal. MAF and Stennis used similar power supplies and intentionally long cabling to simulate the KSC installation, however the required settings were so fine that they still had to be specifically tuned for each location to achieve pump start-up. Prior to KSC operations, a mockup of the ML power system was also built up in the TVC Test Lab at Marshall to further characterize and select the proper power supply settings. Additionally, after the first failed start-up attempt during WDR, contingency steps were written into the launch countdown procedures to temporarily bypass over-voltage protections if required. The ML power supply settings were ultimately fine-tuned such that those contingencies were not needed, and the circulation pumps were all successfully started for the subsequent wet dress rehearsals and launch attempts.

Changing the operational procedures and ground hardware impacted the way the heritage hardware was processed and how it performed. These issues were ultimately mitigated operationally, but not without significant effort.

CONCLUSION

Heritage hardware can be an easy plug and play option if the hardware is well understood and documented, the original vendor is engaged, the subsystem into which the hardware is incorporated is designed to replicate as closely as possible the original system, the heritage requirements envelope the new system requirements, and careful attention is applied throughout the vehicle design process. Else, there can be a myriad of challenges for the program to overcome.

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