WHITE PAPER

Pathfinder Test Results for a Rocket Engine Module Consisting of Three Moog 45 lbf Monopropellant Thrusters

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The MONARC 90 thruster is a robust, flight-qualified monopropellant hydrazine thruster producing a nominal thrust of 26 lbf (116 N) at an inlet pressure of 235 psia. The pathfinder testing performed increased the inlet pressure to produce over 45 lbf of peak thrust and 238 seconds of specific impulse. This paper discusses a Rocket Engine Module (REM) designed for Boeing for the Space Launch System Exploration Upper Stage Reaction Control System. The REM incorporates three MONARC 90 thrusters, or Rocket Engine Assemblies (REA), within a REM bracket with the inlets joined by a common manifold to a single propellant inlet. Test was performed to validate a new Moog dual seat solenoid valve design, validate the REM structural design during environmental testing and to understand the thermal and flow effects during simultaneous multi-REA hot fire testing. The combined propellant throughput on the REM was over 2,000 lbm with over 1,200 lbm on the axial REA. All three REAs demonstrated stable operation over the full pressure range, extending the REA's capabilities beyond the heritage qualification capability. Additionally, the axial REA demonstrated over 15,000 pulses and over 7,000 seconds of on time with a long duration burn of 1,450 seconds. This paper will take an in-depth look into the chamber pressure plots during multi-REA firing tests to understand the water hammer effects within the REM manifold. An additional hot fire test campaign was performed with an extended chamber pressure sense tube. The chamber pressure measurements are compared between Moog's heritage setup and the alternate extended configuration. The REM successfully met all pathfinder objectives and mitigated significant risk prior to proceeding into the qualification and production phase of the program.

I. Nomenclature

SLS	=	Space Launch System
EUS	=	Exploration Upper Stage
REM	=	Rocket Engine Module
REA	=	Rocket Engine Assembly
Moog-ISP	=	Moog In-Space Propulsion
Isp	=	Specific Impulse
MONARC	=	Moog's Monopropellant Thruster Line
EPW	=	Electronic Pulse Width (On Time)
TCA	=	Thrust Chamber Assembly
Pc	=	Chamber Pressure

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II. Introduction

Moog In-Space Propulsion (Moog-ISP), previously Atlantic Research Corporation (ARC) and American Pacific Corporation In-Space Propulsion (AMPAC-ISP), acquired the Hamilton Standard (HS) monopropellant thruster line from Kaiser Marquardt in 2000. The MONARC 90 thrust chamber assembly has extensive heritage and has been in production for over 30 years. In the mid-1970s, HS first produced the thruster for NASA for the Teleoperator Retrieval System (TRS). Since then, extensive testing on this thruster line has been conducted. Moog's MONARC 90 thruster was previously qualified to inlet pressures of 80 to 400 psia with nominal thrust values of approximately 9 lbf at 80 psia and 40 lbf at 400 psia.

These thrusters were configured into a Rocket Engine Module (REM) for the Space Launch System (SLS) Exploration Upper Stage (EUS) Reaction Control System (RCS). The hot fire testing performed on the pathfinder REM was the first known testing of three MONARC 90 thrusters simultaneously together with a common manifold. Additionally, the hot fire testing performed was at a nominal feed pressure of 495 psia compared to Moog's heritage MONARC 90 nominal feed pressure of 350 psia. The pathfinder REM that was built and tested starting in 2018 is shown in Fig. 1.

III. Hardware Configuration

The REM consists of three MONARC 90 thrusters; one axial and two 90 degree turn flow thrusters. The MONARC 90 thruster is a liquid monopropellant thruster designed to operate with hydrazine (N_2H_4). The nominal performance of the heritage MONARC 90 is 26 lbf of steady state vacuum thrust and 230 sec of specific impulse at 235 psia inlet pressure. Fig. 1 illustrates the REM with the three MONARC 90 thrusters installed within a REM bracket. The thruster inlets are joined together by common manifold to create a single inlet for the REM assembly. Fig. 2 on the next page shows the actual pathfinder REM that was built and tested.

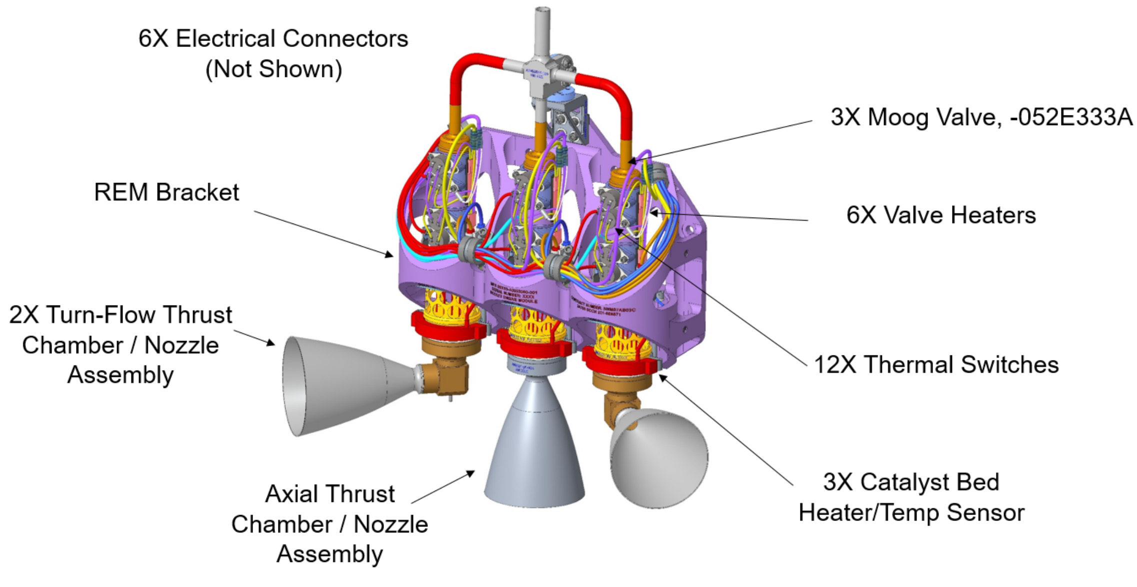

Fig. 1 Rocket Engine Module Configuration

The REM thrust chamber assemblies are manufactured from an Inconel alloy that utilizes a geometry that has a throat-to-exit area ratio of 50:1. The thermal standoff is designed such that it can withstand the vibration and shock environments but also limit the conduction from the thrust chamber back to the valves during soakback. The hydrazine flows through feed tubes and is distributed uniformly over a catalyst bed within the chamber. The reaction of the hydrazine with the catalyst creates a hot gas that is accelerated through the throat of the nozzle.

The REM thrusters include a catalyst bed heater and sensor assembly on each unit. The catalyst bed heater provides heat to the catalyst in order to condition the catalyst prior to firing in a nominal condition while the sensor provides feedback on the chamber temperature.

The REM thrusters utilize a dual seat solenoid propellant valve, which is manufactured by Moog. The valve assembly is a normally closed valve and requires an independent power input to actuate each valve seat. This valve design is new for the SLS program but leveraged significant heritage design techniques and parameters for similarly sized solenoid valves Moog has designed and flown. For the REM configuration, there are redundant thermostat switches mounted to the front of the valves, which are wired in series with redundant valve heaters bonded to the back of the valves. The thermostats and valve heaters will passively ensure the hydrazine remains above its freezing point while on orbit.

The REM manifold consists of bent tubing and an inlet cross piece. Those pieces are orbital welded to the thruster valve inlets at Moog-ISP and then supported via additional bracketry. One-dimensional flow calculations have been performed to ensure the pressure differential between each of the REA inlets is less than 1% when all REAs are firing.

The REM is a fully harnessed assembly with six connectors providing the electrical interface to all the REM components. The REM harnessing is performed by Moog-ISP technicians in accordance with NASA standards.

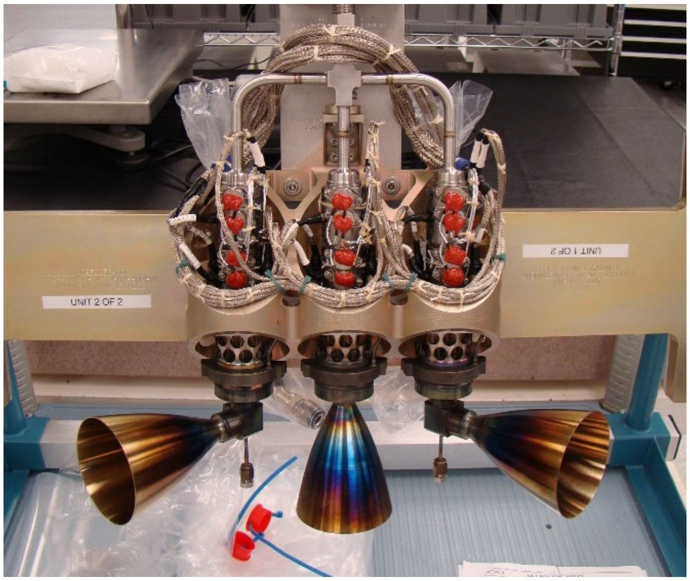

Fig. 2 Pathfinder Rocket Engine Module

IV. Test Plan and Objectives

The overall objective was to demonstrate that Moog's heritage MONARC 90 thrust chamber assembly and the new valve configuration could meet all SLS program environmental tests within the REM configuration. This included vibration, shock, humidity and hot fire testing in order to provide the customer confidence in the design prior to qualification and flight testing.

The testing consisted of initial REA level hot fire testing and REA level electrical functionals. Herein, electrical functionals will typically refer to standard thruster electrical checks consisting of: DC resistance test, insulation resistance test, pull in and drop out current test, valve response test and internal and external leakage tests. After successful completion of REA level testing, Moog assembled the REM, which included harnessing and orbital TIG welding as shown in Fig. 2. Moog's experience harnessing and welding propulsion systems ensured that the REM assembly was a low risk effort even during the pathfinder stage. The testing at REM level started in the fall of 2018 and extended through the fall of 2021 in order to meet an evolving set of requirements. In the end, the pathfinder REM was exposed to the following tests in addition to the aforementioned electrical functional tests throughout:

1. Proof Pressure
2. Acceptance Random Vibration (2 tests)
3. Qualification Sinusoidal Vibration
4. Qualification Random Vibration
5. Qualification Pyrotechnic Shock
6. Humidity Exposure
7. Hot Fire Tests consisting of both single and multiple REA firings

The following sections will only discuss the results of the vibration, shock and hot fire testing.

V. Environmental Testing

A. Vibration Testing

Vibration testing was performed at both Moog's East Aurora and Niagara Falls facilities. Before and after vibration testing in each axis, a low-level signature random vibration test was performed to identify any changes which may have occurred during full level vibration testing. Response accelerometers were installed on the REM to monitor thruster, thruster valve and REM bracket responses.

The vibration tests were performed in the following sequence at Moog's East Aurora facility prior to any REM hot fire testing:

- Low-Level Signature Random Vibration
- Acceptance Random Vibration (8.54 GRMS)
- Qualification Random Vibration (12.08 GRMS)
- Qualification Sinusoidal Vibration

Post hot fire testing, an additional Acceptance Random Vibration test was performed at Moog's Niagara Falls facility to prove out the capability of the vibration table for qualification and flight assemblies.

The qualification sinusoidal vibration testing for each individual axis was done immediately following the qualification random vibration testing for that same axis. Between the random and sinusoidal vibration tests on a given axis, a low-level sinusoidal sweep was conducted. A low-level sinusoidal sweep was also conducted before and after the qualification level vibration for each axis.

For the acceptance random vibration testing performed in Niagara Falls, the REM inlet was pressurized with GN_2. There was no visual leakage observed through the valves during the additional acceptance random vibration testing.

The only anomaly observed during vibration testing on the REM was during a post Y axis inspection in East Aurora of the REM when both Pc tubes on the turnflow REAs had broken off. This was a result of leaving the Swagelok fitting on the end which is used to measure chamber pressure during hot fire testing. This fitting is not on the unit in the flight configuration, as the tube is cut and welded shut. The cantilevered load at the end of the small Pc tube caused the break. Upon returning to Niagara Falls, the tubes were TIG welded back onto the nozzles and testing continued without any further issues at those joints.

Fig. 3 and Fig. 4 show the pathfinder REM in the test configuration at both Moog facilities.

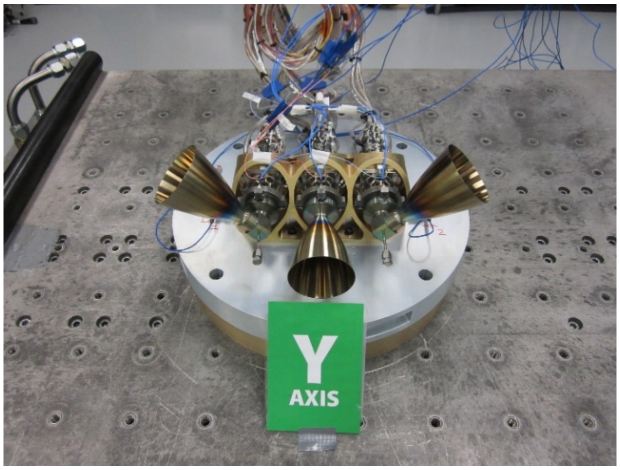

Fig. 3 REM Vibration Setup - Moog, East Aurora

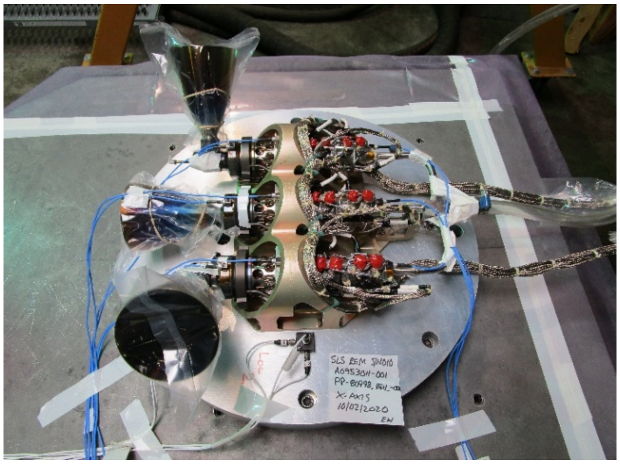

Fig. 4 REM Vibration Setup - Moog, Niagara Falls

B. Pyrotechnic Shock Testing

The pathfinder REM was subjected to the program's qualification level shock testing at Moog's CSA facility in Mountain View, CA. There were no anomalous visual observations made during or after the shock testing. The REM was mounted to a shock test plate and then bolted to the vibration exciter used to impart the shock pulses. The REM was exposed to three shock events in each axis with each event reaching the in-axis magnitude for both the positive and negative directions. Shock testing exposed the REM to up to 1,300 G's.

Response accelerometers were installed on the REM to monitor thruster, thruster valve and REM bracket responses. Fig. 5 illustrates the shock test setup mounted to the shock test stand.

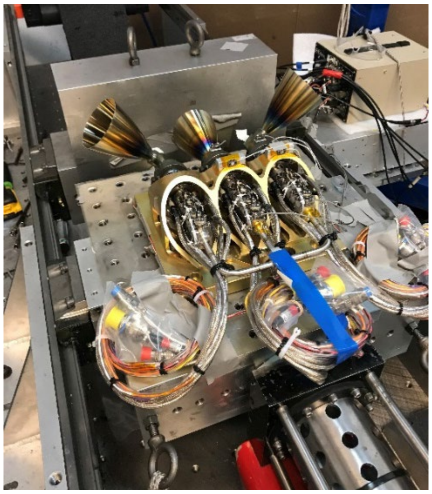

Fig. 5 REM Shock Setup - Moog, Mountain View

VI. Hot Fire Testing

A. Summary

The pathfinder REM made three entries into Moog ISP's altitude hot fire test chambers in Niagara Falls, NY. All REM hot fire testing was performed in Altitude Test Cell A2 using a steam ejection system to provide simulated altitudes above 120,000 feet during firing. The second entry in the test cell was the bulk of the testing and the hot fire installation for that entry is shown in Fig. 6. The two large ducts were installed to direct the turnflow REA plume down the main exhaust duct within the test cell. This was the first time Moog was attempting to fire three MONARC 90s in this configuration at the same time and therefore custom designed all fixturing to ensure the safety of the test cell and all test personnel. All three REAs were tested over a wide range of conditions and environments during the various entries into the test cell. REA 3, the axial REA pointing straight downward in Fig. 6, was the most utilized REA during the REM pathfinder testing. However, both REA 1 and REA 2 were utilized enough to mitigate the identified risks of hot fire testing in the REM configuration. The list below summarizes the conditions at which tests were successfully conducted:

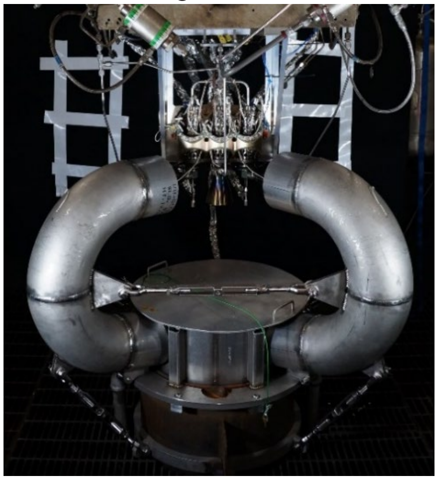

Fig. 6 REM Hot Fire Setup

- Feed Pressures — 250 to 500 psia
- Propellant Temperatures — 45°F to 120°F
- Long Burn — 1,450 seconds
- Catalyst bed cold starts — 3 starts at < 42°F
- Maximum Total On Time — 7,031 seconds (REA 3)
- Maximum Total Pulses — 15,318 (REA 3)
- Maximum Throughput — 1,296 lbm (REA 3)

The turnflow REAs were used primarily in pulse mode, hence the reason for the high number of pulses but lower throughput. Table 1 shows a summary of Total On Time, Total Pulses and Total Throughput for the three REAs. REA 3 is the axial REA, while REA 1 is the right turnflow REA and REA 2 is the left turnflow REA.

Table 1 Summary of Test Program

	Total On-Time (sec)	Total Pulses	Total Throughput (lbm)
REA 3	7,031	15,318	1,296
REA 1	2,901	9,441	505
REA 2	1,571	5,836	266

The hot fire testing on the pathfinder REM successfully mitigated the risks identified for the REM design for hot fire testing. Additionally, the testing demonstrated that Moog's heritage MONARC 90 was capable of meeting the program objectives and showed that the thruster was robust and capable of withstanding an extremely harsh manifold feed pressure environment during multi REA firing as will be explained in the following sections.

B. Single REA Steady State Testing

Steady state testing was performed on each REA throughout the course of each of the three hot fire test entries. As shown in Table 1, REA 3 had the most throughput and therefore was the best candidate for understanding the effects of all the testing performed on the life of the catalyst bed. Moog's heritage MONARC 90 engine is qualified to over 2,000 lbm of throughput but over a pressure range of 80 psia to 400 psia. The testing performed on these MONARC 90s for this pathfinder campaign mainly occurred at 375 psia to 500 psia, therefore expanding the capability of Moog's heritage MONARC 90. It is important to note that the following plots are strictly for single REA firing tests. Tests that included multiple REAs firing together were not designed to get accurate measurements of single REA firing performance as the flow to each engine was not able to be accurately measured, just the flow to the REM inlet.

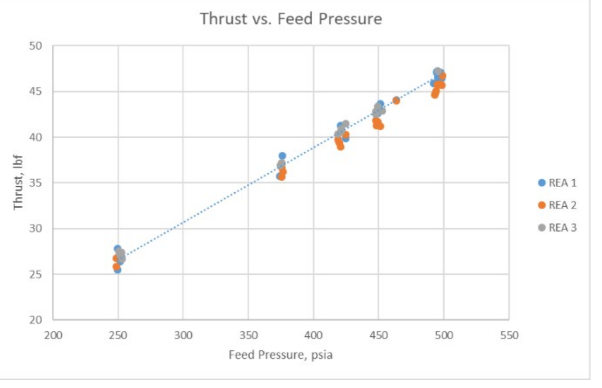

Fig. 7 Thrust vs. Feed Pressure

Given the higher feed pressures compared to heritage, Moog was able to achieve thrust values over 45 lbf on the MONARC 90. Fig. 7 on the right shows the thrust vs. feed pressure for each REA. Moog's heritage thrust calculation for its MONARC thrusters is based on a Hamilton Standard correlation calculation using the chamber pressure measurement. Moog utilized this calculation in the REM configuration to calculate thrust since it was not feasible to test with a load cell in the REM configuration. Additional testing with a load cell was performed at REA level prior to REM level testing to ensure the correlation curve was still accurate at the higher pressures of the pathfinder campaign.

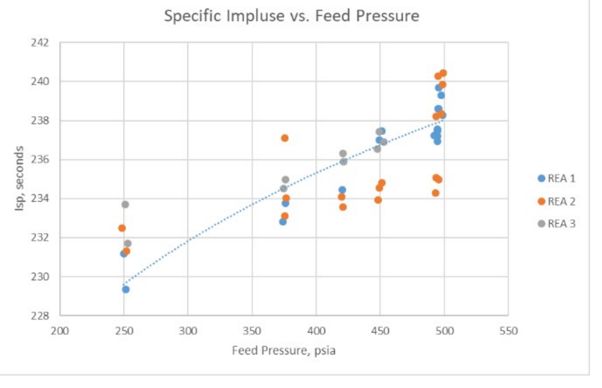

Fig. 8 Specific Impulse vs. Feed Pressure

Fig. 8 shows the specific impulse of each REA vs feed pressure. All specific impulse values at each feed pressure are within 5% of each other between each REA. With the higher feed pressures for this campaign, the MONARC 90 was able to achieve an additional six to eight seconds of specific impulse compared to the lower heritage pressure range.

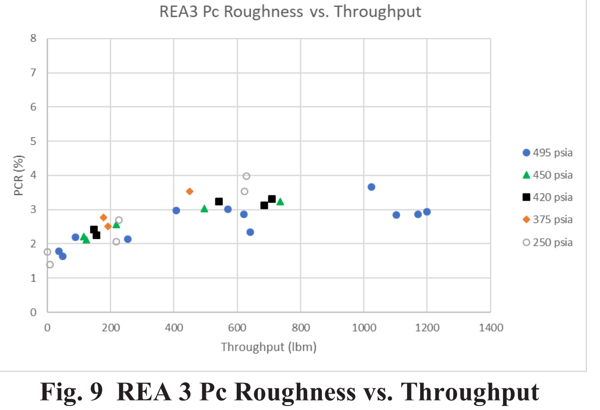

Fig. 9 REA 3 Pc Roughness vs. Throughput

REA 3 was the main workhorse REA for this pathfinder testing. Therefore, it was prudent to focus on REA 3 for evaluating the impact of all of the testing on the life of the catalyst bed. Fig. 9 shows the chamber pressure roughness vs. throughput for REA 3. The figure gives data separated by feed pressure but the general trend over the course of the 1,200 lbm of throughput is a steady slight increase in chamber pressure roughness. The large gap of data points between 800 and 1000 lbm, is due to multi REA firing tests occurring during that time. After all of the multi-REA testing, the chamber pressure roughness was virtually unchanged and did not exceed 5%. As will be shown in a later section, on multi REA firing, the catalyst bed of REA 3 was exposed to a harsher pressure environment over the course of the 1,200 lbm than would have been demonstrated in Moog's heritage MONARC 90 qualifications for single REA firing due to the inlet feed pressure fluctuations. This demonstrated the robustness of Moog's MONARC 90 design and the capability of the catalyst bed.

The last steady state plot is Fig. 10 and this shows the thrust vs. throughput for REA 3. There is very little thrust degradation in REA 3's performance over the 1,200 lbm of throughput. Similar to the conclusion made for chamber pressure roughness, the lack of thrust degradation shows the robustness of the MONARC 90s catalyst bed and ability to withstand the higher feed pressures and multi REA firings. The steady state testing performed on the REM demonstrated the REM will be able to successfully meet all program requirements at the beginning and end of life.

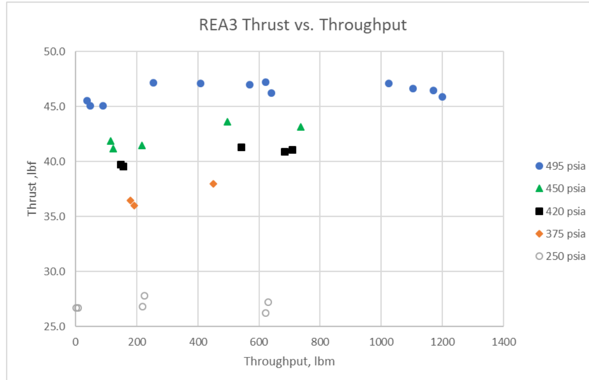

Fig. 10 REA 3 Thrust vs. Throughput

C. Pulse Mode Testing

Extensive single REA pulse mode testing was performed on all three REAs, with a focus on REA 3, as discussed above. Fig. 11 shows pulse mode impulse bit average vs. EPW. A large variety of pulse widths were tested and as expected, on a log-log plot, the impulse bit followed a linear trend. At lower feed pressures, the resulting average impulse bit decreased slightly which is to be expected.

Fig. 12 is a plot of impulse repeatability vs. EPW. All tests were within a 15% impulse bit repeatability with an increasing pulse width significantly decreasing the variability in impulse bit.

Fig. 13 shows pulse mode specific impulse vs. EPW. Pulse mode specific impulse was calculated by taking the total impulse for the run and dividing it by the total mass flow of the run. This output is more in line with an average pulse mode specific impulse as the individual pulse Isp would vary, especially during the beginning of the pulse train as the chamber increases in temperature. As expected, the shorter pulses have a shorter specific impulse and as the pulse width approaches 1 second, the pulsing specific impulse approaches the steady state specific impulse shown in Fig. 8.

Similar to the single REA steady state testing, the pulse mode testing performed demonstrated the REM could meet program objectives at the beginning and end of life.

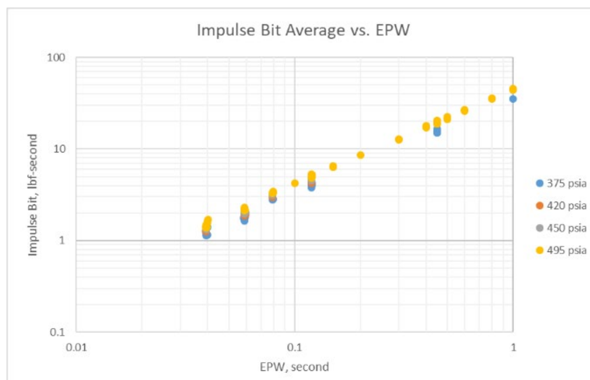

Fig. 11 Impulse Bit Average vs. EPW

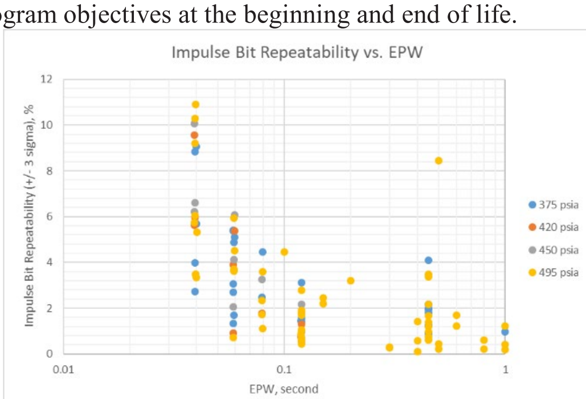

Fig. 12 Impulse Bit Repeatability vs. EPW

Fig. 13 Pulsing Specific Impulse vs. EPW

D. Multi-REA Testing

Several tests were performed when multiple REAs were being fired together during the same test. This consisted of a combination of either two or three REAs firing together with the same or varying duty cycles. There were a number of objectives for this multi REA testing during the pathfinder phase. The first objective was to verify that Moog's heritage MONARC 90 catalyst bed could withstand the rapid fluctuations in inlet pressure, respond accordingly, and then recover to a nominal state during single REA firing. The second objective was to verify that at worst case firing conditions which included maximum propellant temperature, maximum valve voltage and with all three REAs firing in steady state, the soakback temperatures did not exceed the maximum allowable temperatures of the REM. The third objective was to validate the capability of Moog's test cell, feed pressure system and data processing software in preparation for qualification and acceptance testing. The following paragraphs and plots outline some of the raw data plots we reviewed during testing to assess the REM's behavior.

The plots have legends that define the dataset that is plotted. The datasets labeled PC-*X* are chamber pressure measurements. The dataset labeled Pi-1 is the feed pressure measured near the REM inlet. The datasets labeled VAL*X*-E is the valve voltage applied to each REA. The X in the legend name refer to the REA number. For example, a REA 1 chamber pressure recording would be labeled as PC-1. In all of the following plots, the Y-axis scale is the same for each respective dataset. This ensures a comparison can be made when discussing two similar plots and their associated data.

Fig. 14 shows the startup transient for a single REA firing. Fig. 15 shows the startup transient for a multi-REA firing when all three REAs were fired together. A few differences were observed between the two cases. First, there was a shorter initial increase in chamber pressure (PC) during the multi-REA firing compared to the single REA firing. This was due to the significantly larger and extended drop in REM inlet pressure once the valves were actuated open as the flowrate was three times as high when firing three REAs compared to one. This slower increase in feed pressure and chamber pressure also led to the overshoot in feed and chamber pressure to be minimized in the multi REA case compared to the single REA case. The other difference was the feed pressure during the run once the REAs were firing. In the single REA case, and standard for Moog's MONARC 90 when configured in a single REA hot fire campaign, there is a minimal drop in static feed pressure before firing and the actual inlet pressure during firing. This is shown in Fig. 14, with the Pi-1 line returning very close to the pre-fire static pressure once the pressures reached steady state during the run. However, due to the increased flow rates with multiple REAs firing and the pressure drop in Moog's feed system, Fig. 15 shows that with three REAs firing, there is a much larger pressure drop from pre-firing to during firing feed pressure. This helped educate Moog and Moog's customer as to how affected the REM is by the feed system. Lessons learned from this multi REA test were incorporated in tests later on to ensure the feed system and the REM were not over pressurized at the start of a test, but still achieved the desired feed pressures during a test.

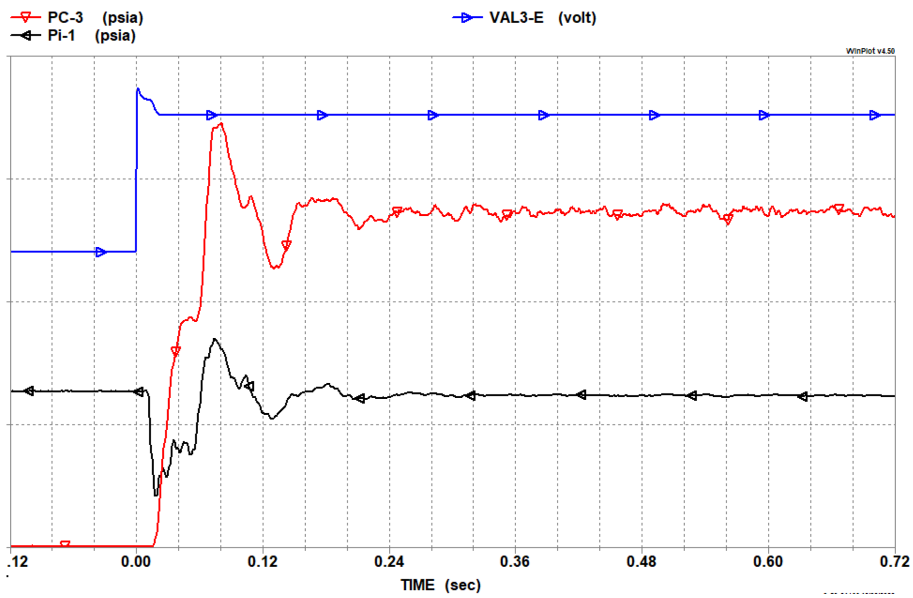

Fig. 14 Single REA Startup Transient

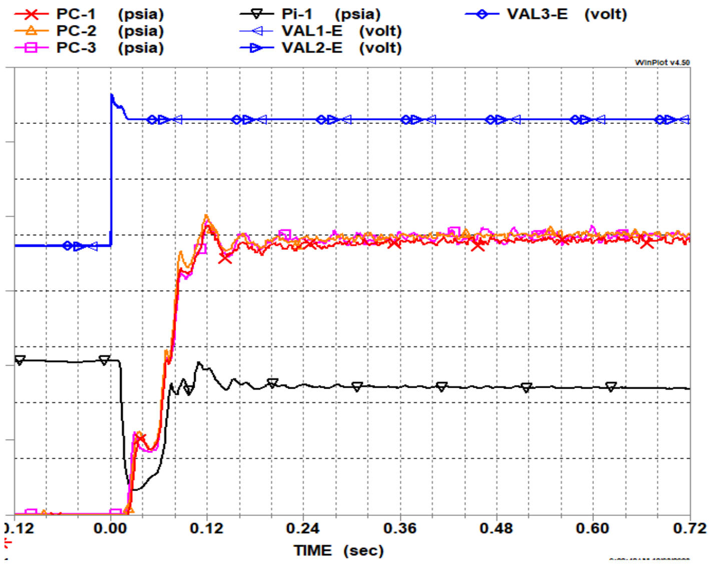

Fig. 15 Multi REA Startup Transient

In addition to the differences in single REA and multi REA startup transients, there were differences observed in the shut down transients. The main difference was the waterhammer response after the closing of the valves. Fig. 16 shows the single REA shutdown transient and Fig. 17 shows the multi REA shutdown transient. Both of these responses are directly corrleated to Moog's feed pressure system and cannot be taken to apply to other feed systems. Therefore the main takeaway was that the REM valves and Moog's feed pressure system were able to withstand the very extreme shutdown transient with three REAs firing at maximum feed pressure.

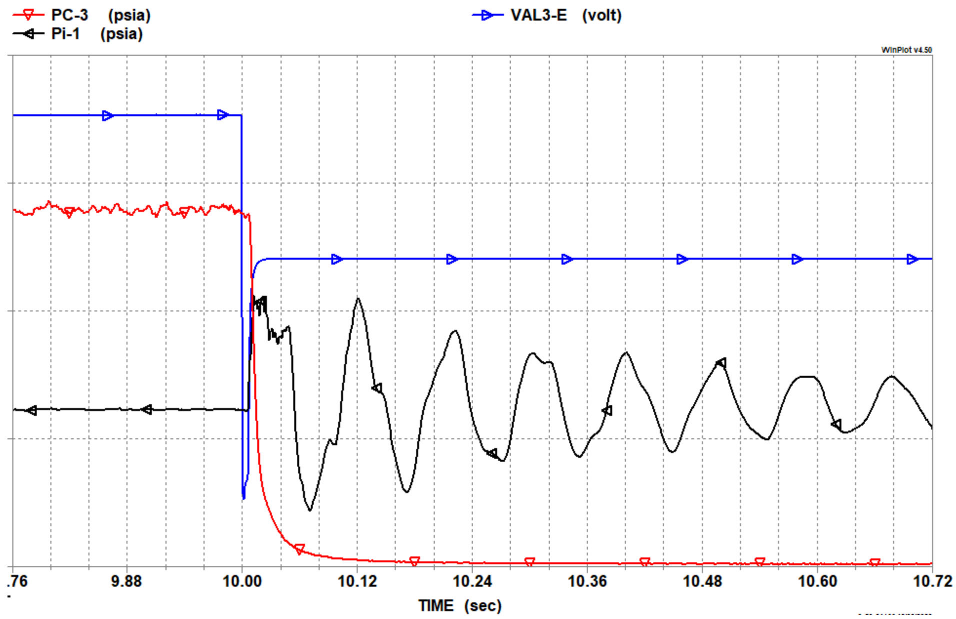

Fig. 16 Single REA Shutdown Transient

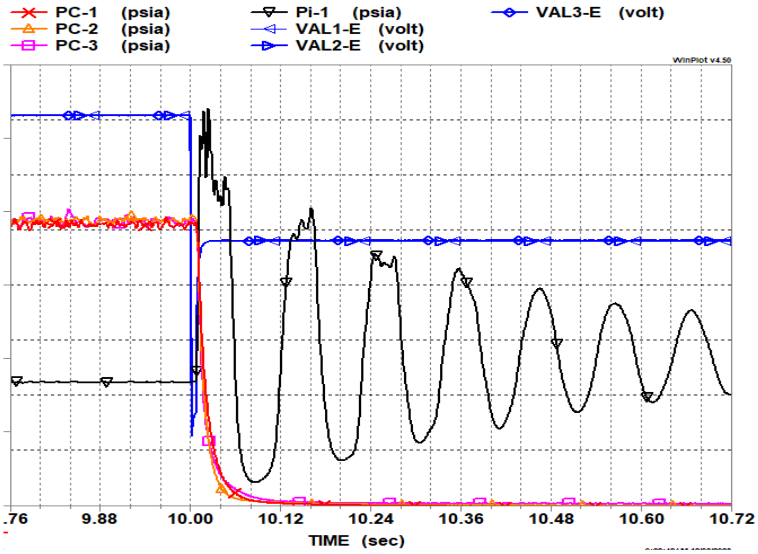

Fig. 17 Multi REA Shut Down Transient

After multi-REA steady-state tests were performed to understand the effects of the startup and shut down transients on the feed pressure system and the REM, Moog moved into testing multiple REAs with varying pulse on times and duty cycles. Fig. 18 shows a test where two REAs were firing simulatenously. REA 1 was firing a 0.45 on / 0.05 off second pulse train and REA 2 was firing a 0.04 on / 0.30 off second pulse train. A single pulse for each REA is shown below with the REA 2 short 0.04 second pulse in the middle of the REA 1 0.45 second pulse. The evidence of the water hammer effect is magnified greatly in a pulse mode test as the feed pressure and chamber pressure of REA 1 are affected by REA 2. At approximately 3.44 seconds, both valves shut and a subsequent spike in feed pressure (black line) occurred. After 0.05 seconds, REA 1 fired again. However, since the water hammer spike as seen in Fig. 16 and Fig. 17 was approximately 6 msec, the feed pressure was about to begin a very sharp decline when REA 1 opened. This resulted in a longer startup time for REA 1 of approximately 12 msec compared to 8 msec in Fig. 14. At 3.74 seconds, as REA 1 and the feed pressure system were beginning to level out to steady state, REA 2 fired for 0.04 seconds. This caused a drop in inlet pressure as expected because of the increased flow rate. The drop in inlet pressure caused REA 1, which had already been firing, to lose chamber pressure. An interesting observation and one that was expected was that while REA 2 was firing, the chamber pressures of REA 1 and REA 2 became almost identical. This is shown at 3.76 seconds in Fig. 18 with the orange (PC-1) and pink (PC-2) lines nearly overlapping. After REA 2 closed, a subsequent spike in inlet pressure and REA 1 chamber pressure occurred. This multi REA test with 2 engines firing demonstrated the capability of Moog's heritage MONARC 90s of being able to withstand extreme waterhammer within the REM and still be able fire nominally in single REA testing.

Fig. 19 is another example of a multi REA firing case. For this test, REA 1 and REA 3 are firing an identical pulse train of 0.04 on / 0.25 off second and REA 2 was firing a 0.12 on / 0.17 off second pulse train. The pulse duration, on time plus off time, is the same for both these trains, but the duty cycle is different. This multi REA test was designed to further evaluate the startup transients of three REAs and then understand the effect on a single REA firing when the other two REAs stop firing. As seen in Fig. 19, all three REAs start a similar transient on the first pulse and then there is a large spike in REA 2 chamber pressure and inlet feed pressure once REA 1 and 3 shut. While the chamber pressures are able to return close to 0 psia at the end of the pulse, there is still pressure fluctuations occuring in the REM manifold and feed system which affect the startup for pulse 2 at 0.29 seconds in Fig. 19. Similar to the multi-REA test discussed in Fig. 18, the test shown in Fig. 19 demonstrated Moog's heritage MONARC 90 can withstand the pressure fluctuations that will be seen in the REM configuration when tested during acceptance and qualificaiton.

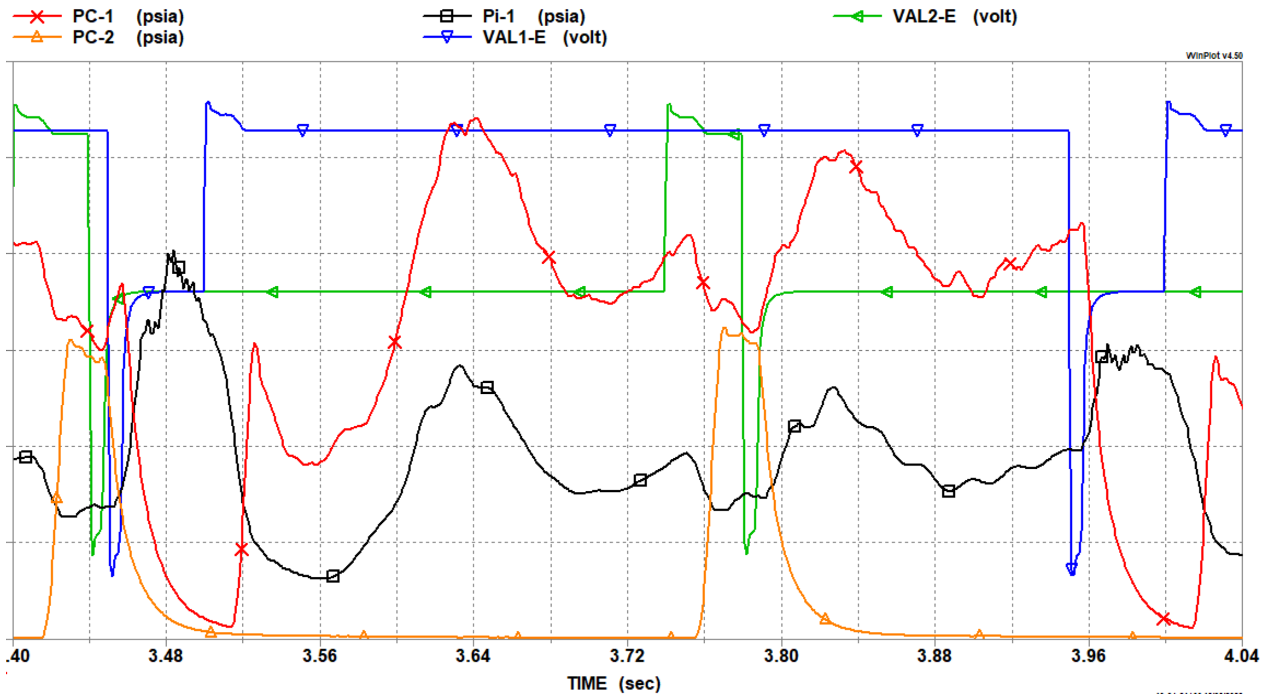

Fig. 18 Multi REA Firing - A2-8792

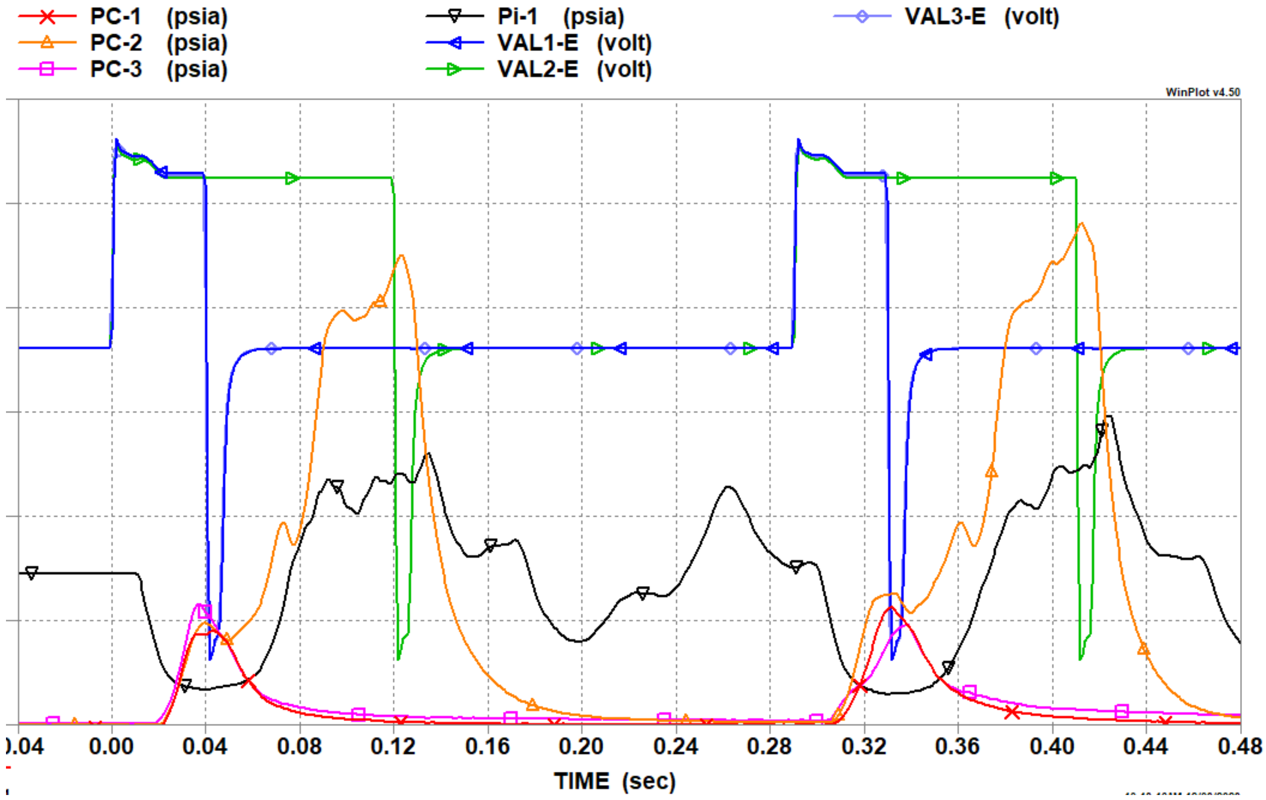

Fig. 19 Multi REA Firing - A2-8837

To verify the objective of ensuring that the soakback temperature of the valve does not exceed the valve limits, a test was performed at the maximum feed pressure, maximum valve voltage and maximum propellant temperature simultaneously with all three REAs firing in steady state. Fig. 20 identifies the thermocouple locations for REA 3 that were installed for the worst case thermal test. Fig. 21 shows the TCA temperatures recorded during test for the 198 second firing and then for an additional 20+ minute soakback. As expected the Nozzle, Chamber and Throat achieved steady state temperatures and then at the completion of the run, began to decrease as the heat radiated out and conducted up to the rest of the REM. Fig. 22 shows the valve temperatures. The Tv3us is the temperature of the upstream valve and Tv3ds is the temperature of the downstream valve. As expected, the valve temperatures were approximately the same as the propellant temperatures during firing and then immediately after the firing concluded, the soakback from the TCAs increased the valve temperatures. The downstream valve temperature peaked at approximately 215°F which is within the intended operating temperature limits of the valve. Overall, this worst case thermal test demonstrated the REMs capability to withstand the worst case firing environment within the test cell.

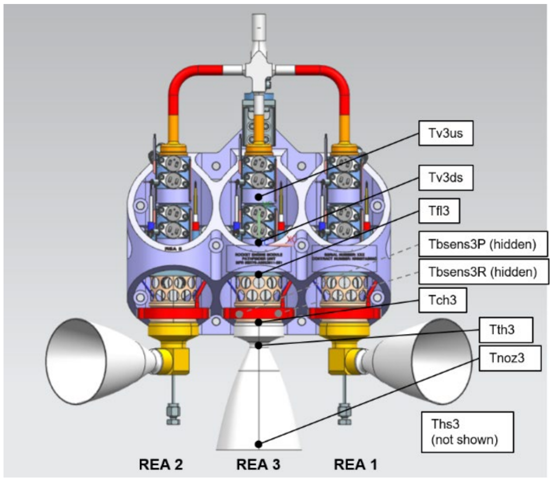

Fig. 20 REA 3 Temperature Locations

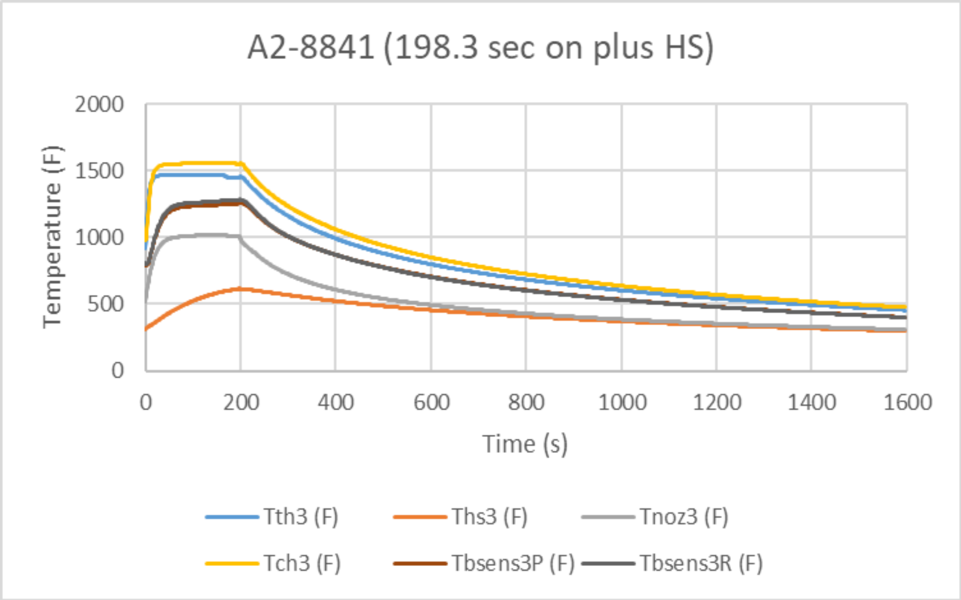

Fig. 21 REA 3 TCA Temperatures

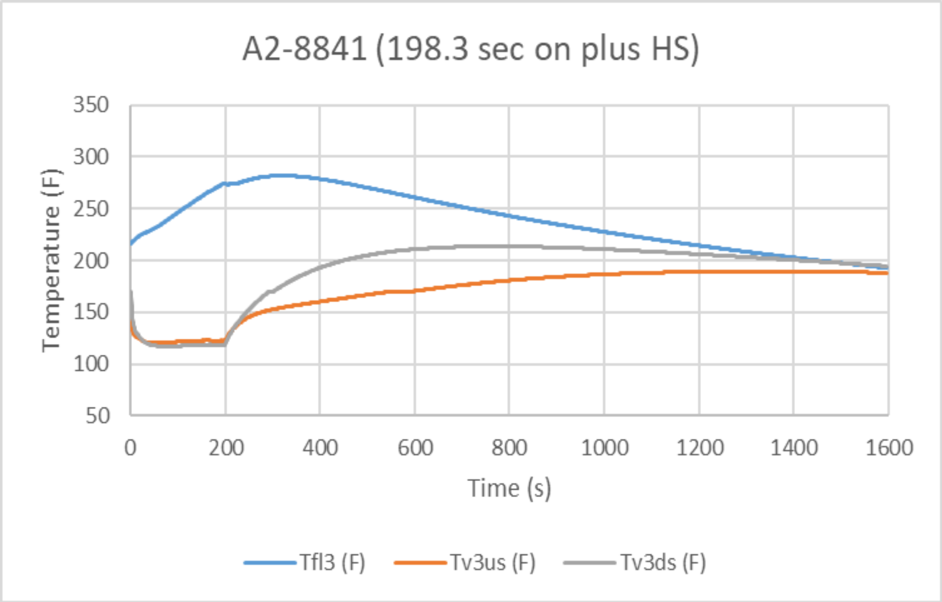

Fig. 22 REA 3 Valve Temperatures

E. Chamber Pressure Tube Extension

The final entry into the test cell included an extension of the REA 3 chamber pressure tube in Moog's hot fire test setup. Moog's heritage MONARC 90 setup includes a short tube exiting the chamber in order to measure chamber pressure during testing. This length is minimized to decrease the increase in effective chamber volume during test. Prior to flight, the tube is cut short and welded shut. However, there was a desire to understand the impact on the MONARC 90 performance with a significantly longer chamber pressure tube and therefore increased effective chamber volume.

Fig. 23 shows two different hot fire tests on REA 3. These two runs were chosen as they had the same on and off time as well as test feed pressure. Additionally, these runs were chosen as two runs there were repeated as soon after each other as possible in order to minimize the impact of catalyst life on the chamber pressure pulse waveform. The red PC-3 line labeled A2-8786 was a test performed with Moog's heritage short Pc tube on REA 3. The blue PC-1 line labeled A2-8910 was a test performed with a long Pc tube on REA 3. The valve voltage for both tests was plotted as well to show the similar valve command between the two tests.

The long Pc tube added approximately 10 msec onto both T90 (time from electrical on to 90% thrust) and T10 (time from electrical off to 10% thrust). However, the overall impulse bit for the pulse and nominal chamber pressure during the pulse remained very similar between the two. This was further evident in the single steady state test performed that showed a similar thrust, specific impulse and chamber pressure at steady state. In addition to the change in T90, it was also evident that the extended Pc tube helped dampen the initial pressure wave into the Pc tube during the start of the pulse. Moog's heritage configuration typically has an overshoot in chamber pressure before settling at the nominal chamber pressure as shown by the red line. However, the blue line shows the extended Pc tube damping that initial pressure spike. Overall, Moog concluded that the Pc tube extension does not negatively affect the overall performance of the MONARC 90 even though some pulse mode performance metrics fell out of line of heritage values. The impact would effect GNC operations and small precision manuvers if this thruster were to be used with extended Pc tubes in the future. Future testing could be performed with a single REA using a load cell and Pc tube extension to fully understand the differences in the pressure transducer readings at the end of a long Pc tube and the actual thrust measured via a load cell. That testing was not performed as part of this test campaign, as the REA was already installed in the REM configuration.

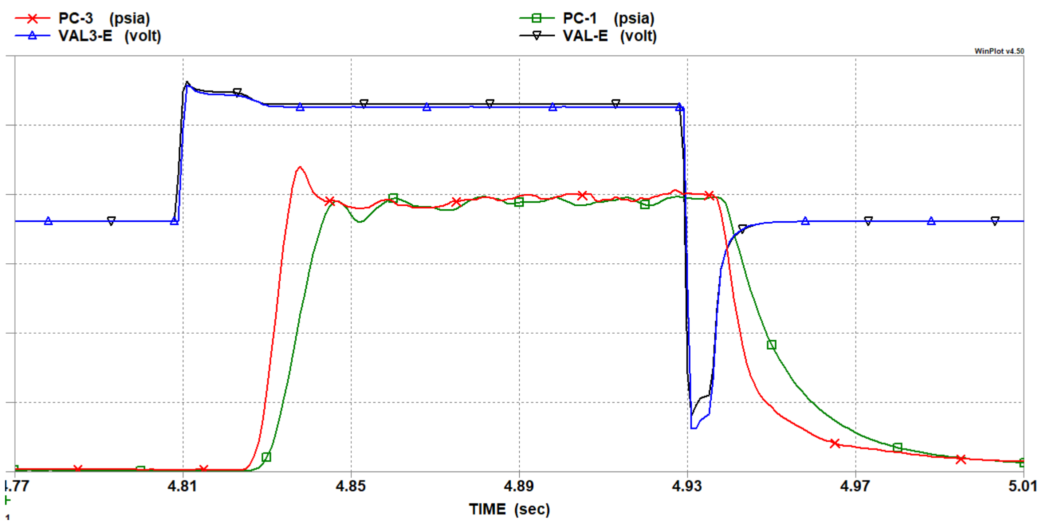

Fig. 23 Chamber Pressure Tube Extension Comparison

VII. Conclusion

Three of Moog's heritage MONARC 90s installed within a REM configuration successfully completed pathfinder testing consisting of random and sinusoidal vibration testing, shock testing and extensive hot fire testing. The REM design is can withstand the anticipated launch environments of the SLS EUS mission and Moog's MONARC 90 thrust chamber and catalyst bed has shown to be very resilient to the extreme volatile pressure environment that it will be exposed to in a close coupled REM configuration. Overall, Moog and Moog's customer chain for this product were very encouraged and proud of the testing that was performed to validate the previous analyses and predictions. Significant program risk was mitigated with the demonstration of the pathfinder campaign. Additionally, Moog gained greater insight into the capabilities of the MONARC 90 which will allow for future business opportunities and support the continuation of expanding the MONARC 90 capability and qualification limits in the future. The REM program will continue at Moog with qualification testing expected to be completed by the end of 2024 for the SLS EUS REM program.

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