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Delta-Qualification Test of Aerojet 6 and 9 lbf MR-106 Monopropellant Hydrazine Thrusters for Use on the Atlas Centaur Upper Stage During the Lunar Reconnaissance Orbiter (LRO) and Lunar Crater Observation and Sensing Satellite (LCROSS) Missions

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This paper discusses a Delta-Qualification test of Aerojet's 6 and 9 lbf monopropellant hydrazine MR-106 thrusters for use on the Atlas Centaur upper stage while operating in an atypical mode and for an extended period of time. This qualification testing was performed in support of the Lunar Reconnaissance Orbiter (LRO) and Lunar Crater Observation and Sensing Satellite (LCROSS) missions. The primary objective of the LCROSS mission is to determine the presence or absence of water ice in a permanently shadowed crater near a lunar polar region. The accomplishment of this objective requires that the Atlas V rocket's Centaur upper stage perform a LCROSS orbit insertion as well as a fly-by of the moon before the Centaur upper stage crashes into a lunar crater to create a debris plume. The LCROSS satellite will pass through the debris to collect and relay plume constituent data back to Earth. Prior to the LCROSS separation from the Centaur upper stage, the Centaur pneumatic pressurization system will transition from regulated to blow-down mode, which requires that the thrusters operate at a lower propellant feed pressure than had previously been qualified. Furthermore, the Lunar Reconnaissance Orbiter (LRO) will be launched simultaneously with LCROSS, requiring the Centaur stage to be responsible for additional maneuvers to position the LRO spacecraft on its correct trajectory. For a more typical mission, the Atlas V Centaur upper stage is not used after spacecraft separation. Since the Centaur upper stage will accompany the LCROSS satellite to the moon, and because the Aerojet Rocket Engine Modules (REMs) that are installed on the Centaur upper stage will be partially responsible for performing the lunar trajectory maneuvers en route to the moon for both the LRO and LCROSS spacecrafts, additional life and low pressure operation beyond that which was qualified for the REMs was required. In June of 2008, Delta-Qualification testing on an Aerojet MRM-106D Centaur REM successfully validated the engines' capability of achieving these mission needs with margin.

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Nomenclature

F = Thrust
Ft = Feet
Hr = Hour
Hz = Hertz
I_{sp} = Specific Impulse
I_{tot} = Total Impulse
Km = Kilometer
lbf = Pounds-Force
N = Newtons
N_2H_4 = Hydrazine
P_c = Chamber Pressure
P_f = Feed Pressure
$psia$ = Pounds per square inch
R_{2S} = 2-Sigma Peak-To-Peak Roughness
R_{pp} = Average Peak-To-Peak Roughness
S = Second

Acronyms

ATP = Acceptance Test Procedure
BOL = Beginning of Life
DC = Duty Cycle
EOT = End of Test
GSO = Geostationary Orbit
GTO = Geostationary Transfer Orbit
HF = Hot-Fire
LCH = Low Cost Hydrazine (type of Aerojet catalyst)
LCROSS = Lunar Crater Observation and Sensing Satellite
LRO = Lunar Reconnaissance Orbiter
MR = Monopropellant Rocket
MRM = Monopropellant Rocket Module
REA = Rocket Engine Assembly
REM = Rocket Engine Module
UV = Ultra-Violet

I. Introduction

The Lunar Reconnaissance Orbiter (LRO) and the Lunar Crater Observation and Sensing Satellite (LCROSS) missions are planned to launch together aboard a single Atlas V launch vehicle during the summer of 2009. The LRO and LCROSS missions require that the Aerojet MRM-106D Rocket Engine Modules (REMs), which are located on the Atlas V's Centaur upper stage, operate in an atypical mode that had not previously been demonstrated. Total impulse (I_{tot}), long duration burn, and blow-down operation mission needs required that the Centaur REM undergo a delta-qualification effort to demonstrate the ability of the REM to meet the LRO/LCROSS mission requirements.

The LRO spacecraft, depicted in Figure 1, will sit atop the LCROSS spacecraft during launch, and will separate from the LCROSS spacecraft approximately one hour after launch[1]. After four days of travel toward the moon, LRO will be placed into an elliptical "commissioning orbit", and then into the final circular polar orbit at an altitude of 50 km for a 1-year mission[2]. LRO's objectives are to identify safe lunar landing sites, locate potential resources, characterize the radiation environment, and demonstrate new space technology[2]. The spacecraft will return global data, such as day-night temperature maps, a global geometric grid, high resolution color imaging, and the moon's Ultra-Violet (UV) albedo[2]. Particular emphasis will be placed on the moon's polar regions because one offers continuous solar illumination for solar power and the other may have water-ice because it is permanently shadowed.

The LCROSS spacecraft, depicted with the Centaur upper stage in Figure 2, will search for water on the moon. To do so, the Centaur upper stage will crash into the moon at nearly 9,000 km/hr creating a crater at the moon's permanently shadowed southern polar region, as well as a debris field through which the LCROSS spacecraft will fly approximately four minutes later[3]. The Centaur stage impact site will be determined using data collected by the LRO spacecraft[4]. The debris field created could potentially contain water vapor and/or water-ice. The constituents of the debris field will be analyzed by LCROSS's on-board instruments to determine whether or not water or hydrated minerals are present before the LCROSS spacecraft itself impacts the moon[2]. The LCROSS spacecraft, while attached to the Centaur upper stage, will swing past the moon a few days after launch and then enter a high Earth orbit where the pair will remain for nearly four months[5]. LCROSS will separate from the Centaur stage approximately seven hours before impacting the moon[5].

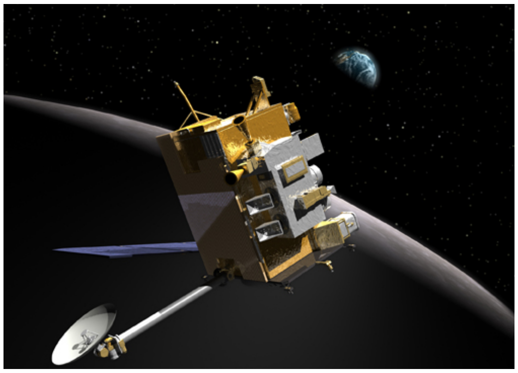


Figure 1. Lunar Reconnaissance Orbiter (Artist's Conception)[2].
Credit: NASA Goddard/Chris Meaney.

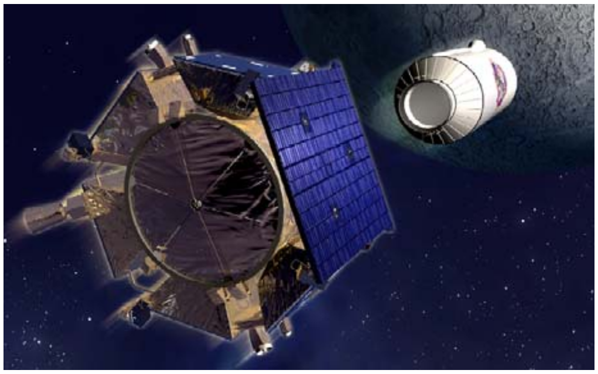
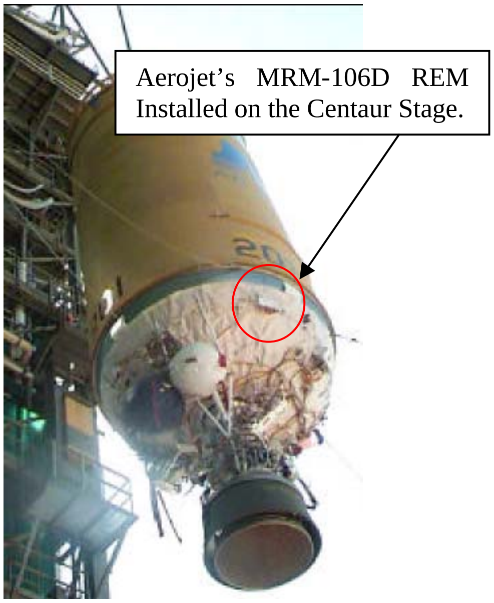


Figure 2. Lunar Crater Observation and Sensing Satellite and Centaur upper stage (Artist's Conception)[6].
Credit: NASA Ames/Northrop Grumman.

Four of Aerojet's MRM-106D REMs are located on the Centaur upper stage. Each Centaur REM has multiple MR-106 monopropellant hydrazine (N_2H_4) engines, for a total of twelve per stage. Figures 3 and 4 show a launch of the Atlas V launch vehicle (left) and the Centaur upper stage (right). There are two REM configurations that are installed on the Centaur upper stage. Two 4-Engine REMs each contain two lateral engines and two axial engines, and two 2-Engine REMs each contain only lateral engines. These two REM configurations are shown in Figures 5 and 6. This REM design was originally qualified in 1999, and experienced a delta-qualification effort in 2001 that increased the qualified random vibration levels.

Figure 3. Launch of an Atlas V launch vehicle.[7]



Aerojet's MRM-106D REM Installed on the Centaur Stage.

Figure 4. Aerojet's MRM-106D REM on the Atlas Centaur stage.[7]

The engines are orificed such that the thrust produced at a propellant feed pressure (P_f) of 450 psia is 9-lbf for the lateral engines (designated MR-106K) and 6-lbf for the axial engines (designated MR-106J). The thrusters are packed with LCH-207 25-30 mesh spontaneous catalyst in the upstream catalyst bed, and LCH-202 14-18 mesh non-spontaneous catalyst in the downstream catalyst bed. The lateral 9-lbf engines provide roll, pitch, and yaw control for the Centaur stage, and the axial 6-lbf engines provide fuel settling prior to starting the Centaur stage's main engine. Each thruster is paired with a single-seat, non-sliding fit propellant valve to provide firing control. The valves are manifolded together within each REM. Due to the relatively short-life application of these engines for Centaur missions, they do not contain valve heaters or catalyst bed heaters.

The MR-106-series thrusters, which were originally developed for the HAS/Peace Courage program over 30 years ago, are inherently robust engines with a long and successful heritage in design, qualification, and flight on both spacecraft (NEAR, Lunar Prospector, Genesis, Mercury MESSENGER, SBIRS, GPS IIR, GPS IIF, LRO, GeoEye-1, IBEX, A2100^{TM}, Star-2^{TM}, various military) and launch vehicles (Atlas and Titan Centaur, Delta III and Delta IV)[8]. Approximately 3,500 MR-106-series engines have been delivered, of which ~2,000 have flown, accumulating over 600 thruster years on orbit.

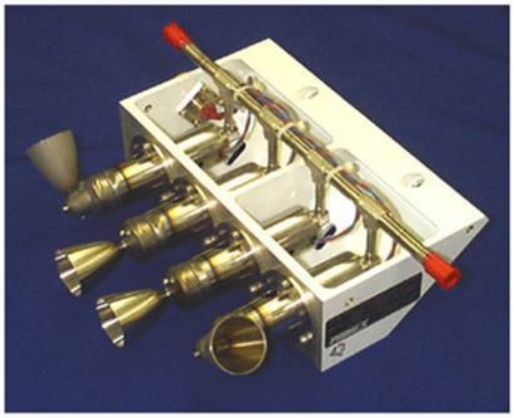


Figure 5. Aerojet's 4-Engine MRM-106D REM.

Figure 6. Aerojet's 2-Engine MRM-106D REM.

The MRM-106D REM design has been used on over 15 successful Atlas launches, with the majority of the Atlas missions being the successful insertion of launch payload into Geostationary Orbit (GSO) or a Geostationary Transfer Orbit (GTO). Similar REM hardware is also used on the Delta IV launch vehicles, though all of the Delta IV REMs are comprised of three 9.0-lbf thrusters—two lateral and one axial. In support of the LRO and LCROSS missions, the Centaur stage of the Atlas launch vehicle will be required to operate in an atypical mode while accompanying its payload to the moon. The LRO and LCROSS missions require that the Centaur REMs be capable of providing significantly higher total impulse, as well as operation under duty cycles (DC) different from which they had previously been qualified. Operation of the REMs under low propellant feed pressure (P_f) conditions is also required because the Centaur stage will operate in a blow-down mode toward the end of the LCROSS mission to deplete excess fuel and Helium pressurant gas prior to the crashing of the Centaur stage into the lunar surface. Required mission maneuvers include long steady-state burns as well as pulse-mode operation.

At the conclusion of the subject delta-qualification test program, the MRM-106D REM had increased the total demonstrated pulse count for the lateral thruster from 7,629 pulses to greater than 9,500 pulses, and from 1,516 pulses to greater than 2,600 pulses for the axial thruster. The lateral thruster had increased the demonstrated total impulse from 21,546 lbf-s to greater than 52,000 lbf-s, and the axial thruster had increased the demonstrated total impulse from 20,521 lbf-s to greater than 42,000 lbf-s. All thrusters survived the delta-qualification program with more life capability evident. As expected, measurable increases in roughness and catalyst bed voiding were noted. Significant catalyst bed voiding was expected because without the presence of a catalyst bed heater, the thrusters do not benefit from the ability to start from a preheated catalyst bed temperature. Firing the thrusters while the catalyst bed is at an ambient start temperature leads to an increase in catalyst attrition and results in faster growth of catalyst bed voids and a decrease of the total life capability of an engine.

II. Test Hardware

The delta-qualification test article was a 4-engine Aerojet MRM-106D REM with a single axial thruster missing (see Figure 7). This REM was originally a deliverable flight unit that was taken out of service and was used for a successful delta-qualification test in 2001. This 2001 test was divided into two phases to qualify the MRM-106D REM for two different random vibration levels, both higher than the original 1999 qualification. Each phase was performed with only two thrusters (one axial and one lateral) installed on the REM. Two thrusters were removed for the first phase, then the two thrusters used in the first phase were removed and the other two thrusters were reinstalled for the second phase. At the conclusion of the 2001 test program, the REM was put into storage at Aerojet with only the two thrusters from the second phase installed. These two thrusters were part of the subject test effort and had been fired extensively during the 2001 test: 2,100 seconds of on-time and 7,300 pulses on the lateral thruster: 3,400 seconds of on-time and 1,400 pulses on the axial thruster. A new and untested lateral thruster was installed on the REM to yield the third engine. Within this document, the lateral and axial thrusters that were fired during the 2001 testing are referred to as the "Used Lateral" and "Used Axial" thrusters respectively. The third thruster that was installed specifically for the 2008 delta-qualification testing is referred to as "New Lateral".

With this REM configuration, it was possible to qualify the MRM-106D REM for higher throughput using the previously fired thrusters, as well as provide a basis of comparison between the beginning of life (BOL) and end of test (EOT) performance of the lateral thruster. Of particular interest for the mission was the worst-case expected blow-down performance. At the point when the Used Lateral thruster started its blow-down performance characterization, it had experienced more firing than would be required during the mission, and therefore provided the worst-case blow-down performance profile for the lateral engines. The blow-down characterization of the New Lateral thruster was performed after firing other mission-related sequences, and better represented the performance that would be expected during the mission. The Used Axial thruster allowed for an efficient means of increasing the qualified throughput for the axial engines because it already had accumulated a significant amount of firing time.

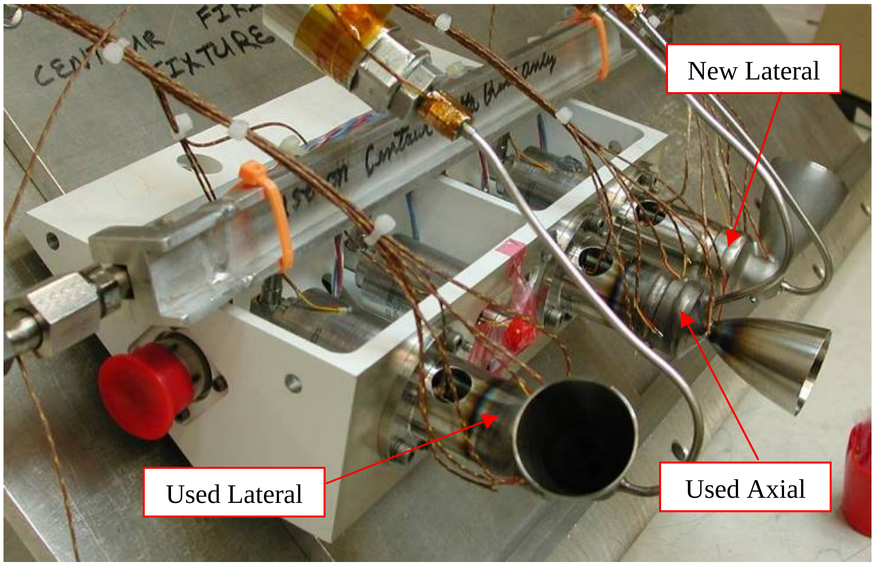


Figure 7. The delta-qualification test article was originally a deliverable Aerojet MRM-106D REM.

III. Delta-Qualification Test Program

Figure 8 presents the delta-qualification test flowplan. The flowplan shows only the delta-qualification testing that was performed in support of the LCROSS delta-qualification effort, which consists primarily of hot-fire testing. The parenthetical descriptions in some test blocks denote which thruster(s) underwent the testing described. Standard MRM-106D REM acceptance test procedure (ATP) hot-fire sequences were fired after each hot-fire test block as a means of monitoring the health of the thrusters. The Used Lateral and Used Axial thrusters experienced random vibration testing and hot-fire testing during the 2001 delta-qualification test effort.

All testing was performed at Aerojet. Functional and catalyst bed X-ray testing was performed at Aerojet's flight hardware assembly and functional testing facility. Hot-fire testing was conducted in a vacuum chamber simulating an altitude of 300,000 ft (91 km) with a vacuum pressure of ~10^{-3} Torr using high-purity grade Hydrazine per MIL-PRF-26536E[9].

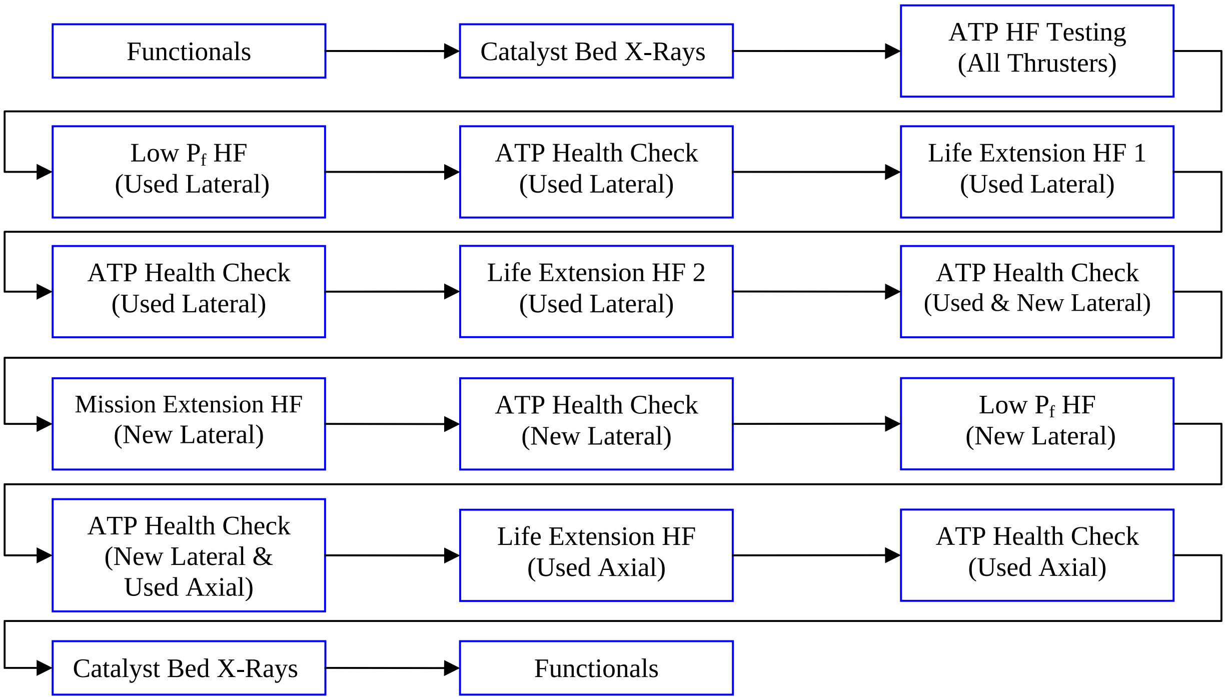


Figure 8. Delta-qualification test flowplan

A. Functional Testing

The purpose of the functional testing shown in Figure 8 is to ensure that the hardware's mechanical and electrical operational requirements were met throughout life. Functional testing includes internal valve seat leakage, external leakage up-to and including the nozzle with the valve seat open and the nozzle plugged, proof pressure testing with the valve seat open, proof pressure testing with the valve seat closed, gas flow testing, insulation and circuit resistance for the valves, and valve voltages for pull-in and drop-out. Since no dynamic/environmental testing was incorporated as part of this delta-qualification test program, no interface dimensions were inspected during this program. Functional test requirements were developed with Aerojet's assistance using the valve's component specification as well as historically acceptable criteria. The delta-qualification test program completed successfully with no identifiable shifts in the mechanical or electrical performance of the REM and its components.

B. Catalyst Bed X-Rays

The purpose of the catalyst bed X-rays was to provide a non-destructive inspection of the catalyst bed before and after hot-fire testing. Catalyst bed X-rays are used to evaluate catalyst bed looseness and void size, as well as the health of the internal components of the thruster. Because the test article had previously been used for a delta-qualification effort in 2001, it was expected that there would be a sizeable catalyst bed void in the Used Lateral and Used Axial thrusters. The pre-test catalyst bed X-ray confirmed this. The New Lateral thruster was confirmed to have no measureable void space prior to hot-fire testing. Post hot-fire testing catalyst bed X-rays indicated measureable increases in catalyst bed void size for all thrusters. Table 1 summarizes the catalyst bed void sizes at the beginning and end of testing for all thrusters. A more significant increase in catalyst bed void size occurred with the Used Lateral thruster because it experienced significantly higher total throughput than the New Lateral thruster.

Table 1. Beginning and End of Test Catalyst Bed Void Sizes

Parameter	Used Lateral	Used Axial	New Lateral
Beginning of Test Void Volume (% of Upstream Catalyst Bed Volume)	18	8	0
End of Test Void Volume (% of Upstream Catalyst Bed Volume)	36	12	8

C. ATP Hot-Fire

The ATP hot-fire matrix is comprised of four sequences, and subjects the thrusters to both steady-state and pulse-mode operation. ATP hot-fire sequences are used during production to demonstrate specification conformance and acceptability of each deliverable item, and validate that an engine operates in a smooth, consistent, controlled, and expected manner. They also serve as a wear-in test to detect material or workmanship defects. Over the course of the hot-fire portion of the delta-qualification program, these ATP sequences were fired as health monitoring sequences to ensure that thruster operation had not severely degraded as a result of any specific portion of the hot-fire testing. None of the ATP health checks suggested that any of the tests were particularly damaging to the engines.

D. Low P_f Hot-fire

The purpose of the low P_f sequences was to characterize the lateral thruster performance as propellant feed pressure decreases. The LRO/LCROSS mission requires that the REM's lateral thrusters be capable of operating in a blow-down mode. To demonstrate the ability to operate as required for the mission and to characterize the REM's performance at lower propellant feed pressures, delta-qualification testing subjected the REM's lateral thrusters to operation at a variety of propellant feed pressures ranging from 450-75 psia. This performance characterization involved the repeated firing of the standard ATP sequences through this pressure range on both the Used Lateral thruster as well as the New Lateral thruster. Exposing both the used and New Lateral thrusters to this testing demonstrates that the thrusters are capable of operation at a range of propellant feed pressures both at BOL and EOT. The REM's axial thruster was not exposed to this low propellant feed pressure testing because this mission will only fire the lateral pitch/yaw thrusters once blow-down operation begins. Figure 9 shows the steady-state thrust as a function of propellant feed pressure for both the New and the Used Lateral thrusters. Figure 10 shows the specific impulse (I_{sp}) as a function of propellant feed pressure for the new and the Used Lateral thrusters. Despite accumulating a significantly higher total impulse, thrust and I_{sp} for the Used Lateral thruster was comparable to the New Lateral thruster. The difference between the two engines is attributable to slightly different orificing and normal engine-to-engine variation, even for BOL data.

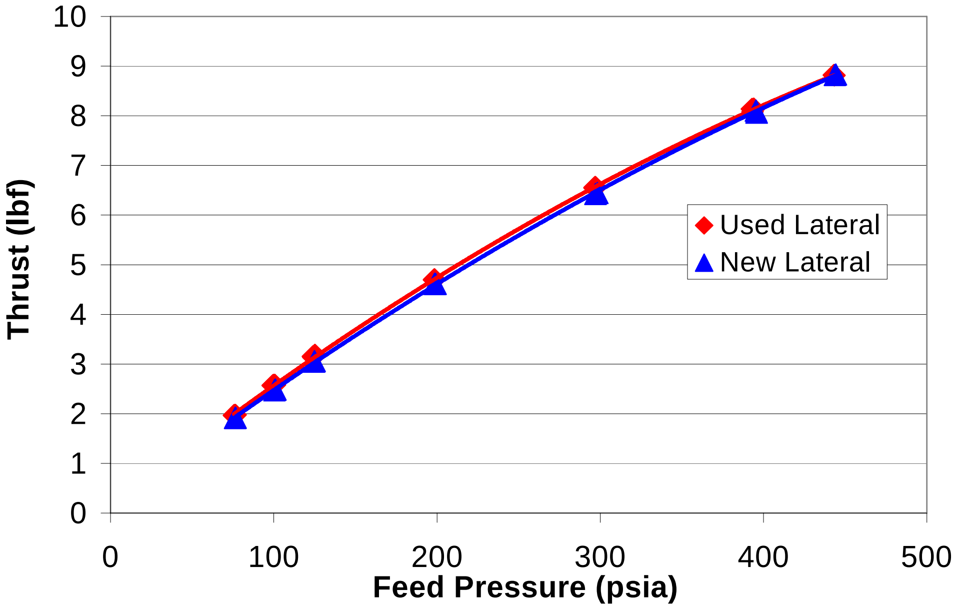


Figure 9. Steady-State Thrust vs. Propellant Feed Pressure for Lateral Thrusters. The difference between the engines is ~1-2% and is within normal variation.

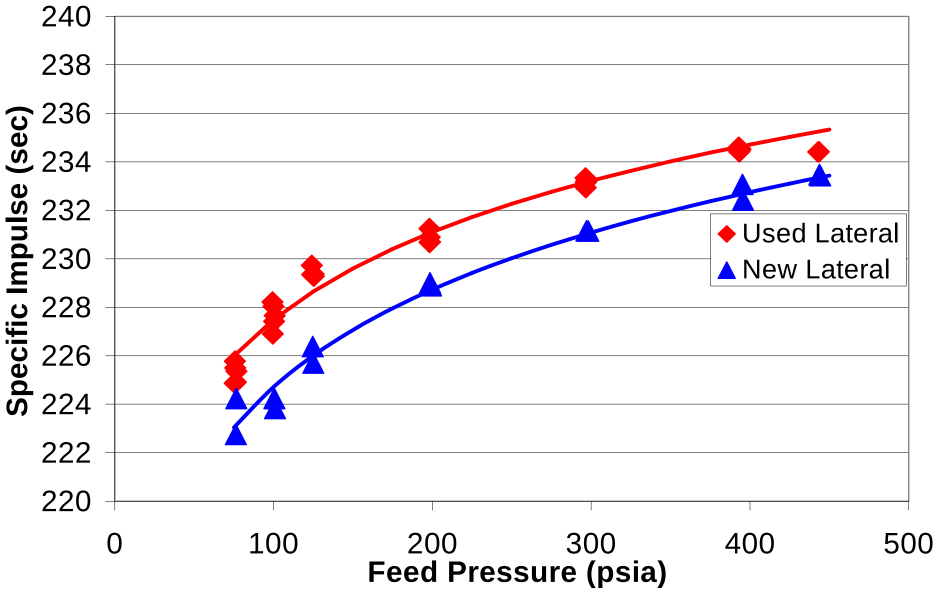


Figure 10. Steady-State Specific Impulse vs. Propellant Feed Pressure for Lateral Thrusters. The difference between the engines is ~1% and is within normal variation.

F. Life and Mission Extension Hot-Fire

The purpose of the life and mission extension hot-fire sequences was to increase the qualified total throughput for the thrusters on the REM. Life extension hot-fire sequences included both pulse-mode and steady-state sequences. During this testing, the longest qualified steady-state firing on the axial thruster was extended from 1,000 seconds to 1,500 seconds. From these sequences, an additional 19,500 lbf-s of impulse was accumulated on the Used Axial thruster, and an additional 23,000 lbf-s of impulse was accumulated on the Used Lateral thruster. Figure 11 shows the steady-state thrust as a function of cumulative total impulse for all three thrusters on the test unit. Figure 12 shows the steady-state specific impulse (I_{sp}) as a function of cumulative total impulse for all three thrusters on the test unit.

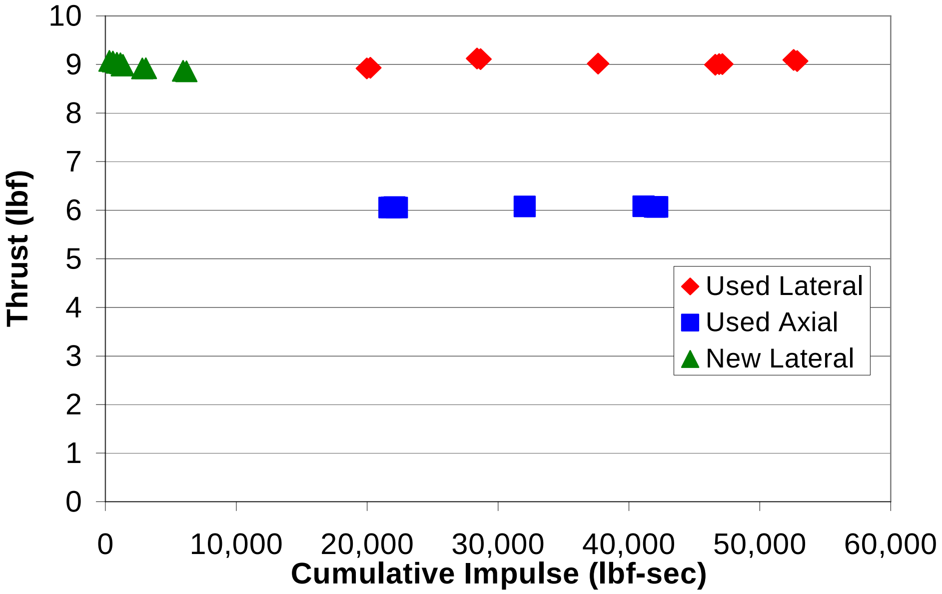


Figure 11. Steady-State Thrust vs. Cumulative Impulse at P_f=450 psia for ATP Sequences. There was no identifiable decay in thrust outside of normal variation.

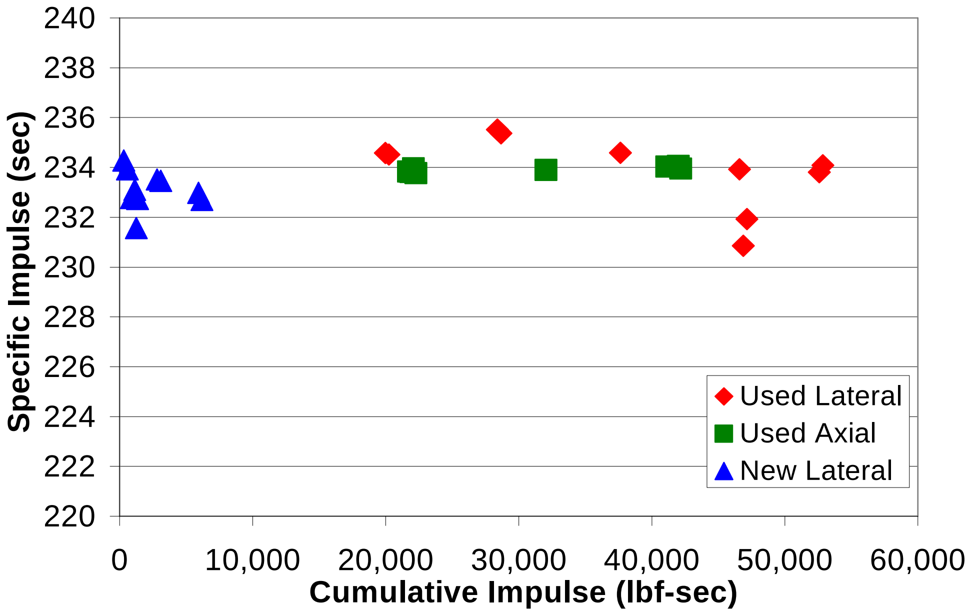


Figure 12. Steady-State Specific Impulse vs. Cumulative Impulse at P_f=450 psia for ATP Sequences. There was no identifiable decay in Specific Impulse outside of normal variation.

Figure 13 shows the pulse-mode impulse bit as a function of cumulative impulse at a propellant feed pressure of 450 psia for three different duty cycles (D.C.). Impulse bit remained relatively constant throughout all testing, despite the significant increase in total impulse. Figure 14 provides the pulse-mode impulse-bit as a function of P_f for the used and New Lateral thrusters. Despite accumulating a significantly higher total impulse, there was no identifiable decay in impulse bit for the Used Lateral thruster, indicating that the reactivity of the LCH catalyst did not significantly degrade.

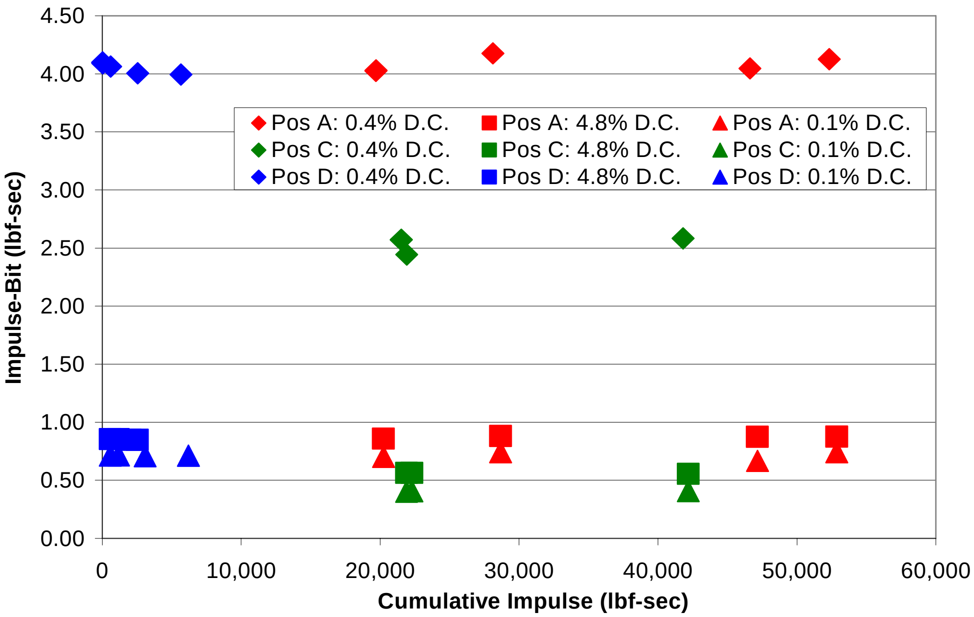


Figure 13. Pulse-Mode Impulse bit vs. Cumulative Impulse at P_f=450 psia for ATP Sequences. There was no identifiable decay in Impulse bit outside of normal variation.

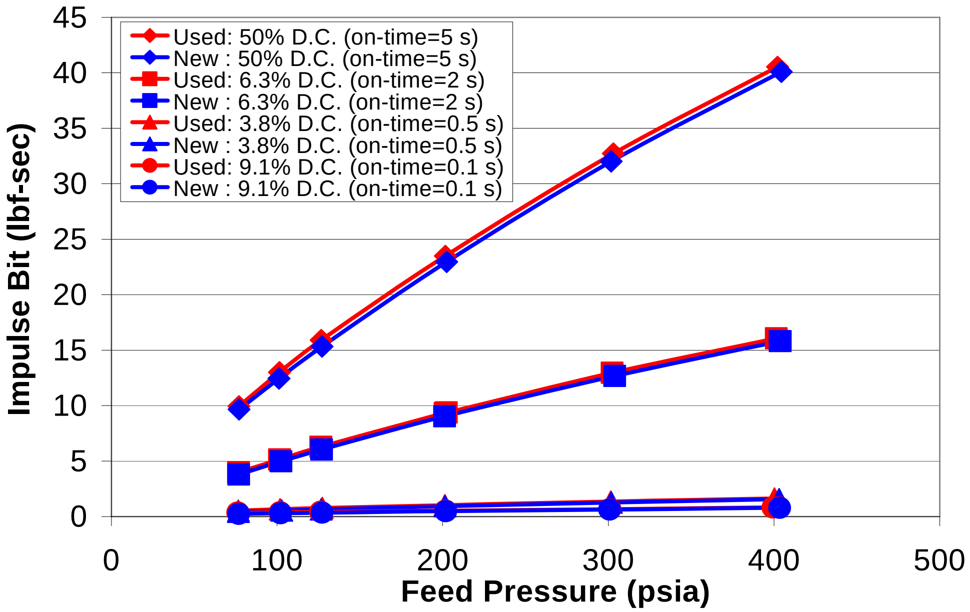


Figure 14. Pulse-Mode Impulse bit vs. Propellant Feed Pressure for the New and Used Lateral Thrusters. Despite accumulating a significantly higher total impulse, there was no identifiable decay in impulse bit for the Used Lateral Thruster, indicating that the reactivity of the LCH catalyst did not significantly degrade.

Peak-to-peak chamber pressure roughness (R_{pp}) is a useful parameter for evaluating the health of the catalyst bed during a steady-state firing. R_{PP} is defined as one-half the difference of the maximum and minimum chamber pressure measurements made during a one second time sample. It is sometimes expressed as a percentage by dividing by the average chamber pressure (P_c) measured during the same time sample. Average R_{PP} is the average of these values throughout an entire steady-state burn. Figure 15 shows the average R_{PP} as a function of cumulative impulse for all three thrusters. Traces of P_c vs. time for 30 second steady-state burns are also provided in Figure 15. The figure shows that roughness increased with accumulated throughput.

At the beginning of this delta-qualification program's testing, the Used Lateral thruster exhibited an average R_{pp} of ±10% at a P_f of 450 psia, and ±50% at the lowest run P_f of 75 psia. This difference is a result of both the average P_c during the steady-state sequence being lower, the natural rougher performance of an engine while operating at a lower P_f, as well as more cumulative total impulse. At the conclusion of hot-fire testing on the Used Lateral thruster, average R_{pp} was ±10% at a P_f of 450 psia, a slight increase over the course of the delta-qualification program.

At the beginning of this delta-qualification program's testing, the average R_{pp} for the New Lateral thruster was ±2% at a P_f of 450 psia, and ±34% at a P_f of 75 psia. At the conclusion of testing, R_{pp} had increased to ±6% at a P_f of 450 psia, an increase of approximately 4% over the course of the delta-qualification program.

At the beginning of this delta-qualification program's testing, the average R_{pp} for the axial thruster, which only experienced hot-fire testing at a P_f of 450 psia, was ±11%. At the conclusion of the delta-qualification program, roughness had increased only slightly.

These results show that steady-state operation and performance of the REAs was relatively smooth and stable throughout the test. Roughness tended to increase early in life, and then leveled off as life was accumulated on the REAs, which is typical for monopropellant Hydrazine thrusters. After the initial rise at BOL, roughness never again had a sharp increase, indicating that the test concluded with catalyst bed margin.

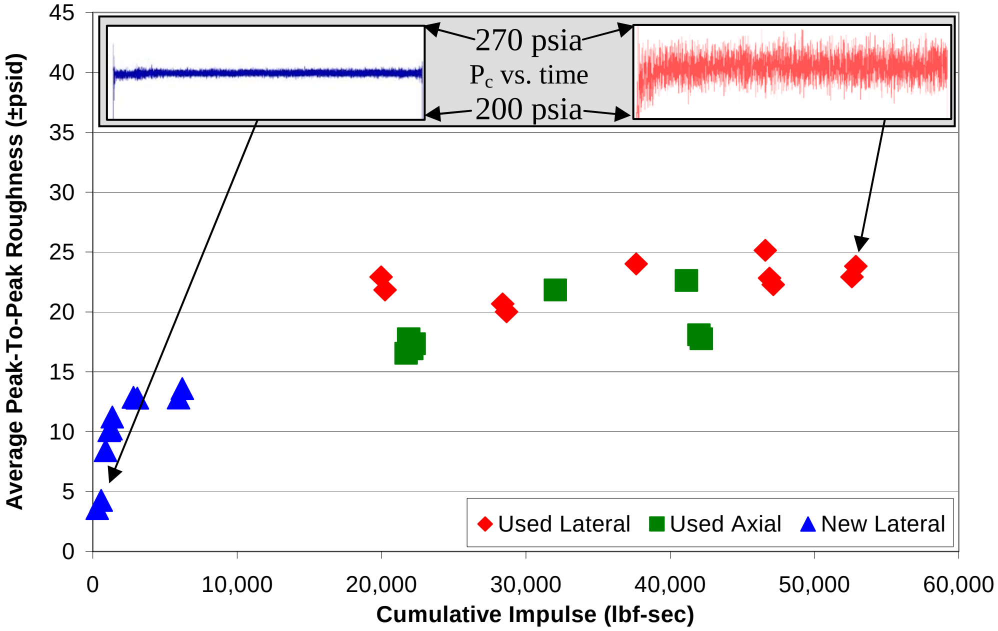


Figure 15. Average R_{pp} vs. Cumulative Impulse at P_f=450 psia for ATP sequences. Chamber Pressure vs. Time is provided for a 30 second steady-state burn for the New Lateral thruster at the beginning of the test (blue P_c trace at upper left) as well as for the Used Lateral thruster at the end of the test (red P_c trace at upper right). The sharpest rise in roughness occurred at the beginning of life for the New Lateral thruster, which is typical for monopropellant Hydrazine engines.

IV. Conclusions

The Rocket Engine Assemblies (REAs) on the Aerojet MRM-106D Rocket Engine Module (REM) have demonstrated the ability to operate successfully with margin for use on the Atlas V launch vehicle's Centaur upper stage during the Lunar Reconnaissance Orbiter (LRO) and Lunar Crater Observation and Sensing Satellite (LCROSS) missions. Even with increased roughness and substantial catalyst bed void growth, roughness did not grow at a an alarming rate and both steady-state and pulse-mode performance remained relatively constant and consistent throughout the life tests, indicating that the engine design is robust and that further margin existed for the mission needs. This qualification effort has opened the door to a wide range of potential new missions for the Atlas V launch vehicle's Centaur upper stage.

V. References

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