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Test Report for 870-lb_f Reaction Control System Tests Using Liquid Oxygen/Ethanol and Liquid Oxygen/Methane at White Sands Test Facility

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ABSTRACT

Since 2001, the National Aeronautics and Space Administration (NASA) has worked to develop spacecraft reaction control systems (RCSs) that use nontoxic and cryogenic propellant combinations, such as liquid oxygen (LO_2) and ethanol and LO_2 and liquid methane (LCH_4), as alternatives to common systems that rely on the highly toxic and more expensive hypergolic fuels. Compared with these propellants, cryogenic propellants offer higher performance and easier ground handling and can be generated in situ on the Moon or Mars. System-level studies have shown performance benefits for an integrated main engine and RCS that reduces mass and simplifies the system. However, advanced technology is required to store the cryogenic propellants in liquid form and feed them to a pulsing RCS engine. Testing began with the firing of three 870-lb_f (3870-N) thrust engines on a LO_2/ethanol feed system; the engines were later modified and fired on a LO_2/LCH_4 feed system across a matrix of propellant inlet temperatures and pressures, engine duty cycles, and pulse times. 1,685 firings using LO_2/ethanol propellants and 733 firings using LO_2/LCH_4 propellants were completed. The impulse bit pulse-to-pulse repeatability of both the LO_2/ethanol and LO_2/LCH_4 thrusters was typically within 5%. Several problems related to igniter ignition reliability were uncovered and resolved, and it was determined that more oxygen in the main chamber was required for reliable main-stage ignition. The hardware proved durable given the number of off-nominal engine firings, and the cryogenic feed system and Thermodynamic Vent System (TVS) were able to maintain propellant temperatures within tight tolerances. Overall, LCH_4 is a better match with LO_2 than ethanol because of its lower freezing point and higher vapor pressure.

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ACRONYMS AND ABBREVIATIONS

µm	micrometer
APSTB	Auxiliary Propulsion System Test Bed
ASME	American Society of Mechanical Engineers
CAD	computer-aided design
CFM	Cryogenic Fluid Management
DACS	Data Acquisition and Control System
DCCS	Distributed Computer Control System
DR	discrepancy report
E	engine
ECV	Electronic Control Valve
EFCS	Engine Firing Control System
EP4	Propulsion Systems Branch
ETM	ethanol to methane
ft	foot, feet
gal	gallon
GHe	gaseous helium
GN_2	gaseous nitrogen
GO_2	gaseous oxygen
GRC	Glenn Research Center
GUI	graphical user interface
hr	hour
in.	inch, inches
IR	infrared
IRIG-B	Inter-Range Instrumentation Group–B
JSC	Johnson Space Center
LASS	Large Altitude Simulation System
lb	pound
lb_f	pound-force
lb_m	pound-mass
LCH_4	liquid methane
LED	light-emitting diode
LN_2	liquid nitrogen
LO_2	liquid oxygen
LOx	liquid oxygen
MAWP	maximum allowable working pressure

MLI	multilayer insulation
MODACS	ModComp Data Acquisition and Control System
ms	millisecond
MSDS	material safety data sheet
MSFC	Marshall Space Flight Center
mtorr	millitorr
NASA	National Aeronautics and Space Administration
Pc	Primary Chamber Pressure
PC	personal computer
PCAD	Propulsion and Cryogenic Advanced Development (Program)
PCIG	Igniter Chamber Pressure
ppm	parts per million
psia	pounds per square inch absolute
psig	pounds per square inch gauge
PWM	pulse-width modulation
R	Degree Rankin
RCE	reaction control engine
RCS	reaction control system
ROV	remotely operated valve
RTD	resistive thermal device
SASS	Small Altitude Simulation System
sec	second
TA	test article
TAD	Test Article Director
TLV	threshold limit value
TPS	task performance sheet
TVS	Thermodynamic Vent System
UV	ultraviolet
WSI	WSTF standard instruction
WSTF	White Sands Test Facility
Δ	delta

1 INTRODUCTION

This paper discusses tests conducted at the NASA White Sands Test Facility (WSTF) in 2005 and 2006. The tests were performed on the Auxiliary Propulsion System Test Bed (APSTB) in Altitude Test Stand 401. To advance the technology readiness level of a cryogenic reaction control system (RCS), multiple thrusters were tested on an integrated cryogenic feed system in a simulated space environment. These tests were the technical responsibility of the Propulsion Systems Branch (EP4) of the NASA Johnson Space Center (JSC) in Houston, Texas, and were funded by the Propulsion and Cryogenic Advanced Development (PCAD) Program managed by the Glenn Research Center (GRC). Aerojet provided the test article engines under contracts managed by the Marshall Space Flight Center (MSFC) for the second-generation reusable launch vehicle program and later by JSC EP4 for the ethanol-to-methane (ETM) conversion. System-level hot-fire testing at altitude was conducted at the WSTF near Las Cruces, New Mexico.

This paper summarizes over 1,600 firings using LO_2/ethanol propellants and 733 firings using LO_2/ liquid methane (LCH_4) propellants. The engines were pressure-fed propellants from vacuum-jacketed tanks through feedlines and a flight-weight manifold equipped with a Thermodynamic Vent System (TVS). The TVS is a bleed path that uses an orifice for volumetric expansion of the cryogenic propellants. By bleeding a small amount of propellant through this system, the main propellant manifolds were maintained at cryogenic conditions. During the majority of the tests, the propellant tank, propellant manifold, and engine inlets were contained in a rough vacuum chamber at approximately 0.075 torr (~220,000 ft), while the entire test article was contained inside a large altitude chamber, which evacuated the engine combustion plumes using a steam ejector system at approximately 8 torr (~100,000 ft). Figure 1 shows the test article outside of the vacuum chamber and a simultaneous hot-fire of two 870-lb_f LO_2/LCH_4 engines.

Figure 1: Test article and a two-engine LO_2/LCH_4 870-lb_f hot-fire

Development challenges being addressed by the testing can be divided into two areas: Cryogenic Fluid Management (CFM), which includes efficient long-term storage of conditioned propellants and their distribution to engines, and engine performance, which includes ignition, cold starts, restarts, heat soak-back, reliability, and repeatability. These issues are being addressed in relation to common RCS demands, such as varying duty cycles, high cycle life, and short pulse times.

1.1 Test Objectives

The specific test objectives for the system and engine tests were as follows:

1. Evaluate and compare LO_2/ethanol and LO_2/LCH_4 propellants.
    a. Evaluate pulse repeatability, thrust response (via chamber pressure), and ignition reliability.
    b. Evaluate engine performance over an extended duty cycle map of pressure and propellant temperature.
    c. Evaluate system and engine performance at typical mission duty cycles over extended periods of time.
    d. Evaluate system performance for delivering propellant at the required conditions to the engine.
    e. Evaluate system pressure transients for a four-engine startup and shutdown.
    f. Evaluate plume contamination.
    g. Evaluate spark ignition system life.
    h. Evaluate engine operation without purges in a simulated space vacuum.
2. Evaluate operational procedures for rapid loading, conditioning, and maintaining propellants.
    a. Evaluate operational techniques and timelines for reactivation of the system after extended dormant periods.
    b. Evaluate system and engine health monitoring software algorithms and hardware.
    c. Evaluate leak detection sensors.

1.2 Test Bed Description

The test article used for both the ethanol and methane systems consisted of the primary structure, the propellant tanks, the feed system, the RCS stinger box, three RCS engines, three engine simulators, and two accumulators, as shown in Figures 2 and 3. The propellant tanks were vacuum-jacketed 500-gallon (gal) tanks that had a maximum operating pressure of 375 psia and a maximum allowable working pressure of 415 psia. The integrated system simulated a shuttle or reusable launch vehicle with a centrally located orbital maneuvering system, RCS propellant, and distributed RCS engines in the front and aft of the vehicle to create two flow paths to the reaction control engine (RCE) manifold: aft feed and forward feed. For the forward feed, the 50-ft and 110-ft lengths were selected by configuring the feed system valves. An accumulator was installed on the forward line lengths to damp transients. The aft feedline was 28 ft in length. Two isolation valves were placed between the tank and the RCS engines so that engine work could be performed safely when the propellant was loaded. Figure 2 shows the test article and instrumentation setup and the Pro-E assembly drawing.

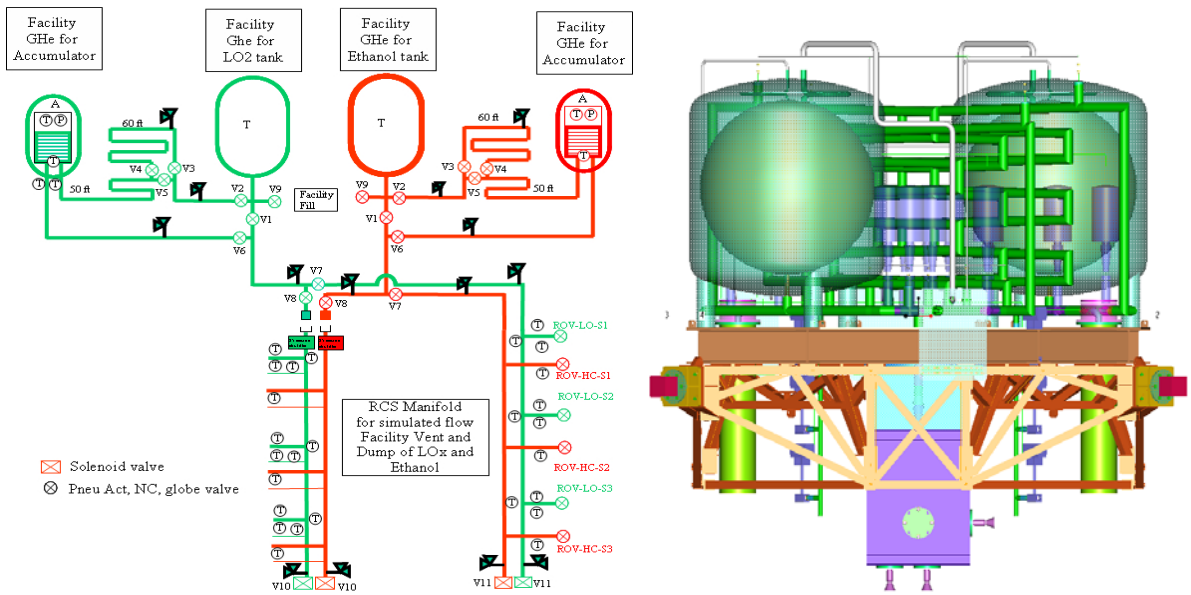


Figure 2: Test article assembly

Two RCS manifolds were used: one with three engine-flow simulators and one with three engines. The three RCS engines were mounted in a box that allowed a space vacuum to be simulated on the manifolds and thruster head end. The three primary engine flow simulators were mounted on the manifold opposite the manifold with the three engines, so that up to six operating engines could be simulated. All of the feedlines and tanks were insulated with 22 to 50 layers of multilayer insulation (MLI). Figure 3 shows the RCS stinger box being installed at WSTF and the Pro-E assembly drawing.

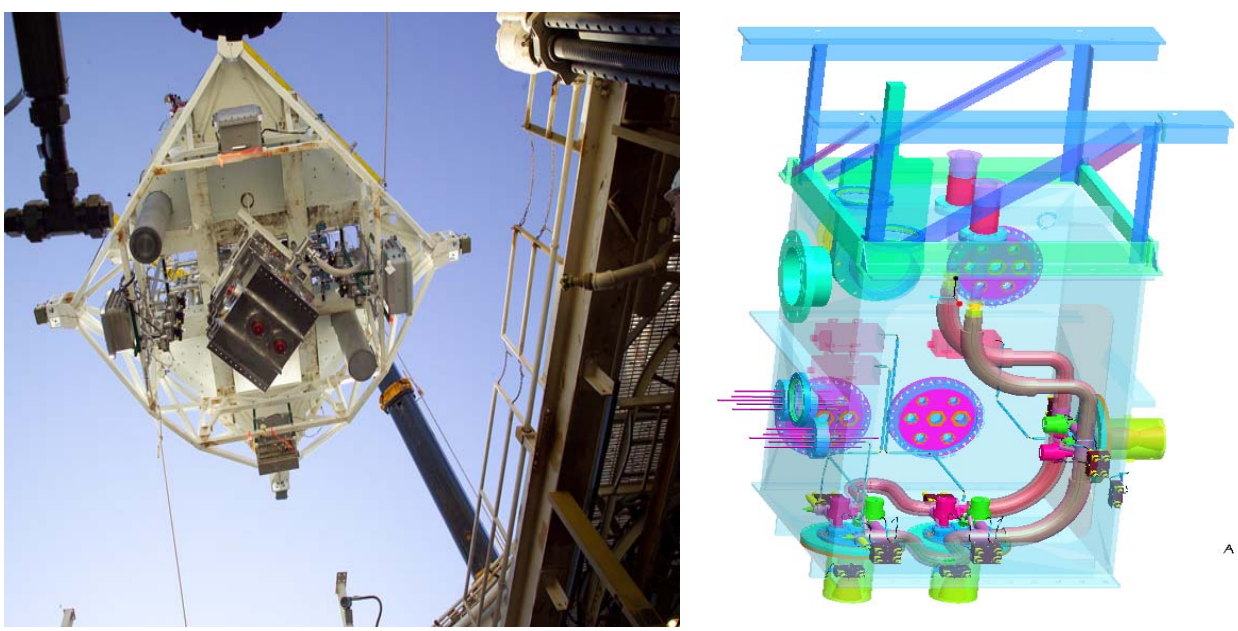


Figure 3: RCS stinger vacuum box with three Aerojet engines installed

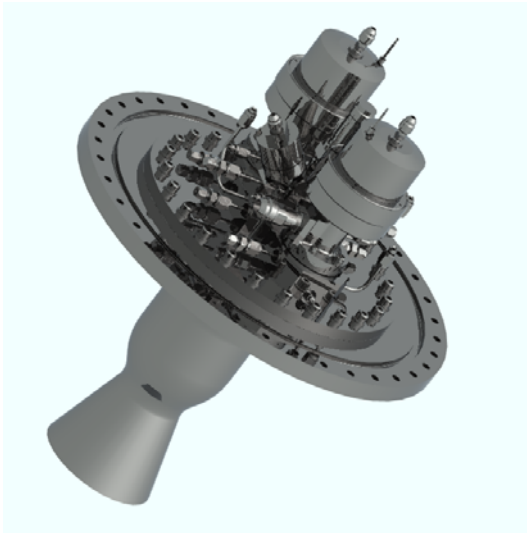
A vacuum chamber called the RCS stinger vacuum box was constructed to contain the three RCS engine head-end assemblies, which consisted of the valves, spark plug, exciter, and injector. A vacuum flange separated the injector and the chamber, allowing a rough vacuum to be pulled on the engine head end and manifolds while the engine exhausted into the Test Stand 401 altitude cell at a 90,000-ft or higher altitude equivalent (~12.8 torr). The rough vacuum was required to improve MLI performance and allow

the engine to start under vacuum conditions. Figure 4 shows the RCS cryogenic manifold with the engines installed and the Pro-E assembly drawing.

Figure 4: RCS cryogenic manifold with three engines installed

1.3 Aerojet Engine Description

The Aerojet RCE, configured with a 3:1 nozzle, is shown in Figure 5. It produces 600 lb_f in the primary mode. The engine has four valves: two for the igniter and two for the main injector. A more detailed description of the engine is provided by Robinson, Veith, and Turpin.[1]



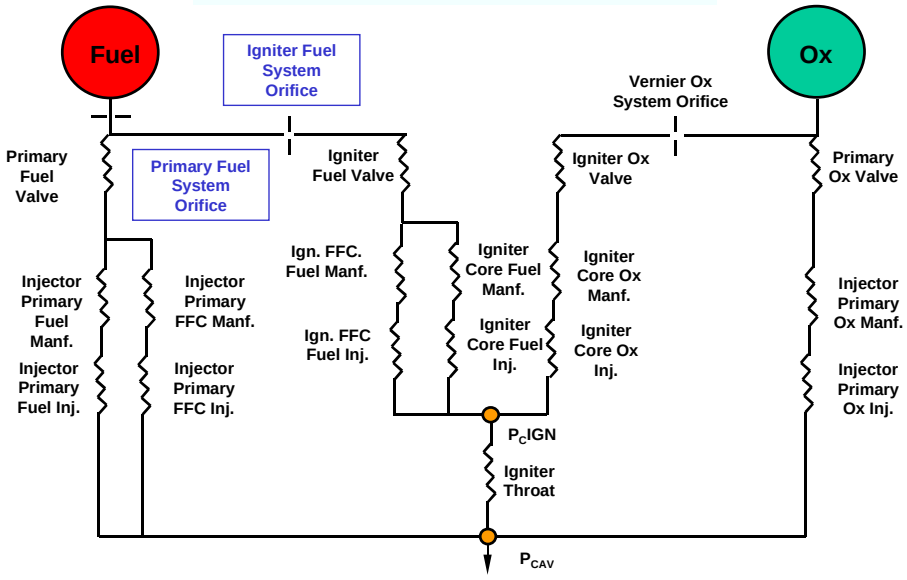


Figure 5: Aerojet 870-lb_f RCE

1.4 Summary of the Major Findings

1. The impulse bit pulse-to-pulse repeatability of both the LO_2/ethanol and LO_2/LCH_4 thrusters was excellent, within approximately 12% and typically within 5%.
2. Several problems related to igniter ignition reliability were uncovered and resolved.
   a. Orifices on the valve inlets were removed, as they restricted LO_2 flow and created a weak torch.
   b. The exciters were found to be incompatible with vacuum operation without a purge on the plug and cable. This incompatibility created intermittent ignition failure.

3. It was determined that reliable main-stage ignition required more oxygen in the main chamber; this is true for both LO_2/ethanol and LO_2/LCH_4 propellants. In some cases, the igniter lighted, but the main-stage ignition was delayed or did not occur within redline limits. It was determined that the main chamber was fuel-rich during the start transient.
   a. A LO_2 lead of 50 ms improved main-stage ignition reliability for both the ethanol and methane systems.
   b. Ignition improved with higher LO_2 pressures and colder temperatures. Future engine designs should ensure that enough oxygen is delivered on startup.
4. The hardware (e.g., valves, injectors, and chamber) proved durable given the number of off-nominal engine firings.
5. The cryogenic feed system and TVS were able to maintain propellant temperatures within tight tolerances; e.g., 204 R ± 5 R. These set points could be adjusted from 167 R to 214 R. Many heat leaks occurred due to poor insulation and vacuum levels, but the TVS maintained the required temperatures.
6. Methane is a better choice than ethanol for use with cryogenic oxygen because of methane's lower freezing point and higher vapor pressure. Additionally, the need to purge circuits to prevent the accumulation of unburned fuel is a lesser concern with methane.

2 LO_2/Ethanol Hot-Fire Tests

A total of 1,685 firings from three different engines were performed during the LO_2/ethanol test campaign. The engine firings consisted of single-engine pulse strings and three-engine pulse strings that simulated mission profiles on the space shuttle for on-orbit, external tank separation, and entry duty cycles. Initially, the testing consisted of initiating cold flows to check out the system, measuring the pressure drop, and calculating heat leaks. Next, igniter hot-fire tests were performed for steady state at 5 and 30 seconds(sec). Duty cycles were performed on the igniter, and single-engine firings of the main stage were conducted. The final test series consisted of simultaneous multiple-engine firings that simulated the external tank separation burns (two-engine, 6-sec burns), on-orbit attitude hold (0.1-% duty cycle), and shuttle entry duty cycle (~5%). A sequence of these is shown in Figure 6. Overall, the test firings were successful. However, numerous ignition issues were worked over the course of the test program.

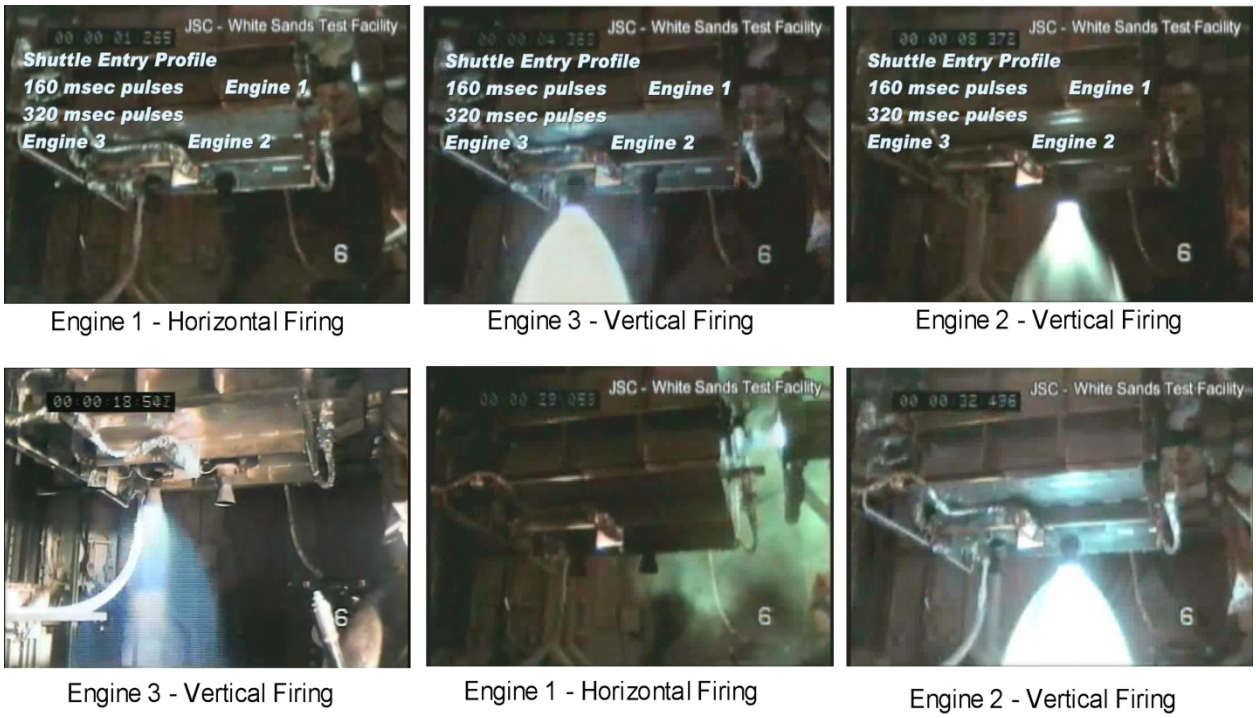


Figure 6: Views of three engine firing sequences: engine E1 horizontal, engines E2 and E3 vertical

2.1 Impulse Bit Repeatability

A major objective of the test program was to measure impulse bit repeatability. The concern was that the use of cryogenic propellants would result in variable impulse bits. The test matrix was designed to determine whether the subcooled propellants in the cryogenic feedline would help provide a repeatable pulse. The impulse bit repeatability was calculated by integrating the chamber pressure and time and recording the area under the curve for each pulse, since a direct thrust measurement was not provided. The conversion to thrust was made using the measured C-star of the engine (obtained during vendor tests) and the engine's throat area. Figure 7 shows a representative sample of a 5-sec pre-burn and five 320-ms engine pulse-width firings with a 15% duty cycle. Figure 8 shows the pulse repeatability (impulse bit) using a 1-sec interval to calculate the area under the curve over the entire run.

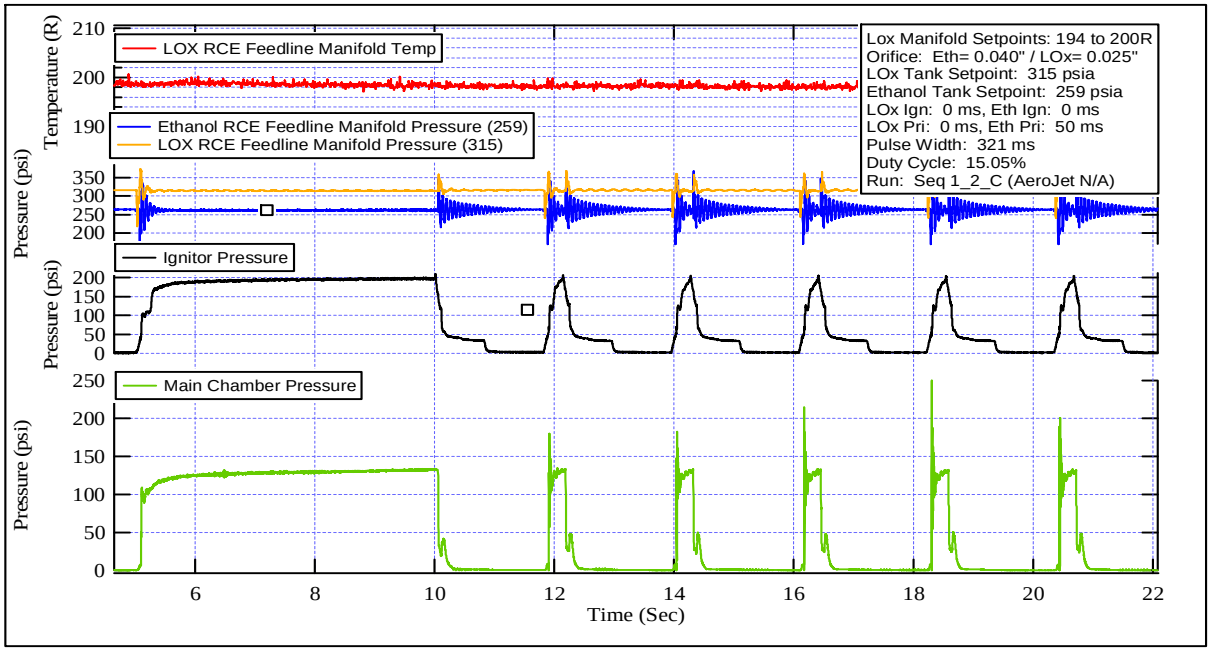


Figure 7: Representative sample of a 5-sec preburn and five 320-ms engine pulse-width firings with a 15% duty cycle (110 successful pulses; the first 6 are shown)

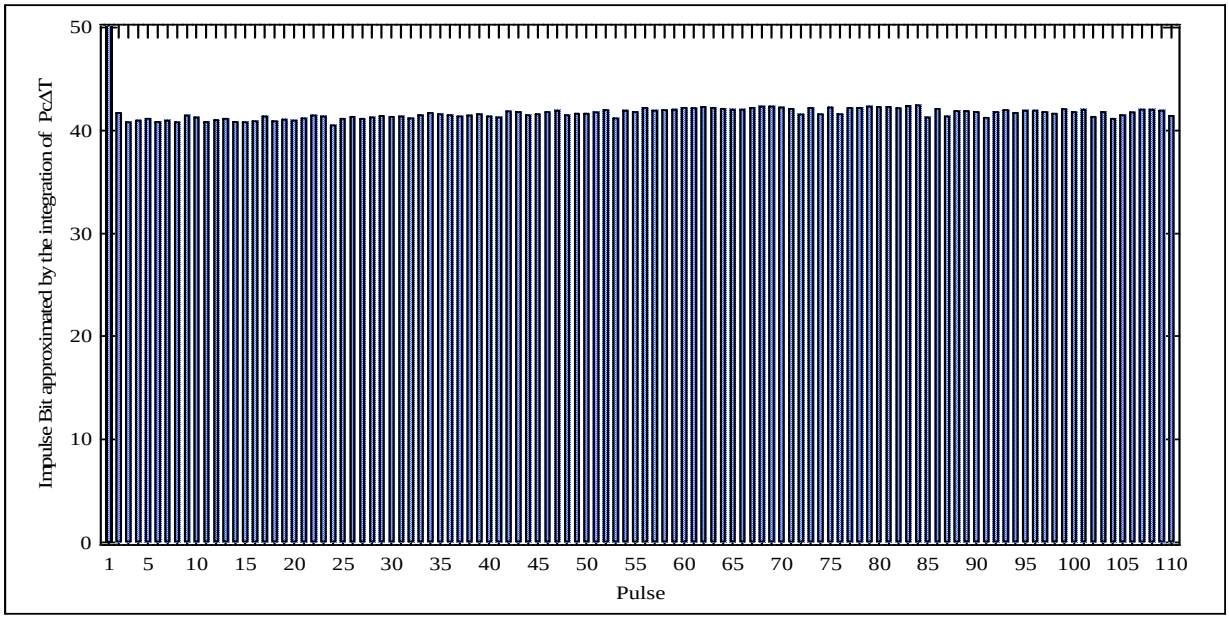


Figure 8: Impulse bit for each of the 110 pulses in Figure 7 (integration of Pc Δt)

2.2 Ignition Reliability

Evaluation of ignition reliability was another major objective of the test program. During testing, 1,685 firings using LO_2/ethanol propellants and 733 firings using LO_2/LCH_4 propellants were completed. Reliability issues arose during the tests, but were resolved. During testing, either the igniter or the main stage of the engines failed to ignite in 22 cases, as discussed below. Of the 16 igniter non-ignitions, 8 were due to facility or instrumentation problems. Most of the remaining ignition problems were resolved by changing the trim orifices installed at the igniter valve inlets. The orifice change increased the flow rates of both the LO_2 and ethanol into the main chamber. Only one non-ignition (sequence 3_12D) occurred after the LO_2/ethanol orifice size was increased. This non-ignition may have been related to exciter problems caused by corona that were experienced during vacuum operation; this was confirmed in follow-on testing of the 870 igniter at GRC in 2007 (Please see Section 0, 3.6 Exciter Vacuum Compatibility – GRC Follow-On Igniter Testing later in this report).

Figure 9 shows how the orifice change resulted in a better ratio of the LO_2/ethanol propellant mixture into the igniter and helped guarantee igniter lighting. Figure 9 helps explain the igniter failures by highlighting three separate 5-sec pulses: one in the original configuration represented by sequence 0_1B, another after the orifice changes were made (sequence 0_1D), and the third after orifice changes were made and PFJIGN1 was capped (sequence 0_1F). As seen in the figure, the original configuration contributed to lower igniter chamber pressures early in the ignition phase, resulting in a weak torch or no torch at all. In the runs that occurred after the orifice was changed, the igniter chamber pressure rose much more quickly, resulting in a strong torch.

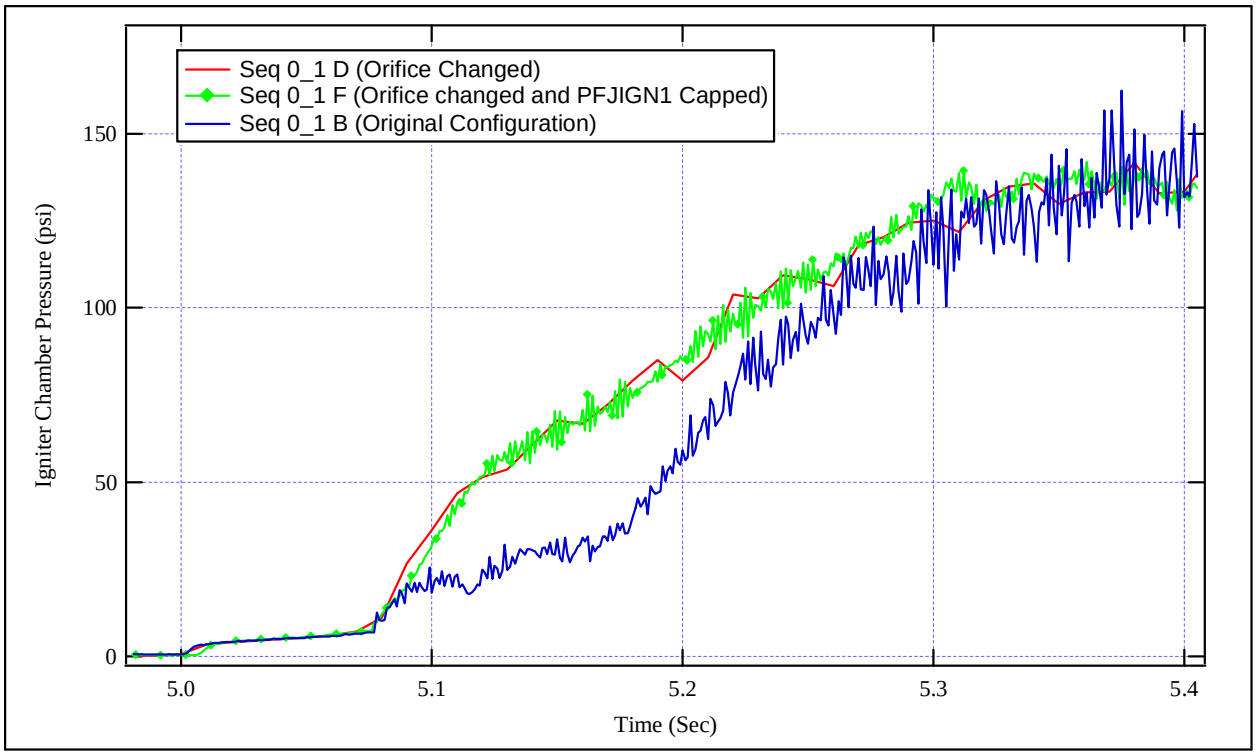


Figure 9: Igniter chamber pressure, original configuration versus orifice changes

2.3 LO_2/Ethanol Main Chamber Non-Ignitions

The ignition failures of the engine main stage were caused by excessively fuel-rich conditions in the main chamber at the time of normal ignition. Increasing the main LO_2 lead time decreased these problems, but did not eliminate them. When repeat pulses were performed using a cryogenic oxidizer and

a liquid fuel with a fairly low vapor pressure, accumulation of fuel tended to be the issue. Unpurged manifolds do not drain completely on short coasts, so fuel arrives in the main chamber more quickly on the next pulse. Vaporization of fuel in the chamber may also affect the mixture ratio. Since there were multiple instances of the engine not lighting at the appropriate time despite an operating igniter, the problem appeared to be an overly fuel-rich mixture. The engine start sequence was modified to include a 50-ms LO_2 lead, which meant that the main LO_2 valve and the igniter valves opened simultaneously. Based on soon-to-be-published 100-lb_f thruster work performed at WSTF in 2009, a potential solution is to change the propellant mixture ratio to increase the temperature of the igniter exhaust gas.

3 LO_2/LCH_4 HOT-FIRE TESTS

The test article used with both the ethanol and methane systems was modified after the LO_2/ethanol testing as follows:

1. A TVS was added to the LO_2 and LCH_4 lines.
2. Only two engines were used in this testing, and both were installed in the vertical, down-firing configuration.
3. The purge system was simplified such that only the main fuel and oxidizer ports on each engine injector were purged, and the system was installed as shown in Figure 10.
4. More effort to fix leaks was made to improve vacuum level; this effort was successful.

While these changes improved the feed system performance and TVS operation, they created problems related to exciter vacuum.

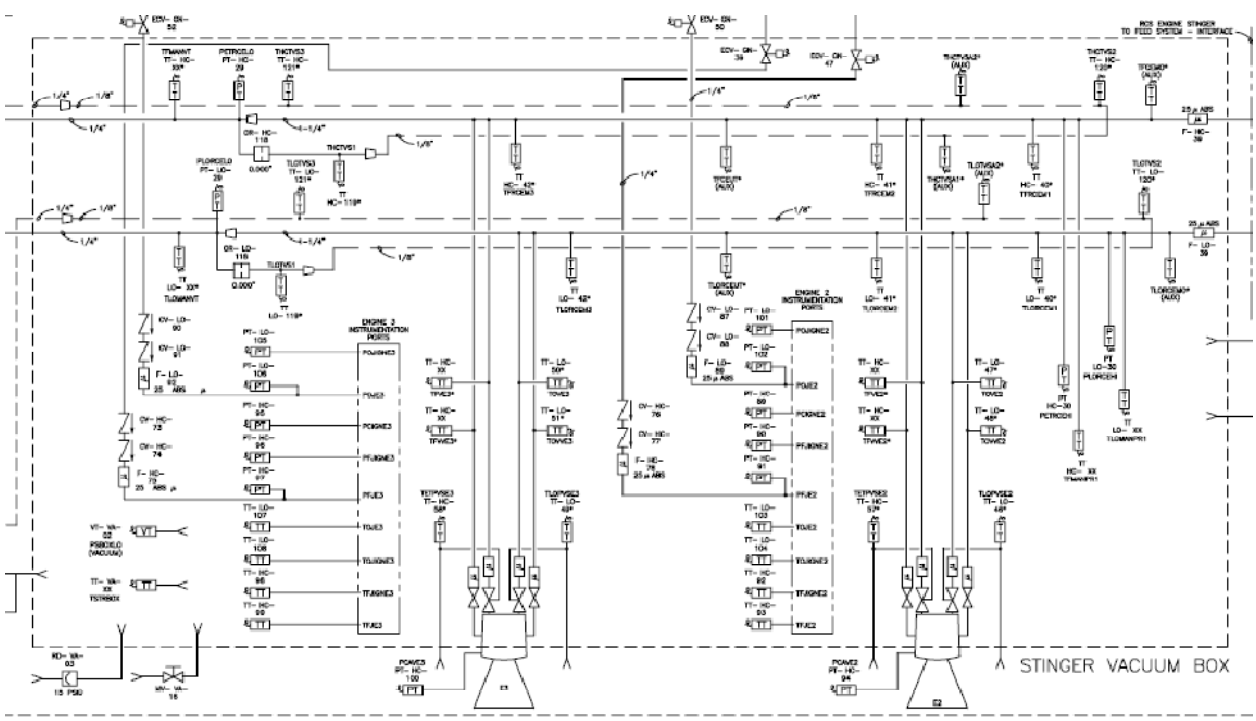


Figure 10: Purge system simplified to purge the main fuel and oxidizer ports on each engine injector

Initially, testing began in January 2007 with an unmodified LO_2/ethanol engine installed in the E2 position. In February 2007, Aerojet delivered an engine that had been modified for the methane operation

and installed it with an ablative chamber in the E3 location. In April 2007, Aerojet delivered another LO_2/LCH_4 870-lb_f engine. The unmodified engine was replaced with the new engine. Modifications to the main injector consisted of increasing the orifice dimensions to improve stability margins per the Hewitt Correlation.

The hot-fire test program was broken into three sets of firings: igniter-only firings on E2 and E3, single-engine hot-firings of E2 and E3, and simultaneous firings of E2 and E3. More than 733 hot-fire tests were conducted. Several modifications were required to obtain reliable ignition of the igniter and main stage. In addition, some ignition issues related to the exciter's vacuum compatibility were not resolved until testing was conducted at GRC after the WSTF tests were completed.

3.1 E2 Hot-Fire of Unmodified LO_2/Ethanol Igniter on LO_2/LCH_4

Initially, 232 igniter-only pulses were performed on an unmodified LO_2/ethanol main injector in the E2 location. Three configuration changes were made, one at a time, to eliminate the firing failures: the spark plug gasket thickness was increased, but this had no effect; the eroded and dirty plug from the ethanol tests was replaced with a new plug, but the results showed no clear effect on the ignition failure rate; and the spark timing was moved from T-zero to 10 ms before T-zero, which reduced the number of non-ignitions.

3.2 E3 Igniter Hot-fire

The E3 position igniter was hot-fired 364 times. The results improved with this igniter, although late in the day it would start to experience non-ignitions. Several pulse profiles were completed over a wide range of pressures and temperatures, from 275 to 375 psia and from 170 R to 224 R for LO_2 and from 200 R to 240 R for LCH_4. The igniter successfully completed these profiles. The profiles consisted of 160-ms pulses at 1% duty cycle and steady-state 0.5-sec firings. However, during a nominal firing attempt late in the day, several non-ignitions occurred in a row, and testing was halted. Subsequent investigation at GRC showed that different exciter-plug combinations were more leak tight, and hence could operate longer in a vacuum before the gas evacuated and corona issues caused non-ignitions.

3.3 Initial E3 Hot-Fire Testing of Engine Position 3

The first few days of vacuum testing the 870-lb_f LO_2/LCH_4 engine at WSTF were conducted at altitude in Test Stand 401. Numerous non-ignitions of the igniter and several non-ignitions of the main stage occurred, even when the igniter lighted successfully. Engine tests performed at sea-level in Aerojet facilities showed successful, reliable ignition of the 870-lb_f engine under similar propellant conditions, with the primary differences being altitude (sea level versus 100,000 ft) and differences in the feed systems. Investigation of these issues provided valuable insight into the ignition of LO_2/LCH_4 engines. One of the factors contributing to non-ignitions was the lack of oxygen during the start transient in the igniter or in the ignition of the main stage. Another factor, which was discovered in later testing at GRC, was the configuration of the exciter, which was not properly configured for vacuum operation and experienced corona, degrading the spark output.

Several steady-state approximately 5-sec burns were performed; these burns looked good, but shut down early at higher tank pressures when igniter chamber pressure crept up and resulted in a redline kill. In addition, several pulse profiles of 0.25-sec pulses with 4.75-sec coast times were performed, but the engine would run for only 12 of the designated 38 pulses due to engine main injector pressure measurements creeping up and not bleeding off with each successive pulse. Failure to bleed off the pressure may have been caused by the accumulation of ice or propellant in the pressure transducer lines.

Engine serial number 1, in position E3, ignited more reliably at low temperatures. The igniter did not fail to light even when the propellant was coldest, after being in the test and cold soaking for hours. However, the main stage did fail to light when the propellant was warmer, despite a strong igniter. It was determined that the engine started best with an oxygen lead, just as it had during LO_2/ethanol testing at altitude at WSTF in 2006. The LO_2/LCH_4 testing at WSTF initially used simultaneous fuel and oxygen main valve timing.

3.4 Initial E2 Hot-Fire Testing of Engine Position 2

E2 experienced more non-ignitions than E3. Several areas were investigated. The spark exciter's output diagnostics were measured at ambient pressure, but nothing significant was found. WSTF then made a diagnostic, boroscopic movie of the spark plug dry firing and noted that the rate of non-ignition increased over time on a given test day. During testing, it was incorrectly believed that this was caused by the hardware becoming more chilled over time. The cause was later determined to be corona issues related to the exciter as explained in follow-on testing at GRC. See Section 0, "3.6 Exciter Vacuum Compatibility – GRC Follow-On Igniter Testing" of this document.

3.5 Final Single and Simultaneous E2 and E3 Testing

With the test program running out of time and funds, and after making the changes to add a LO_2 lead, 2 days of testing were conducted. The primary objective was to perform simultaneous firings of E2 and E3. Testing was performed with two engines, both of which were installed in the down-firing test stand: E2 had a 0.030-inch (in.). thick spark plug gasket and a relatively new, unworn spark plug, and E3 had a 0.030-in. thick spark plug gasket and a new spark plug. Except where noted otherwise, pressures were set at 315 psia for both propellant tanks, and valve timing at the beginning of each pulse was simultaneous for the two igniter valves and for the two main stage valves, with the mains opening 50 ms after the igniter valves. Closure valve timing varied to prevent shutdown pressure spikes. Typically, pressure inside the stinger box was held at 50 mtorr, although during some E3 firings, it rose to 300 mtorr. Propellant temperatures varied during the tests, as indicated below.

3.5.1 Tests Performed on E2 – May 3, 2007

A 5-sec steady-state burn was performed on E2. Propellant temperature set points were 240 R for LCH_4 and 204 R for LO_2. The firing ran to completion as shown in Figure 11.

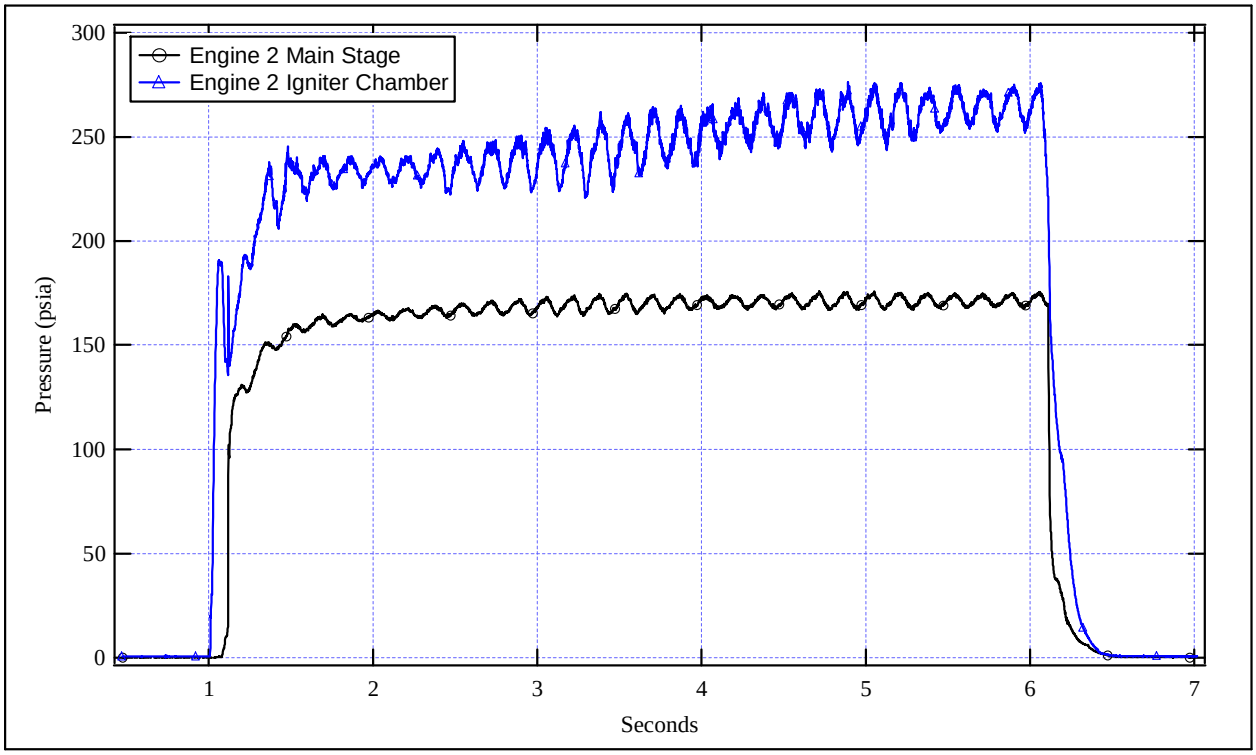


Figure 11: Five-second hot-fire of E2

Several tests were then run on E3, after which testing resumed on E2. Approximately 1 hour had elapsed since the first test of E2. Propellant temperature set points were 210 R for LCH_4 and 170 R for LO_2. Four sequential attempts to fire E2 were performed in 45 minutes (mins) and, during each one, the spark failed to light the igniter torch. Each attempt used different valve timing, but in no attempt did the torch ignite.

The next day, the first test on E3 was conducted with propellant temperature set points of 240 R for LCH_4 and 204 R for LO_2. The temperature changes resulted in the lighting of the igniter torch, but not the main stage, so the engine redline system halted the test immediately.

The second test of E3 was a successful 5-sec firing. The 5-sec firing, shown in Figure 12, used the same propellant conditions as the first test (in which the igniter torch failed to ignite), but with different valve timing. The third test of E3 used propellant temperatures of 210 R for LCH_4 and 170 R for LO_2. The torches of both the igniter and main stage ignited well, but shut down early as the igniter chamber pressure (PCIG) climbed over the 275 psia redline during the single 5-sec burn. It was considered a successful firing, however, because it was determined that the redline was too conservative.

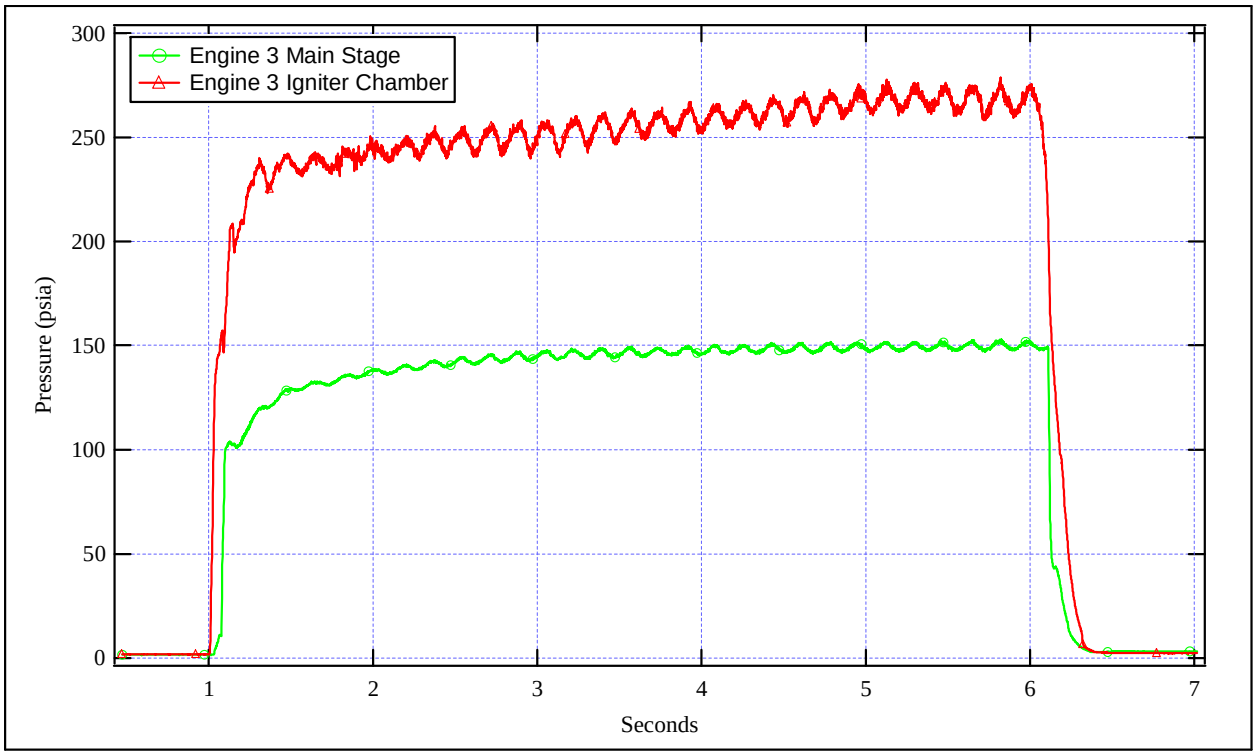


Figure 12: Five-second hot-fire of E3

Approximately 80 mins later (after several E2 tests), E3 was tested again. The default valve timing was used at the beginning of the pulse, and the fuel valves were closed after the LO_2 valves closed. The propellant condition set points were 210 R for LCH_4 and 204 R for LO_2. The profile was a 5% duty cycle of 38 pulses of 0.250-secs each of the main stage (with the valve timing used, the igniter pulse was 0.300 secs). The engine successfully pulsed 14 times, then shut down on the 15th pulse when the main stage failed to light. The first three pulses and last three pulses are charted in Figure 13. Figure 14 shows the impulse bit for each of the 14 pulses in Figure 13 (impulse bit equals integration of Pc Δt).

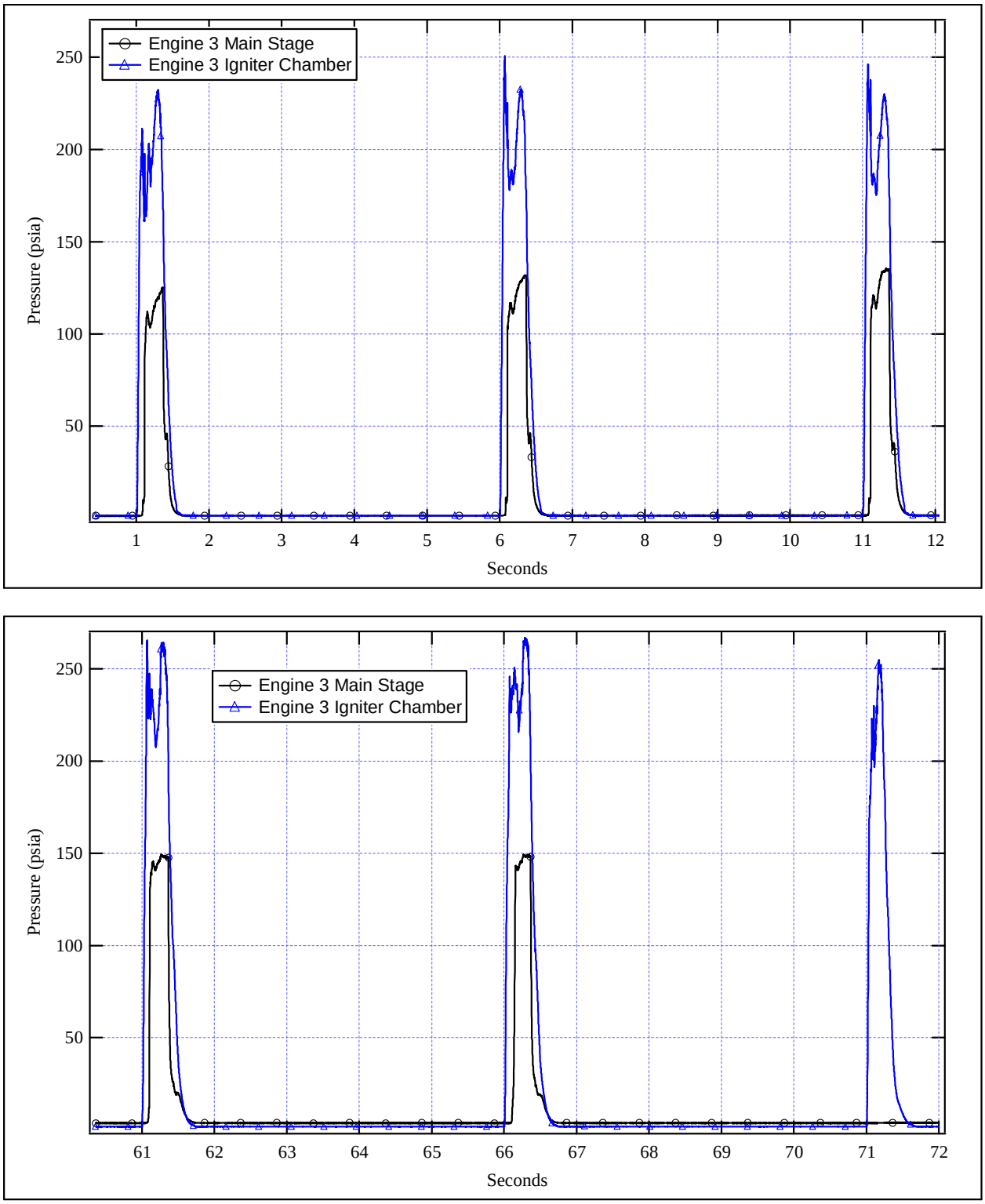


Figure 13: Multiple pulses on E3

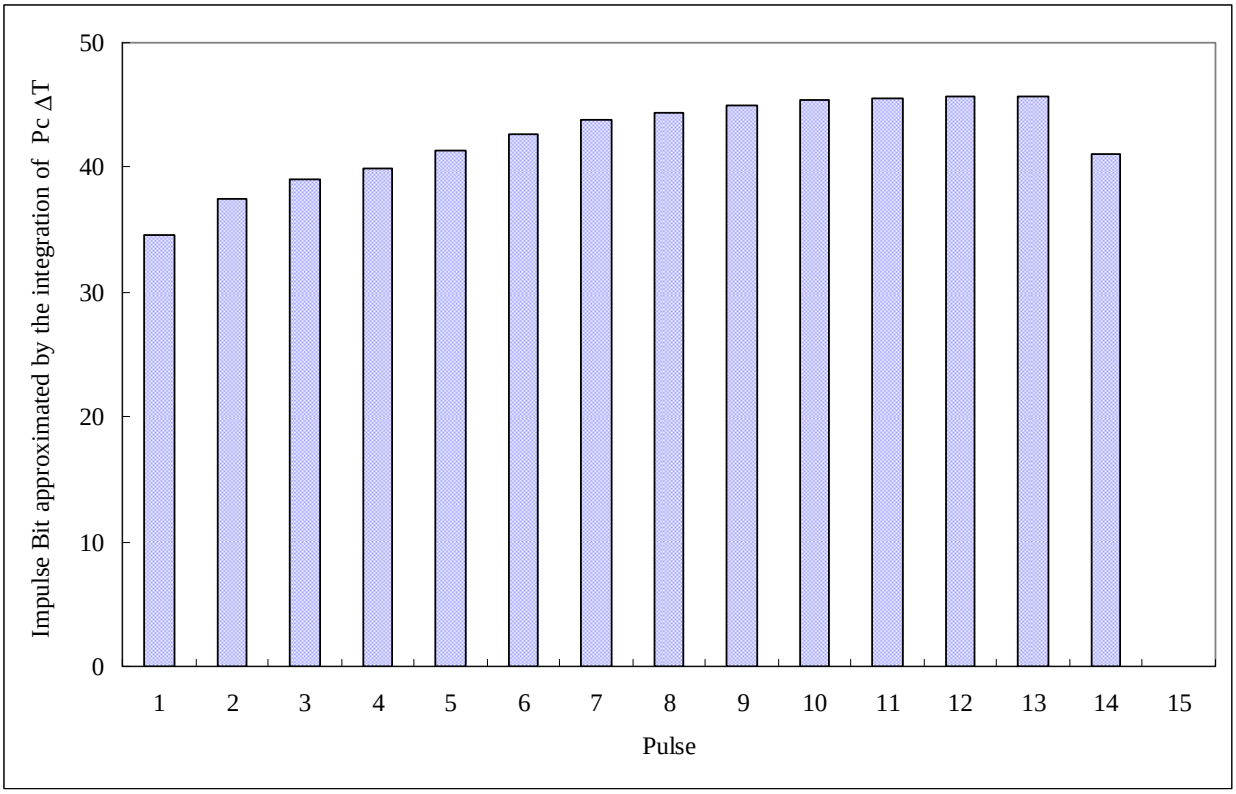


Figure 14: Impulse bit for each of the 15 pulses in Figure 13 (integration of Pc Δt)

3.5.2 Simultaneous Firings of E2 and E3 – May 4, 2007

Testing continued with the same engines, configuration, igniters, default tank pressures, and default valve timing as were used on May 3. May 4th was the only day of dual engine firings. Typically, pressure inside the stinger box was 50 to 80 mtorr at the beginning of each test and rose to between 140 and 200 mtorr during engine firings. The 401 altitude chamber established approximately 8 torr at the nozzles at the beginning of each test. Propellant temperatures varied during the tests as indicated in this report.

The first two firing attempts achieved proper ignition of the igniter and main stages in both engines, but they were shut down prematurely due to a flaw in the test stand's valve driver system. The flaw caused both main LO_2 valves to close prematurely. Diagnosis indicated that this problem occurred only during simultaneous valve actuations in both engines, so the remainder of the dual-engine tests were run with staggered engine timing, such that E2 started 0.250 secs before E3.

The next two attempts were shut down by the automatic engine redline system when the igniter torch in E2 failed to light. Because of the non-ignitions, the decision was made to halt the test, repressurize cell 401, and perform visual inspections of the E2 engine.

Before disturbing E2, its exciter was powered on, and the spark was observed through the nozzle opening. Although the exciter appeared to behave normally, a new igniter was installed based on the theory that the existing plug had a defect that manifested itself only at cryogenic temperatures, and the igniter gasket was changed from a thickness of 0.030 inches (in) to one of 0.020 in. to allow the tip of the igniter to reach deeper into the engine, where the propellant mixture ratio might be more favorable to ignition. In addition, the process of installing a new plug and shim resulted in reintroducing air back into

the exciter and plug assembly, which has a mechanical seal. It was later learned that the exciter design required pressure seals to maintain pressurized air to prevent corona. The pressure seals on the exciter cable and plug leaked over time, and eventually evacuated the igniter so that its pressure matched the pressure in the vacuum chamber, resulting in non-ignitions due to corona.

After reintroducing air into the exciter cable after changing the spark plug, testing was resumed with much better results. Five back-to-back, dual-engine firings were performed. The pulse duration was 3.000 secs, with the engine firings staggered by 0.250 secs. The pressure in both propellant tanks was 315 psia. The LO_2 manifold temperature was set at 204 R, and the fuel manifold temperature was set at 240 R.

A sixth attempt to fire the same profile with lower propellant temperatures (LO_2 at 170 R and LCH_4 at 210 R) was halted by the redline system as the igniter chamber pressure on E3 spiked above its 275-psia limit when the valves on E2 closed, causing a spike in propellant pressure. Figure 15 represents that test run.

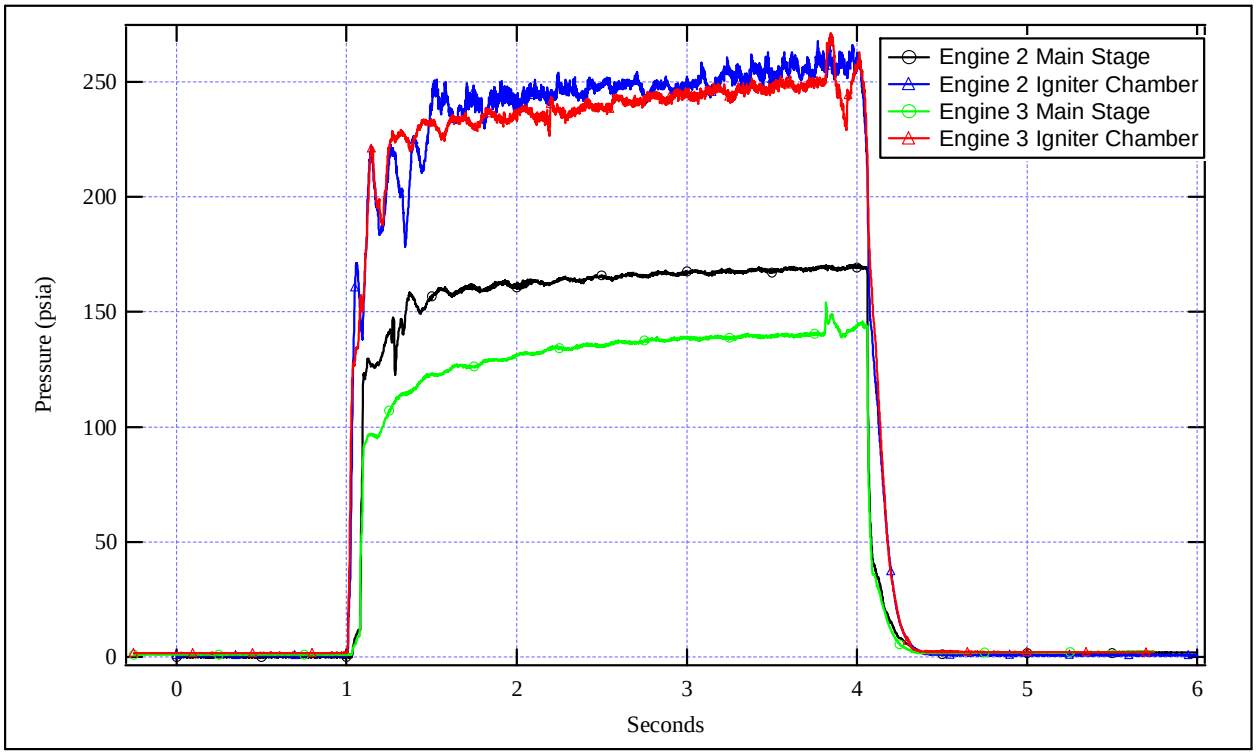


Figure 15: Comparison of E2 and E3 during simultaneous engine firings

Three more tests were conducted, and all were pulse trains on E2 alone. The propellant conditions were left as they were in the previous test: both tanks at 315 psia, with the LO_2 manifold temperature set at 170 R and the fuel manifold temperature set at 210 R. Two attempts to fire were made, both of which shut down early after two or three pulses. Both shutdowns appeared to have been caused by exciter problems, as indicated by off-nominal exciter feedback signals. The third, and final, test firing was set up the same way as the previous two, except that the LO_2 tank pressure was raised to 350 psia. It shut down during the second pulse because of a high igniter pressure redline. The main stage showed normal combustion pressure. This concluded testing of the 870-lb_f engine at WSTF.

3.6 Exciter Vacuum Compatibility – GRC Follow-On Igniter Testing

Following the testing at WSTF, the cause of the igniter non-ignitions was investigated at GRC. It was thought that the non-ignitions were caused by the temperatures of the propellant quenching the spark. GRC used a WSTF 870 LO_2/LCH_4 igniter and an exciter at a vacuum. The test replicated the non-ignitions of the igniter; however, the non-ignitions did not correlate to temperature. The igniter lighted successfully over a broad range of propellant and igniter body temperatures. Non-ignitions tended to occur later in the day. The vacuum compatibility of the exciter then came into question.

GRC tested the exciter purged at ambient pressure and exposed to vacuum. All 800 ignitions were successful at ambient pressure. At vacuum, there were 2 non-ignitions out of 90.

Some of the later igniter non-ignitions at WSTF can be attributed to a weak spark. In hindsight, several observations from the WSTF testing corroborate this fact:

1. The non-ignitions at WSTF tended to occur later in the day and as the vacuum improved. The exciter cable and connection to the plug are sealed, but the trapped gas does leak out over time, eventually leading to corona discharge and a weaker spark.
2. Vacuum was broken on the last day of testing, and the spark leads were switched.
3. The exciter cable design, which was originally designed for another application, is meant to be purged as part of the exciter box, but this was not known during testing. The exciter box was hermetically sealed and potted, but the cable required purging.

4 CONCLUSION

The APSTB and 870 RCS development and test program provided valuable data on impulse bit repeatability and ignition reliability. The feasibility of a cryogenic RCS system is supported by this data. Additional fine tuning of the engine igniter, development of a vacuum-capable exciter, and improvement of injectors are required, but overall the project was successful. Both ethanol and methane are feasible propellants for an RCS. The methane has an advantage due to its higher vapor pressure.

The significant test results show that the engine pulses are repeatable. Initial ignition problems were resolved, and a better understanding of the physics developed. Ignition issues were resolved during testing by changing the igniter orifices to improve injector priming and adding an LO_2 lead to the primary valve. Ethanol and methane perform similarly during engine pulses. The fuel primes the injector first, regardless of which fuel is used. However, ethanol drips from the chamber, whereas methane easily evaporates. Pressure transient data for both the ethanol and methane feed systems was obtained and correlated to model predictions. Operational procedures and timelines for loading and checking propellant leakage were developed, and these can be extended to space vehicle launch processing. A TVS was installed and used to condition the manifolds during the LO_2/LCH_4 testing.

Another lesson learned from the testing is the necessity of performing vacuum and sea-level testing during technology and advanced development testing, since the test stand atmospheric pressure may cause differences in ignition behavior. This data will also be useful for the 100-lb_f thruster that is in development.

5 REFERENCES

1. Robinson, Philip J.; Veith, Eric M.; Turpin, Alicia A., "Test Results for a Non-toxic, Dual Thrust Reaction Control Engine", 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 11-13 Jul. 2005, Tucson, AZ, United States, AIAA Paper 2005-4457.

APPENDIX A: TEST STAND 401 FACILITY TEST SYSTEMS

A.1 Overview Structure

The APSTB support structure was designed to mount directly on the WSTF-supplied PA-1 frame (the structural frame originally used to hold Apollo propulsion systems). The total weight of the unloaded test article assembly is 19,600 pound-mass (lb_m). The weight of the PA-1 structure is approximately 2,500 lb_m. The major components of the test article were assembled in WSTF Building 413, then transferred to Test Stand 401 through the top of the test stand using a custom fabricated 4-point spreader bar. The PA-1 with the tank and feed system was attached to the screw-jack lifting/positioning assembly (Western Gear Jackscrew Assembly). The total lifting capacity of the jackscrew assembly is 40,000 lb_m.

A.2 Fluid Systems Overview

The nontoxic propellant system (Figure A-1) includes liquid and gaseous oxygen (GO_2) tanks; an ethanol (hydrocarbon) tank; and a liquid methane supply, dump, and vent system. The GO_2 system consists of GO_2 high-pressure storage and low-pressure run tanks, piping, manual and remotely operated valves, a test chamber wall feed through, instrumentation for pressure temperature and flow measurements, and associated piping systems required to supply propellant from the run tanks to the test article. The system also includes some gaseous nitrogen (GN_2) piping and components (not shown here) that supply GN_2 as a motive fluid and inert gas to the GO_2 system. A GO_2 recharger system is used to provide oxygen recharge capability to the system, but it is not considered a permanent part of the system.

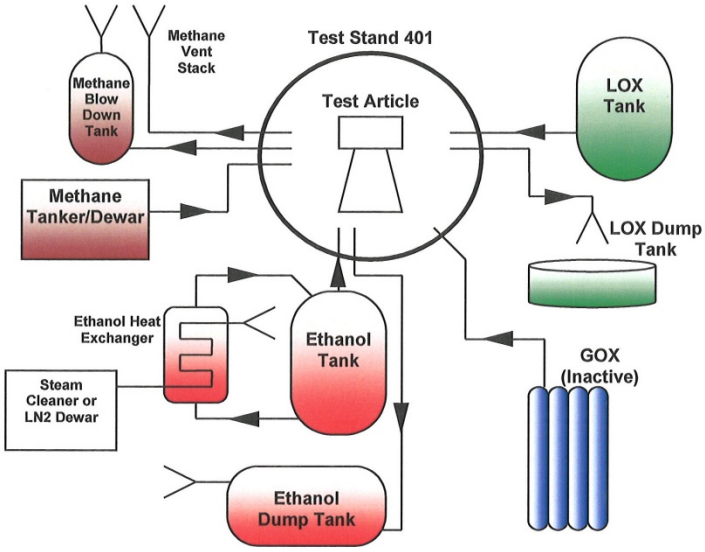


Figure A-1: Test Stand 401 nontoxic propellant systems

The LO_2 system consists of an LO_2 run tank, LO_2 dump tank, piping, manual and remotely operated valves, test-chamber wall feed-through penetrations, instrumentation for pressure temperature and flow measurements, and associated piping systems required to supply propellant from the run tank to the test article. The LO_2 run tank is a vacuum-jacketed 4,200-gal, 715-psig maximum allowable working pressure (MAWP) tank. The LO_2 run tank is pressurized with gaseous helium (GHe) through a proportional control valve. The system also includes some GN_2 piping and components that supply GN_2 as a motive fluid and inert gas to the oxygen system. The LO_2 tank is filled from a vendor-owned LO_2 transporter, which is not considered to be a part of the system. The dump system consists of a 1,175-gal open tank, located in the Test Stand 401 flume, that captures LO_2 and allows for boil off into the atmosphere. A back-pressure regulator was installed on top of the storage vessel to help condition and maintain an ullage pressure of 100 psia while LO_2 was in the tank. GN_2 is interfaced with the LO_2 storage system and used to cycle pneumatic operated valves and purge the offload, transfer, and dump lines as required. GHe is used to pressurize the LO_2 storage tank.

The methane system consists of a welded supply line, LCH_4 blow down tank, vent system, piping, manual and remotely operated valves, test-chamber wall feed-through penetrations, instrumentation for pressure and temperature measurements, and helium and GN_2 purge systems required to purge LCH_4 from the system. The LCH_4 system provides supply, dump, and vent interfaces for test articles that are installed inside the test chamber. The LCH_4 blow down tank is a 400-gal, 500-psig MAWP tank. LCH_4 is provided by a vendor-owned LCH_4 transporter, which is not considered to be part of the system, and supplied to the test article through the welded supply system. Helium at 100-psig is used to purge LCH_4 from the welded supply line to the blow down tank located approximately 250-feet (ft) north of the test chamber. A 12-psig GN_2 trickle purge is plumbed into the dump and vent lines to prevent any air from migrating back down the lines and causing a flammable condition.

All systems supporting test operations fell within current WSTF pressure vessel certification, in accordance with WSTF standard instruction (WSI) 09-SW-0005.[1] This WSI includes instructions for pressure tests to meet the requirements of American Society of Mechanical Engineers (ASME) B31.3, Process Piping (1999). The test stand fluid system is documented in WSTF drawings 413-15290[2] and 413-12484.[3]

A.3 Liquid Oxygen (LO_2)

The LO_2 was procured per MIL-P-25508F; analyzed for composition per SES-0073; and verified to level 100A per SN-C-005, revision D, within 10 ft of the test article interface. The LO_2 was passed through a 25-µm absolute filter before entering the test article from the facility storage tanks.

A 4,200-gal, vacuum-jacketed, LO_2 storage tank was used to store the LO_2 needed for testing and other operations. LO_2 tankers offloaded the LO_2 into the storage tank, which was then conditioned and transferred through insulated lines into the test cell and into the test article run tanks.

A.4 Methane (LCH_4)

The liquid methane used in the supply, dump, and vent systems is propellant grade methane (MIL-PRF-32207 – Grade B). The hazards associated with liquid and gaseous methane are documented in Chemwatch material safety data sheet (MSDS) No. 1971-1. The MSDS meets the requirements of 29 CFR 1910.1200 (g). It contains toxicity information, permissible exposure limits, physical data, thermal and chemical data, and reactivity data. The MSDS documents a threshold limit value (TLV) level of 1,000-ppm for liquid methane and lists gaseous methane as a simple asphyxiate. LCH_4 poses a cryogenic hazard when exposed to skin and will form explosives when mixed with air and oxidizing agents as described in the MSDS.

A.5 Filtration

All fluids interfacing with the test article were filtered using 25-µm nominal filters just downstream from the test stand supply isolation valves before proceeding to the test article through the appropriate flexhose, which was the closest practical point to the test article.

A.6 Inert Gas Systems

GN_2, supplied at pressures as high as 500-psig throughout the test cell, was used for system purging, system leak checks, muscle pressure for pneumatic actuated valves, and pressure for test cell and test article stinger box vacuum operations. A 250-psig GN_2 source was plumbed to provide purge pressure for the test article engines.

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[1] In-house document. WSI 09-SW-0005.H. *Certification, Recertification, and Deactivation of WSTF Pressure Vessels and Pressurized Systems (PV/S).* March 13, 2003.

[2] In-house document. WSTF Drawing 413-15290. *400 Area TS 401Non-Toxic Fluid Schematics. February* 16, 2007.

[3] In-house document. WSTF Drawing 413-12484. *TS 401 Fluid Schematic.* Rev. AC-1, February 16, 2007.

GHe was supplied from a 2,200-psig source, regulated as required for pressure to the test article run tanks, and provided muscle pressure for pneumatic actuated valves on the test article flow simulator systems.

Dual check valves were used to protect against propellant migration into the inert gas supply lines.

See Figures A-2 and A-3 for the GHe and GN_2 facility interfaces to the test system.

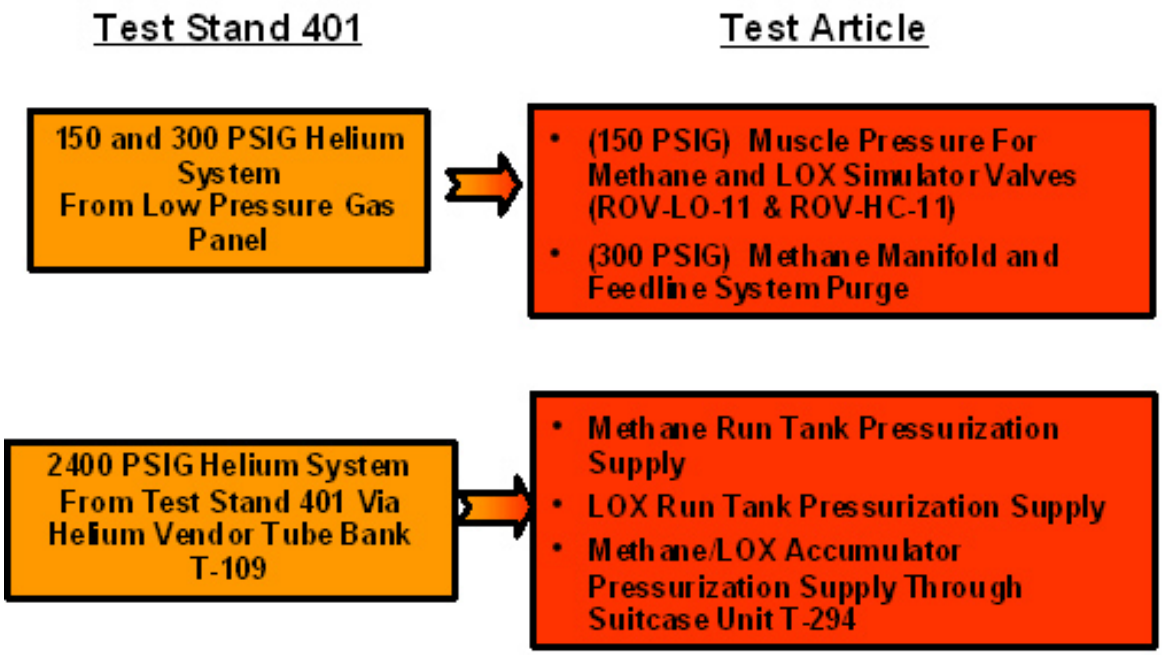


Figure A-2: Test Stand 401 and APSTB GHe interface chart

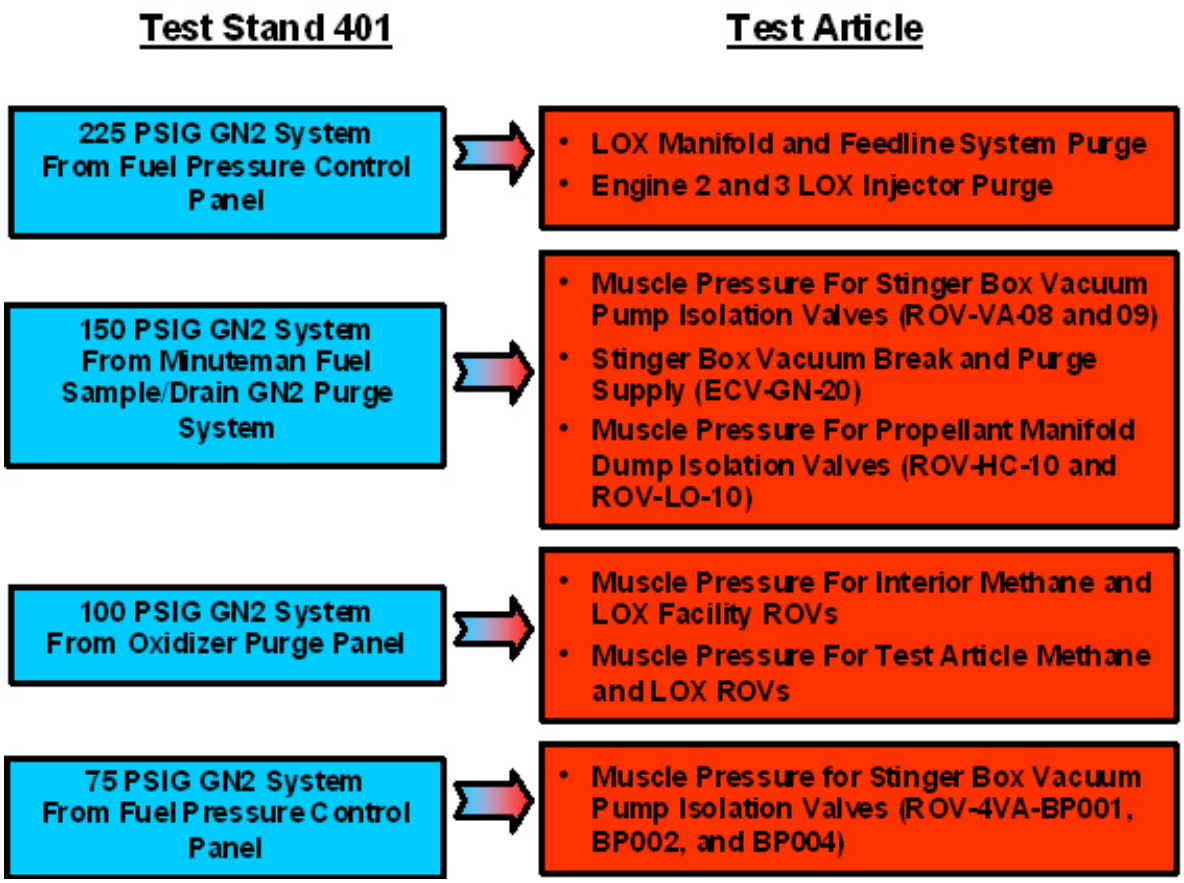


Figure A-3: Test Stand 401 and APSTB GN_2 interface chart

A.7 Safety Systems

The interior of Test Stand 401 is equipped with an ultraviolet (UV) fire detection system that is designed to initiate the fire alarm. The fire alarm rings locally and at the fire department. The UV fire detection system provides 24-hour (hr) coverage. The cell interior is also covered with FIREX systems. Infrared (IR) methane detectors are installed inside the test cell to detect methane vapors.

A watch-dog alarm system is programmed to alert personnel after hours in the event of an equipment failure. This alarm system provides 24-hr coverage of systems. UV detectors, IR detectors, and the GN_2-supply low-pressure alarm are part of the watch-dog alarm system. If an alarm is detected, the watch-dog system sends an indication of the type of alarm to the fire department. Depending on the alarm, the fire department personnel will contact the appropriate personnel to address the alarm. The GN_2-supply low-pressure alarm supports the LCH_4 dump and vent system trickle purge system. A GN_2 trickle purge is supplied through the LCH_4 dump and vent lines to prevent migration of outside air through the piping, which could create an explosive hazard during non-working hours. If the main GN_2 supply pressure drops below an established pressure, the watch-dog alarm system notifies the fire department, and the appropriate personnel are contacted to address the anomaly.

A.8 Altitude Simulation

It was anticipated that the 400-Area Large Altitude Simulation System (LASS), Small Altitude Simulation System (SASS), and vacuum pumps would be used to support testing in Test Stand 401. However, only the SASS was used to support testing for reasons described below:

1. Due to the incompatibility of oxygen with the oil used in the altitude vacuum pumps (10W30 motor oil) and the potential for oxygen to leak from the test article into the cell, the vacuum

pumps were not used during APSTB hot-fire operations. The Oxygen Hazards Group reviewed the pumps and the vacuum oil. There was very little data on the ignition properties of 10W30 oil. Because of this lack of information, the Oxygen Hazards Group assumed that it would be possible to ignite the oil at any oxygen concentration greater than the oxygen concentration in air.

2. An analysis was performed to determine the cost saved by using SASS rather than LASS. The results showed a significant reduction in cost and prompted the project office to reduce the altitude requirement from 80,000 ft to 40,000 ft for hot-fire profiles with active engine purges. With this modification, SASS or vacuum pumps could be used to maintain the minimum altitude for all planned test profiles.

The SASS was used to pull a vacuum through the 24-in. chamber outlet valve (the north-side port of Test Stand 401). Before the steam ejectors were activated, the 24-in. cell isolation valve was opened by opening the vacuum isolation valves at the large and/or small ejectors. This prevented (or at least minimized) pressure differential at the cell outlet, which in turn minimized any chance of picking up particulates in the vacuum header or the cell and causing particle impact and unintentional combustion. The north chamber outlet valve remained open throughout testing (with SASS support) and was closed once the GN_2 cell break valve was opened, the ejectors were isolated, and the cell was brought back to ambient pressure.

A jet direction device was designed, fabricated, and installed to divert the exhaust from the horizontally firing engine into the Test Stand 401 77-in. diffuser. The water-cooled device acted as a low-performance diffuser and was intended to recover only enough pressure to overcome line friction and convey gas safely into the 77-in. inlet. The inlet of the jet direction device was initially positioned 3 in. from the horizontal engine chamber exit. After observing what appeared to be exhaust “spill over” from the diffuser inlet, it was positioned within 1 in. of the engine chamber inlet.

During preliminary hot-fire tests, the jet direction device moved back and forth along the axial plane of the horizontal engine when the horizontal engine was firing. The total movement was estimated to be 1 in. to 1.5 in. in the horizontal plane. Additional bolts were installed near the exit of the jet direction device to prevent further movement during testing.

A.9 APSTB Electrical Controls

The electrical controls system, as configured for APSTB testing, consists of three distinct subsystems. These are the Distributed Computer Control System (DCCS), the ModComp Data Acquisition and Control System (MODACS), and a separate hard-wired safing and backup system. The DCCS controls and monitors the positions of most of the valves and other devices in the APSTB electrical controls system. Exceptions are controlled and/or monitored via the hard-wired safing and backup system or by the MODACS. The MODACS provides precision timing for the thruster valves and ignitors, controls the firing profiles, and runs the algorithms used to monitor such things as thruster chamber pressures during firing profiles. The hard-wired safing and backup system provides control of power buses and provides another layer of control and safing for the APSTB and related propellant systems.

A.10 Distributed Computer Control System (DCCS)

The DCCS consists of a master controller (Opto22 G4LC32) located in Bunker 1 that communicates with the various input/output units that are responsible for control and monitoring of the individual input and output modules, both digital and analog. These units are directly wired to the various valves and talkbacks installed on the APSTB test article and related propellant systems. Using an ArcNet link (a communications protocol much like Ethernet), the master controller communicates with the Engine Firing Control System (EFCS) operator’s personal computer (PC), located in the Blockhouse Control Center on which the graphical user interface (GUI) is resident. This provides an easy way for the EFCS operator and the test conductor to verify the positions of valves (because a computer monitor on the test

conductor's table mirrors the EFCS operator's PC screen), to verify pressures and levels in the propellant tanks, operation of various algorithms controlled by the DCCS, and ready logic of the DCCS to support firing operations. Remotely operated valve (ROV) positions are indicated on the GUI by color changes—blue for closed, yellow for open, and "barber-poled" for transitional states. Proportional valve positions are indicated by text boxes on the GUI that indicate the commanded value as a percentage from 0 to 100%. Proper operation of such valves can be inferred by noting whether the appropriate action is taking place (usually pressurization or venting). For manual control of valves and other devices, the EFCS operator selects the devices on the GUI using the computer mouse and, depending on the level of confirmation required, either clicks the mouse button or opens a dialog box to control the device.

For the purpose of testing the APSTB, two new purged J-boxes were configured and installed on the APSTB support structure (the PA-1) in Test Stand 401. Each of these J-boxes contains slave input/output units (Opto22 B3000s) and associated input and output modules that control the valves located on the APSTB and perform system health monitoring.

The DCCS master controller runs the WSTF-designed subroutines that compose the DCCS computer program and are required to perform various functions and to monitor the system and verify its health. These include subroutines to verify that all valves are commanded closed when valve power is off, to verify that all parts of the system are communicating with one another, and to perform various other functions, such as conversion of voltage levels to temperature values for display on the GUI.

A.11 MODACS Interface

A third junction box (the engine-firing J-box) containing WSTF-designed valve drivers was configured to accept timing commands from the MODACS to drive the thruster propellant valves and igniters. The engine-firing J-box is located on the PA-1 structure in Test Stand 401 to reduce the voltage drop inherent in sending high currents over long distances. The valve drivers monitor over- and under-current conditions and provide a high current (limited to 5A) input to the engine valves to open them quickly. After a programmed time delay of 100 ms, the valve drivers lower the current flow to the valve and begin a pulse-width-modulated output that provides sufficient holding power to keep the valve in the open position as long as the command input from the MODACS is maintained.

A.12 Hard-Wired Safing

The hard-wired safing and control system is designed to provide redundant control of critical valves and voltages from the EFCS operator's panel in the control center. Switches on the EFCS console allow the operator to turn the valve power bus on or off, providing motive force to all valves that are part of the APSTB electrical control system. In addition, all valves that are considered to be tank outlet valves, whether they are on the facility storage tanks or on the APSTB test article, require switches on the EFCS console to be in the Enable position before they can be operated remotely by the DCCS. This is also true of power provided to the engine-firing J-box, which contains the thruster valve drivers and is located on the PA-1 structure in Test Stand 401. In this case, the arm key switch on the EFCS console must be placed in the armed position for power from the engine firing power supply to be connected to the power bus in the engine-firing J-box.

A.13 APSTB EFCS Panel Control Center

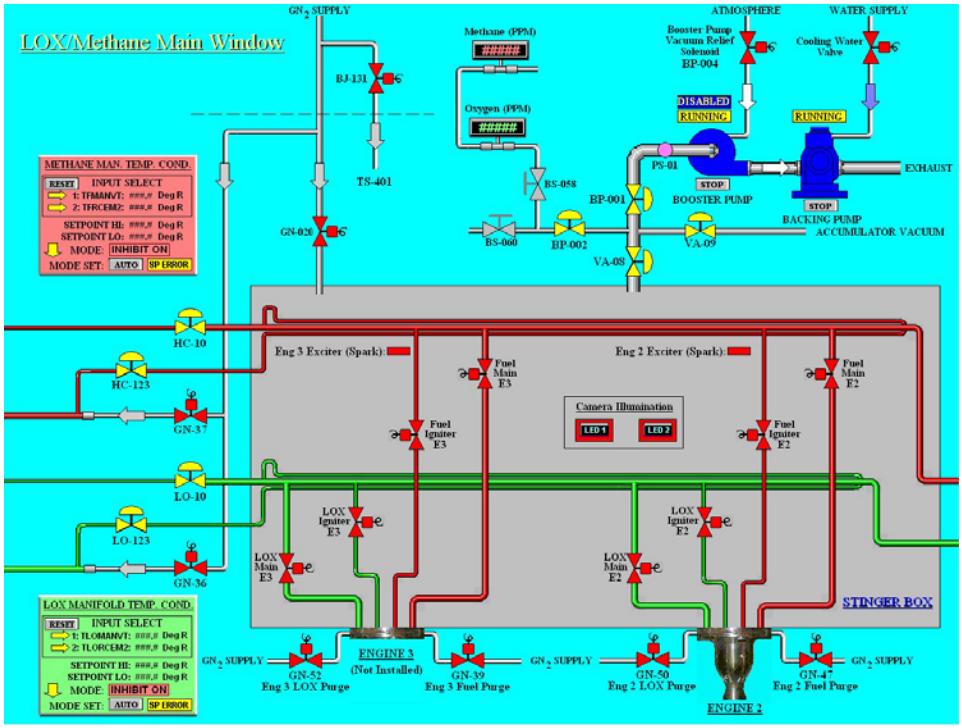


Figure A-4: GUI main screen control panel, part 1

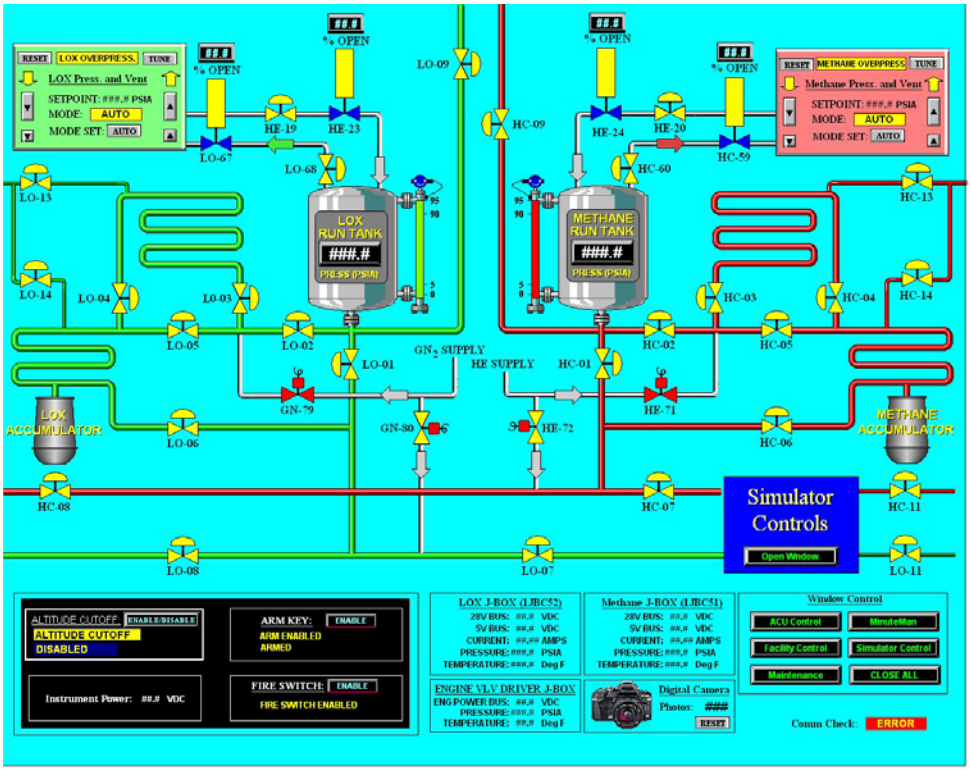


Figure A-5: GUI main screen control panel, part 2

A.14 Valve Driver Operation

The valve driver described herein is a lightweight, compact, microcontroller-driven unit capable of providing up to 10A at 30 VDC to a single solenoid valve coil with minimal internal heat dissipation and very low standby power requirements. A detailed schematic and a flow diagram of the firmware in the driver's microcontroller are available upon request.

This driver provides the capability for opening a solenoid valve while monitoring the valve's coil current to provide positive indication of whether the valve armature has moved. Additionally, the valve driver will limit the total current delivered to the valve coil by switching to a pulse-width modulation (PWM) mode if the current in the coil exceeds a value defined by the user. If the valve driver detects an opening of the valve armature, the valve driver will automatically reduce the power delivered to the valve coil after a user-defined period ranging from 50 to 500 ms, again using PWM with feedback, to maintain the open valve while minimizing power and heat within the coil. If the valve driver does not detect valve armature movement within the specified period, then the "NO movement" light-emitting diode (LED) will be lighted, and the microcontroller will start the reduced-current PWM mode. Additional error signals provided by the valve drivers indicate whether the output is short circuited or there is no load (open circuit). The output stage of the valve driver contains circuits that minimize the closing time of the solenoid valve allowing rapid valve cycling. The "turn-off" portion of the output stage is optically coupled to the valve driver input command signal such that the "off" command is immediate and overrides the PWM control electronics. Finally, initial valve driver power-up diagnostics with indicators are incorporated; these check for defective components in the input stage, the power output stage, and the analog–to-digital converters used within the valve driver.

Two major motivating factors resulted in the development of this valve driver. First, a requirement exists for operating the cryogenic propellant solenoid valves of an Aerojet rocket engine currently under test at WSTF. The requirement is to provide 28 VDC at no more than 5A for 100 ms to open the valve, then reduce the current to 2A to maintain the valve open. Under cryogenic conditions, the coil resistance of these valves will decrease to less than 1 ohm, which at 28V applied to the coil would imply more than 30A. One previous method for operating these valves used a current-limited power supply that would automatically switch to "current mode" regulation once the 5A level was established in the coil. When the 100-ms opening period expired, the power supply would be programmed to drop to the 2A constant current level. The disadvantages of using traditional current-limiting power supplies or a voltage regulator include bulky size, the need to provide adequate environmental protection for them, and higher costs. Another motivation stemmed from the generally inefficient practice of applying the stated voltage to any solenoid valve coil to have it reliably open. Once a solenoid valve has opened, the power required to hold it open is usually considerably less that the power required to overcome the mechanisms that held it closed. This results in excess power consumption and heat dissipation. Traditional valve voltage reduction techniques such as voltage regulators and power resistors reduce the power in the valve coil, but only move the heat dissipating effects to those circuits.

The other major motivating factor in developing this WSTF-designed valve driver stems from the fact that unless there is a limit switch package or some form of sensor attached to a solenoid valve, it is difficult to determine if the valve has opened. One can use upstream or downstream indicators (i.e., pressure change, flowrate), or the valve current trace can be monitored to verify the valve's operation, but for closed loop processes and valve sequencing applications, it is better to have the valve's state known electrically. Adding a limit switch to a solenoid valve, the traditional favorite, increases the valve's weight and requires additional wiring and connection points. This valve driver can determine if the solenoid armature has moved and provide positive indication of the movement within a few milliseconds.

When 28-VDC power is first applied to the circuit, the microcontroller performs a set of diagnostics that determine if there are any off nominal conditions. If any problems are detected, the valve driver will flash all four LEDs, and it will remain in this state until power is removed.

An input signal between 4V and 32V will start the operation of the valve driver. First, the input signal is optically coupled to the output circuity such that the driver transistor is allowed to switch on, making the transistor conduct across the zener flyback diode, which effectively shunts the zener. If the command input signal is removed, then the driver transistor is forced off and the zener shunting transistor opens, allowing the current in the valve coil to decay quickly through the zener diode.

As shown in the flowchart, the microcontroller first turns the driver transistor on and monitors the current rise in the coil by digitizing the voltage dropped across the current sense resistor. While the valve is opening, a current dip occurs as the valve armature moves from closed to open. The microcontroller detects this current dip and illuminates the "valve OK" LED at that time. The delay period set by the jumpers is the interval between the time that the driver transistor is turned on fully,to the time that it switches to PWM mode. If this delay period expires and the current dip is not detected, the "NO movement" LED is lighted, and the microcontroller starts the reduced current PWM mode.

If the voltage drop across the current sense resistor exceeds the voltage set by the current limit potentiometer before the valve opens, the microcontroller will flash the "over current" LED and remove all power from the valve. If this voltage is exceeded after the valve has opened, but prior to the end of the delay period, the microcontroller will begin closed-loop PWM control to maintain the current at the current limit value. This is the operating condition under which this valve driver was originally developed to meet the project requirements.

Once the delay period has expired, the microcontroller will begin closed-loop PWM control of the valve driver transistor, such that the voltage drop across the current sense resistor equals the voltage set by the PWM current potentiometer. The valve driver will maintain this closed-loop control until the command input signal is removed. If during this time the current drops to zero or increases to the point that the PWM can not reduce it, the microcontroller will flash the corresponding error LED, and power will be removed from the valve coil. This condition may be caused by failure (open or short) of the valve's coil due to unforseen conditions.

Finally, when the command input signal is removed, the microcontroller will monitor the voltage drop across the current sense resistor as the coil decays (through the zener clamping diode) until current approaches zero. The software will not respond to the command input until the valve coil has decayed.

A.15 High-Speed Video Control

The high-speed video system is triggered by the firing profile through a dedicated MODACS channel. The Inter-Range Instrumentation Group – B (IRIG-B) circuit that was originally used for the Cine Camera is now providing the IRIG-B signal to this system. An Opto-22 unit has been installed to monitor the operating pressure and temperature of the explosion-proof enclosure that houses the camera controller.

A.16 IR Camera Control

The IR camera is used to monitor the temperature of any desired area of interest inside the test stand. The camera operator has complete control of this system via the control computer. All of the settings for this camera system are set prior to initiation of the firing profile. The camera is manually triggered by the operator upon a verbal command from the test conductor. This command is included in the countdown sheet for each firing profile.

A.17 Digital Still Photo

A still camera inside Test Stand 401 may be triggered manually from the EFCS control panel during the test and at altitude.

APPENDIX B: LO_2/ETHANOL HOT-FIRE TEST MATRIX AND DATA

Date	Filename		Profile Name	DC% EPW	Aerojet Test#	Actual # of Pulses			Test Time (Sec)	Total On Time (Sec)			Propellant conditions	Shutdown Rationale	Changes/Comments	Non-ignition?
						E1	E2	E3		E1	E2	E3				
01-14-06	SEQ 0_1	A	ATP_1	100% 5 seconds		1	0	0	25.0	5.01	0	0	Ambient temperature Ethanol & Ox temp (R) 184 tank, (R) 200 Manifold	PCIGNE1 and PFJIGNE1 low in Limit Group 3	POJIGN, PFJIGN and PCIGN all lowered for Limit Group 3 and 4.	
01-14-06	SEQ 0_1	B	ATP_1	E2 & E3: 100% 5 seconds	2	0	1	1	25.0	0	5.01	5.01	Ambient temperature Ethanol & Ox temp (R) 184	PFJIGNE1 and POJIGNE1 high in Limit Group 5.	Determined that engine 1 had completed full 5 second burn before shutdown. Decided to start profile midway to test igniters on engine 2 and 3. Igniters lit at 50ms at ATP and 76ms for E2 and E3 at WSTF	
01-14-06	SEQ 0_1	C	ATP_1	?	3	0	1	1	25	0	5	5	Ambient temperature Ethanol & Ox temp (R) 184	Successfully completed planned portion of profile.	Successfully completed Engine 2 and 3 igniter only steady state burn. Igniters lit at 50ms at ATP and 76ms for E2 and E3 at WSTF	
01-14-06	SEQ 0_2	A	ATP_2	100% 5 seconds		1	0	0	25.0	0.14	0	0	Ambient temperature Ethanol & Ox temp (R) 184	PFJE1 low in Limit Group 3.	Redlines adjusted slightly to account for negative pressure read on engine transducers due to altitude environment	
01-18-06	SEQ 0_2	B	ATP_2	100% 5 seconds	5	1	0	0	25.0	1.84	0	0	Ambient temperature Ethanol & Ox temp (R) 184	PCIGNE1 high in Limit Group 4 (~160 psi)	At 3:38 PM yesterday, we proceeded with a test sequence that sequentially fires each engine for 5 seconds (Sequence 0, Test 2, Run B). We hit an engine redline at 1.86 seconds into the Engine 1 firing. After looking at the strip charts, it was determined that after a nominal startup the pressure in the igniter chamber exceeded the redline limit by approximately 160 psia. Charlie Carter, the Aerojet representative, suspected that a piece of ceramic from the spark plug broke off and was lodged in the igniter chamber. Post test purges indicated that something was definitely blocking the igniter chamber outlet. We broke altitude and performed a cell entry and proceeded to inspect the spark plug by removing from engine 1 – with the stinger box configuration this was easier to do than it was at Aerojet. We did have to raise the western gear because the side-firing diffuser prevented looking down the chamber. We found that the spark plug ceramic had, in fact, broken but it was a clean fracture such that the ceramic sleeve slid down to the end of the spark plug. The spark plug removal and boroscope inspection showed that the fragments were minimal (~0.040-0.050 mil) and were blown out using canned air this morning. Charlie did see a couple of small anomalies inside the igniter that we will do some further checkout this morning but planned on discussing it with Phil and Eric V. The ceramic cracking may be a thermal shock issue that has resulted from bleeding LO2 in to the igniter, but we're not sure yet. Once we complete these checkouts and get Aerojet approval we plan to replace the spark plug on all three engines, just in case, with spark plugs that we have in hand, and proceed with testing. We also found a LO2 leak in the stinger manifold on both sides of the filter (at the bayonet fitting and where the flexline connects to the adapter). Because the leaking was minimal and we did not get an improvement on the leak from the day before when we re-torqued, we will proceed with testing today with the minor leak unless it shows change. The more detailed repair will occur on an ops day. High pressure in igniter chamber indicated spark plug was damaged. Inspection showed that ceramic barrel was completely broken. Spark plug replaced. Ceramic fragment lodged in igniter barrel. Stakeholders agreed to proceed with further testing, but not perform LOX engine valve cycling prior to hotfire. Suspected that thermal cycles on spark plug may have caused failure.	
01-26-06	SEQ 0_2	C	ATP_2	100% 5 seconds	7	1	1	1	26.0	4.95	4.95	4.95	Ambient temperature Ethanol & Ox temp (R) 184	Profile successfully completed.	Successfully completed steady state burn of all 3 engines. Tests from warm/empty manifolds showed a 550ms delayed filling of IGN#1 fuel manifold. This caused the igniter to be back driven when the engine starts and to be clearly fuel limited after the main chamber lights. However, this did not result in difficulty lighting the engine in steady-state testing. E2& E3 showed a reduced delay (300ms) compared to E1 in reaching full power. Also, no significant back driving of igniter occurred when main chamber lit	
01-26-06	SEQ 0_3	A	ATP_3	100% 30 seconds		1	0	0	26.0	0.13	0	0	Ambient temperature Ethanol & Ox temp (R) 184	PCAVE1 low in Limit Group 3	Engine redlines adjusted	?
01-26-06	SEQ 0_3	B	ATP_3	100% 30 seconds		1	0	0	26.0	0.13	0	0	Ambient temperature Ethanol & Ox temp (R) 184	PCAVE1 low in Limit Group 3	LOX Manifold Vent Valve iced over. Not cycling when commanded by manifold temperature control loop. Unable to conditionion temperatures in manifold.	X
01-26-06	SEQ 0_3	C	ATP_3	100% 30 seconds		1	0	0	26.0	0.75	0	0	Ambient temperature Ethanol & Ox temp (R) 184	PCAVE1 low in Limit Group 3	High temperatures at engine inlets preventing full ignition. During cell inspection, found that LOX Manifold Vent Valve actuation pressure line was damaged, preventing valve from cycling when commanded. All instrumentation and control wrapped with refractory material	?
01-27-06	SEQ 0_3	D	ATP_3	100% 30 seconds	11	1	1	0	40.999 / 19.999	29.95	11.08	0	Ambient temperature Ethanol & Ox temp (R) 184	PCAVE2 low in Limit Group 4	Video showed that PCAVE2 cabling is damaged. PCAVE2 replaced. LOX Manifold Vent valve is still not funtioning properly. Actuation line repaired and wrapped. E2 aborted due to burned PCAVE2 cable at 11.1sec. PCIGN readings becoming noisier as testing proceeded. Cable damage?	
01-29-06	SEQ 0_3	E	ATP_3	100% 30 seconds	12	0	0	1	31.0	0.00	0.00	~30	Ambient temperature Ethanol & Ox temp (R) 184	Successfully completed planned portion of profile.	Completed event 40 through completion. Data stopped premature.	
01-29-06	SEQ 0_5	A	ATP_5	25% 1 second	13	23	0	0	95.0	26.83	0.00	0.00	Ambient temperature Ethanol & Ox temp (R) 184	PCIGNE1 low in Limit Group 5	PCIGNE1 showing signs of damage due to high pressure and temperature. Test repeated to see if transducer behaves this way again. Tests 13 and 14 sequence hold for PCIGNE1 out of limits. SENSOTEC A302-05 erratic during pulsing. These tests were the first attempt to pulse	
01-29-06	SEQ 0_5	B	ATP_5	25% 1 second	14	31	0	0	125.7	33.48	0.00	0.00	Ambient temperature Ethanol & Ox temp (R) 184	PCIGNE1 low in Limit Group 5	Same results as previous test. Team decided to attempt a pulse train that provides less strain on PCIGNE1. Tests 13 and 14 sequence hold for PCIGNE1 out of limits. SENSOTEC A302-05 erratic during pulsing. These tests were the first attempt to pulse	
01-29-06	SEQ 0_6	A	ATP_6	5% .111 seconds	15	200	0	0	645.0	27.04	0.00	0.00	Ambient temperature Ethanol & Ox temp (R) 184	Successfully completed planned portion of profile.	Completed 200 0.16-second pulses of engine 1. Decided to try a shorter "ON" time test to see if transducer would get through without a cabin entry. Full duration pulses-but PFJE2 takes a 25 psi offset on second relight. No other parameters show spikes. Subtle changes in PCIGNE1 start transient in the first pulsing test in which transducer shifts did not cause an exit. However, all 200 pulses lit in the nominal 90-100ms time frame	

Date	Filename		Profile Name	DC% EPW	Aerojet Test#	Actual # of Pulses			Test Time (Sec)	Total On Time (Sec)			Propellant conditions	Shutdown Rationale	Changes/Comments	Non-ignition?
						E1	E2	E3		E1	E2	E3				
01-29-06	**SEQ 1_1**	**A**	**SEQ 1_1**	**5% .32 seconds**	**16**	**176**	**0**	**0**	**1,136.0**	**52.38**	**0.00**	**0.00**	Ambient temperature Ethanol & Ox temp (R) 184	**Fire white called after 4 consecutive non ignitions**	**Test 16 1st No-Light of campaign. 3rd relight attempt, should have exited sequence but continued due to flag error. Did not call for an immediate fire-white as the occasional missed pulses appeared benign. Igniter peaks and swoons however, at 95ms it was still 18.5 psia, which is will above igniter cold flow pressure with baseline orifices-engine should have lit. Concern that 100ms of spark "On" time was insufficient prompted an increase from 100ms to 160ms on all igniters, this was 1st implemented on E2 test 21 2-5-06, E3 test 25 2-23-06 and on E1 test 26 on 2-23-06. (further info see page 31 in report). The changes were prompted by Tests 16 (320ms On/6.08 sec Off 1-30-07) on E1 in which several pulses were missed and at times PCIGN would peak and begin to fall (Swoon) near 100ms. Suspect that engine purge is too high and is extinguishing the engine's flame even though it lights temporarily. No major changes made to system before resuming testing. After this test it was decided to re-orifice Ign#1.**	**X**
01-30-06	SEQ 1_2	A	SEQ 1_2	15% .32 seconds		342	0	0	801.0	97.36	0.00	0.00	Ambient temperature Ethanol & Ox temp (R) 184	Fire white called after 2 consecutive non ignitions	Post test investigation of the firing profile uncovered a design flaw. The FS2 variable was not reset after limit group 5 time window expired. The profile was corrected and revalidated before testing resumed.	X
02-15-06	**SEQ 4_2**	**A**	**SEQ 4_2**	**5% .32 seconds**	**21**	**0**	**2**	**0**	**25.0**	**0.00**	**5.08**	**0.00**	Ambient temperature Ethanol & Ox temp (R) 204	**PCAVE2 low in Limit Group 3**	**PFJIGNE2 transducer/purge plumbing was removed and the tube on the igniter capped to reduce the volume that had to be filled through the 0.031" ign fuel orifice on the valve inlet.. It was felt that this was safer than removing the igniter fuel purge on the horizontally oriented E1 to check the effect of igniter fuel manifold volume on igniter performance. Overall, the reduced volume appeared to have helped PCIGNE2 on the warm up burn in this test, It lit 6ms later, but was slightly stronger at 95ms. PCIGNE2 on the relight attempt (test aborted no main stage ignition within time specified) was strong (32psia at 93ms). Note this was the 1st attempt to pulse E2. Despite the 32 psia PCIGN torch at 95ms, the engine did not light until the abort. Both main valves were open, but it appears that there was not an ignitable mixture ratio. On 2/06/06, extensive cracking found on Engine 1 chamber. Engine 1 chamber removed and capped off with cover plate. Test operations resumed on 2/8/06 on engines 2 and 3. During pretest operations, team saw indications of LOX temperatures and pressures in the ethanol feedsystem. Later determined that mixing had occurred through engine 1's valves. Replaced engine 1 cap with a pristine chamber. Received approval to proceed with testing on 2/15/06. Shutdown on 2/15 required data review by Aerojet before proceeding. Engine redlines adjusted. Hot gas circulation observed in cell during steady state firing at greater than 100K ft altitude.**	**?**
02-16-06	SEQ 4_2	B	SEQ 4_2	5% .32 seconds	22	0	2	0	25.0	0.00	5.07	0.00	Ambient temperature Ethanol & Ox temp (R) 204	PCAVE2 low in Limit Group 3	To address issues from test 21, on Test 22 the facility GN2 purge source pressure was lowered to give an 82psia running POJE2 purge level (135psig source). This was nearly identical to the purges used at ATP. The change was made to see if late checking of the main ox purge at WSTF was impeding ignition. The chamber lit earlier, but hard. PCIGNE2 recorded a steep spike to about 510 psia and PCAVE2 died in a negative direction without ever having risen. This furthered suspicions that an overly fuel rich condition was to blame for late or non-ignitions. However, given the violence of test 22, the decision was made to advance the main lox cmd rather than experiment with purges at this point in the test campaign. Shutdown identical to yesterday's. Immediately following shutdown, PCAVE2 began reading at high end of range. Replaced with a spare. LOX Manifold vent line leaking. Replaced teflon seal and leak checked. Wrote two new profiles for SEQ 4_2. One titled Seq 4_2a, where the LOX valve opens at FS+1 and one titled Seq 4_2b, where the LOX Primary opens at FS-1+ 20ms. Plan to use Seq 4_2b first.	
02-17-06	SEQ 4_2	C	SEQ 4_2b	5% .32 seconds		0	1	0	12.9	0.00	4.59	0.00	Ambient temperature Ethanol & Ox temp (R) 204	PCIGNE2 high in Limit Group 4	PCIGNE2 redline limits increased from 50-225 psi to 50-300 psi prior to proceeding with next test. Since we are going back to the same engine purge pressure that we were previously testing a couple days ago, could you please update the engine redlines (actually, go back to the way that we had them two days ago.) I have attached the Test Request Sheet for this test, with the assumption that we are going to start with the 20 ms lead on the MOOG LO2 valve, which is profile SEQ_4-2B. If I hear something different from Aerojet or MSFC I will redline the TRS at that time.	
02-17-06	**SEQ 4_2**	**D**	**SEQ 4_2b**	**5% .32 seconds**	**23**	**0**	**7**	**0**	**55.0**	**0.00**	**6.63**	**0.00**	Ambient temperature Ethanol & Ox temp (R) 204	**PCAVE2 low in Limit Group 3**	**No changes to redlines. Next, plan to run Seq 4_2a, with LOX primary and igniters opening at FS-1.**	**?**
02-17-06	**SEQ 4_2**	**E**	**SEQ 4_2a**	**5% .32 seconds**	**24**	**0**	**127**	**0**	**830.0**	**0.00**	**45.26**	**0.00**	Ambient temperature Ethanol & Ox temp (R) 204	**PCAVE2 low in Limit Group 3**	**PCAVE2 read off-scale low after shutdown. Plan to replace instrument with identical spare.**	**?**
02-23-06	SEQ 4_18	A	SEQ 4_18a	5% .32 seconds		0	0	75	490.0	0.00	0.00	30.03	Ambient temperature Ethanol & Ox temp (R) 184	PCIGNE3 high in Limit Group 3	PCIGNE3 showing pressure after purges were stopped. Appears to be an erroneous reading. Transducer will be replaced at end of test day. Plan to proceed with Seq 1_1a_b. PCIGNE3 pressure holding at 158 psia (O2 purge turned off).	
02-23-06	SEQ 1_1	B	SEQ 1_1a	5% .32 seconds		188	0	0	1,300.0	64.85	0.00	0.00	Ambient temperature Ethanol & Ox temp (R) 184	Profile completed successfully	Plan to proceed with ATP_1_d. Recorded at 0.01 samples per second so pulse width cannot be determined (says 0.34)	
02-23-06	SEQ 0_1	D	ATP_1	100% 5 seconds		0	1	0	25.0	0.00	5.02	0.00	Ambient temperature Ethanol & Ox temp (R) 184	Profile completed successfully	Plan to proceed with SEQ 1_2a_b	

Date	Filename		Profile Name	DC% EPW	Aerojet Test#	Actual # of Pulses			Test Time (Sec)	Total On Time (Sec)			Propellant conditions	Shutdown Rationale	Changes/Comments	Non-ignition?
						E1	E2	E3		E1	E2	E3				
02-23-06	SEQ 1_2	B	SEQ 1_2a	15% .32 seconds		98	0	0	220.0	305.73	0.00	0.00	Ambient temperature Ethanol & Ox temp (R) 184	PCAVE1 low in Limit Group 3	Stopped testing to review data and inspect engine 3. Following day, decided to remove all PCIGN and PCAV transducers and replace with Aerojet-provided transducers. Plan to proceed with mission simulations 3_10 and 3_12 on 2/27/06. Recorded at 0.01 samples per second so pulse width cannot be determined (says 0.34). Fire White after pulse 98 and 211822 ms. Low PCAVE1 Waiting for data on low PCAVE1 fire white. It's 4:54 PM, we're done for today!	?
02-27-06	SEQ 3_10	A	SEQ 3_10a	E1: .1% .16 seconds E3: .1% .16 seconds		1	0	1	15.0	0.16	0.00	0.12	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	PCIGNE3 low in Limit Group 2	Redline adjusted. Testing continued. During all runs and throughout the day the vent valve was cycled, but the limits were changed at 15:43. DPLOTNK=53.69 at 14:27 Worked issue with no engine 1 O2 purge. Resolved by resetting valve control at 15:03 Run A: starting mission simulation sequence 3 firing profile now at 15:30 Start of profile at 15:25 Engine 1 okay early shutdown on engine 3 in limit group 2, due to low PCIGN 6 psia < 8 psia after 80 msec	?
02-27-06	SEQ 3_10	B	SEQ 3_10a	E1: .1% .16 seconds E2: .1% .45 seconds E3: .1% .16 seconds		1	1	1	15.0	0.16	0.27	0.16	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	PCIGNE2 low in Limit Group 3	Decided to add 100Hz filters to all PCIGN signal conditioners before continuing with testing. Run B: Adjusted manifold temp control loop to 214 high, 209 lo., and adjusted PCIGN redline group 2 to 5 psia instead of 8 psia. Start profile over ~16:00 Engine 1 okay Engine 3 okay Engine 2 kill on PCIGN high reached 408 psia in limit group 3 Continuing to auto cycle temperature control on LO2 manifold The PCIGN Tabor transducers are noisy and causing the kill. It is believed that the data is not real, since other measurements do not show anything similar. Aerojet uses filters with these Tabors, but these were not used at WSTF. WSTF is going to install filters at ~100 Hz that will allow redline algorithm to function properly in terms of catching non-ignitions, but to not trigger on noise. DPLOTNK=52.594 at 17:05:33	?
02-27-06	SEQ 3_10	C	SEQ 3_10a	E1: .1% .16 seconds E2: .1% .45 seconds E3: .1% .16 seconds		7	3	7	912.0	1.13	1.09	1.13	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	PCAVE2 low in Limit Group 3	No changes made before proceeding. Plan to enter profile at a specific event during next test. Run C: Restarted profile with the signal filters installed at 17:44 Ran for ~15 minutes, with good pulses on all 3 engines, and then killed on engine 2 PCAV low in limit group 3. Non-ignition of the main, but did ignite after valve commanded closed. Data shows PFJ response lower than normal, could be valve driver, etc DPLOTNK=51.773 at 18:22 DPLOTNK= 51.069 at 19:18	x
02-27-06	SEQ 3_10	D	SEQ 3_10a	E1: .1% .16 seconds E2: .1% .45 seconds E3: .1%		3	2	3	453.0	0.48	0.62	0.48	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	PCAVE2 low in Limit Group 3	Suspect that warmer engine manifold temperatures may be creating "hot spots" in lines, preventing full ignition. Plan to run with colder manifold temperatures tomorrow (199-204R).. Run D: Going to restart profile to see if it repeats at 20:00 Problem repeated on engine 2 on second pulse as it had before Turned off purges at 21:23, DPLOTNK = 49.729 DPLOTNK = 48.986 at 22:37	?
02-28-06	SEQ 3_10	E	SEQ 3_10a	E1: .1% .16 seconds E2: .1% .45 seconds E3: .1% .16 seconds		10	4	10	1,375.0	1.61	1.80	1.61	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	Completed planned portion of profile. Manually called shutdown.	Successfully completed planned portion of 3_10a at colder temperatures. We are in the middle of a long test day again today. We ran Sequence 3 Test 10 again today with lower manifold temps and ran successfully, relighting engine 2 a total 3 times (total of 4 pulses). We called a manual fire white after successfully lighting engine 2 rather than continuing with the 4 hour long profile. We are now proceeding to test Sequence 3 Test 12 Run A, which is a one hour mission simulations profile. I will send out an update as we continue to test.	
02-28-06	SEQ 3_12	A	SEQ 3_12a	E1: .58% .16 seconds E2: 1.65% .4 seconds E3: .58% .16 seconds		4	5	4	115.0	0.64	1.79	0.64	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	PCAVE2 low in Limit Group 3	The profile was performed at warmer manifold temperatures. Adjusted manifold temperature control loop to 199-204 before continuing with testing..	?
02-28-06	SEQ 3_12	B	SEQ 3_12a	E1: .58% .16 seconds E2: 1.65% .4 seconds E3: .58% .16 seconds		3	3	2	58.0	0.48	0.98	0.32	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	PCAVE2 low in Limit Group 3	Data review showed that ignition occurred. Proceeded with next planned test sequence.	?
02-28-06	SEQ 1_10	A1	E2_IGN	?		0	1	0	10.0	0	1.01	0	Ambient temperature Ethanol & Ox temp (R) 184	Limit group changed after fast algorithm was loaded.	Corrected limit group and restarted algorithm.	
02-28-06	SEQ 1_10	A2	E2_IGN	?		0	1	0	10.0	0	1.03	0	Ambient temperature Ethanol & Ox temp (R) 184	Profile completed successfully	Plan to proceed with SEQ 1_4a.	
02-28-06	SEQ 1_4	A	SEQ_1-4A	5% 2.56 seconds	38	5	0	0	215.0	12.86	0	0	Ambient temperature Ethanol & Ox temp (R) 184	PCIGNE1 and PCAVE1 low in Limit Group 3.	Profile stopped after 4 pulses. Engine TADs asked that testing stop for the night so a thourugh engine inspection can be performed. No spalling or cracking were noted during post test inspection.	?
March 3rd, 2006 Igniter Orifice Change: LOx 0.0205" to 0.025" - this will increase flow rate fy approx. 27% (from 0.0134 to 0.17 lbm/sec at steady state fully chilled) Fuel 0.031" to 0.04" increase the feil flow rate by approx. 8.4% (from 0.0134 to 0.0145 lbm/sec)																
03-06-06	SEQ 0_1	E	ATP_1	100% 5 seconds	39	1	1	0	15.0	5.01	5.01	0	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown.	Igniter #1 was re-orificed to increase propellant mass flow. The LOx orifice diameter was increased from 0.0205 to 0.0245 inch. The fuel orifice diameter was increased from 0.03 to 0.039 inch. Profile intentionally stopped after 5 second firing of engine 2. Plan to proceed with E1_IGN. Second set of igniter-only firings completed, (E1, one 1 sec pulse with fuel lead, then one with lox lead, quick look appears nominal....prepping for next firing.	
03-06-06	SEQ 1_11	A	E1_IGN	?		2	0	0	11.0	2.04	0	0	Ambient temperature Ethanol & Ox temp (R) 184	Profile successfully completed.	Plan to proceed with ATP_2 after TAD reviews strip charts.	
03-06-06	SEQ 0_2	D	ATP-2	100% 5 seconds		1	0	0	15.0	5.00	0	0	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown.	Profile intentionally stopped after 5 second firing of engine 1. Plan to proceed with E1_IGN	

Date	Filename		Profile Name	DC% EPW	Aerojet Test#	Actual # of Pulses			Test Time (Sec)	Total On Time (Sec)			Propellant conditions	Shutdown Rationale	Changes/Comments	Non-ignition?
						E1	E2	E3		E1	E2	E3				
03-06-06	SEQ 1_2	C	SEQ_1-2A	15% .32 seconds		110	0	0	245.0	39.99	0	0	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown.	Maintained GN2 break and BJ131 open to keep cell temperatures down during pulses. Approximately 70F was maintained. Able to complete 110 pulses before GUI temperature exceeded 200-degrees F.	
03-06-06	SEQ 1_4	B	SEQ_1-4A	5% 2.56 seconds		25	0	0	1,250.0	66.47	0	0	Ambient temperature Ethanol & Ox temp (R) 184	Profile successfully completed.	Stop testing for day to review data.	
03-07-06	SEQ 0_1	F	ATP_1	100% 5 seconds	44	1	1	0	15.0	5.01	5.01	0	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown.	Began with Tank Temp = 173 R, with PFJIGN removed from Engine 1, port capped close to engine, AND with the appropriate redlined disabled to accommodate the change. The PFJIGNE1 plumbing was disconnected and capped. The effect was complex. Overall the igniter was stronger, however, before 115 ms it was slightly weaker. ATP 1, SEQ 0, Test 1, Run F - Engine 1 IGNITER and Engine 2 IGNITER. 5 sec igniter firings with 60 sec coast between them. Stop after E2 igniter fires. Completed successfully. Plan to proceed with E1_IGN profile	
03-07-06	SEQ 1_11	B	E1_IGN	?		2	0	0	11.0	2.04	0	0	Ambient temperature Ethanol & Ox temp (R) 184	Profile successfully completed.	Plan to proceed with ATP_2 profile. E1_IGN, SEQ 1, Test 11, Run B - Engine 1 IGNITER, 2 pulses of 1 second duration as follows: 1 firing with 20 ms fuel lead, 5 minute hold, then one firing with 20 ms, LOX lead. Completed successfully.	
03-07-06	SEQ 0_2	E	ATP_2	100% 5 seconds		1	0	0	15.0	4.95	0	0	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown.	ATP_2, SEQ 0, Test 2, Run E , ONLY Engine 1 Full Engine 1 firing for 5 seconds. Completed successfully. Plan to proceed with Seq 1_2A profile.	
03-07-06	SEQ 1_2	D	SEQ_1_2A	15% .32 seconds		22	0	0	55.0	11.74	0	0	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown after 22 pulses.	SEQ_1-2A, SEQ 1, Test 2, Run D, Engine 1 ONLY, 20 pulses , 0.32 SECOND ON, 1.813 SECOND OFF, Completed successfully. Plan to proceed with Seq 3_12A profile.	
03-07-06	SEQ 3_12	C	SEQ_3-12A	E1: .58% .16 seconds E2: 1.65% .4 seconds E3: .58% .16 seconds		2	2	2	45.0	0.32	0.59	0.32	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	PCAVE2 low in Limit Group 3	The LOX tank was conditioned to 163 R for mission simulations and the LOX temp control loop was set at 189R to 194R per TLORCEM1. 5. SEQ_ 3-12a, Run C with nominal purge pressure. Test went into hold automatically, based on a low PCAV pressure on engine 2 shortly after the profile started. Testing ended for the day and work to change igniter orifices in engine 2 and 3 was initiated. The last attempted profile, SEQ 3-12a, shut down after just a few pulses due to low E2 PCAV, which has happened before with the higher LOX temp, so lowering the lox temp alone did not fix that issue. We are shutting down for the day, and moving to change orifices in E2 and E3 before additional tests. Exact timeline for changing orifices is TBD, so testing may, or may not resume tomorrow.	?
03-08-06	SEQ 0_1	G	ATP_1	100% 5 seconds		1	1	0	15.0	5.01	5.01	0	Ambient temperature Ethanol & Ox temp (R) 184	Profile successfully completed.	Stinger box evacuated, cell 401 closed, will pull down with steam within a few minutes Prepping for first firing of the day - igniters only, 5 sec on each engine - first test since replacing orifices in E2 and E3 igniters. LOX tank full, conditioning temp and filling manifold All with nominal LOX temp, and nominal purge pressure. PFJIGN removed from Engine 1 and from Engine 2, & those ports capped close to engine, AND with the appropriate redlines disabled to accommodate the change. This is the first day of tests since changing igniter orifices in E2 and E3. 1. ATP 1, SEQ 0, Test 1, Run G Engine IGNITERS 1,2,and 3. 5 sec igniter firings with 60 sec coast between them. One shot each. Completed successfully. Plan to proceed with E2_IGN profile.	
03-08-06	SEQ 1_10	B	E2_IGN	?		0	0	0	11.0	0	1.03	0	Ambient temperature Ethanol & Ox temp (R) 184	Profile successfully completed.	E2_IGN, SEQ 1, Test 11, Run C Engine 2 IGNITER, 2 pulses of 1 second duration as follows: 1 firing with 20 ms fuel lead, 5 minute hold, then one firing with 20 ms, LOX lead Completed successfully. Plan to proceed with ATP_2 profile	
03-08-06	SEQ 0_2	F	ATP_2	100% 5 seconds	51	1	0	0	10.0	0.12	0	0	Ambient temperature Ethanol & Ox temp (R) 184	PCAVE1 low in Limit Group 3	Engines 1, 2, & 3 Full Engine firings for 5 seconds, sequentially. One shot each. Profile automatically shut down on engine 1, PCAV low pressure, so E2 and E3 did not get a chance to fire. This run was not attempted again, once it was discovered that the profile did not incorporate the lox lead for the main valve. Instead, the main lox and fuel valves opened simultaneously, per the profile commands. Since It would take too long to modify the ATP_2 profile valve timing and re-run it on the same day, it was not attempted again. Team determined that shutdown was due to the profile not including the updated valve timing.(LOX lead) Valve timing update required after reorificing. Team agreed to skipt this profile and proceed with SEQ 3_12a. Only Test that engine did not light on the first pulse if the igniter was running.	

Date	Filename		Profile Name	DC% EPW	Aerojet Test#	Actual # of Pulses			Test Time (Sec)	Total On Time (Sec)			Propellant conditions	Shutdown Rationale	Changes/Comments	Non-ignition?
						E1	E2	E3		E1	E2	E3				
03-08-06	**SEQ 3_12**	**D**	**SEQ_3_12A**	E1: .58% .16 seconds E2: 1.65% .4 seconds E3: .58% .16 seconds	**52**	**8**	**8**	**7**	**205.0**	**1.14**	**3.21**	**1.13**	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	**PCAVE1 low in Limit Group 3**	**Shutdown cause not known. Decided to avoid Engine 1 for remainder of tests. Plan to proceed with Seq 1_5A profie. All 3 engines, pulsed one at a time, sequentially in varying engine sequences per profile. It was to run 58 pulse sets in approximately 25 minutes.** **Ran 8 sets of pulses on all 3 engines, then the profile automatically shut down on engine 1, PCAV low pressure due to apparent non-ignition in engine 1 during the 9th pulse set.** **This was first test to incorporate all the proposed "fixes" for non ignites. Igniters re-orificed, PFJINGN plumbing removed for Ign E1 and E2. Exited low PCAVE1 on 8th E1 pulse. All problems obviously still not sorted out as PCAVE1 lit late first pulse at 140ms. Then settled down to light at 90-95ms until the igniter cold-flowed on the last pulse. Several issues working on this test. Note that the previous test (Test 51) was the only test of the entire campaign in which an engine did not light on the first pulse if the igniter was running. Need to figure out why the Ign E1 did not light on the last pulse.**	**X**
03-08-06	SEQ 1_5	A	SEQ_1-5A	100% 6 seconds		0	1	1	16.0	0	6.00	6.00	Ambient temperature Ethanol & Ox temp (R) 184	Profile successfully completed.	Engine2 and 3 simultaneously for 6 seconds. Completed successfully. Visually, it looked great, 2 robust plumes. Testing ended for the day. Stop testing fo the day to inspect engine 1 and review data. Engine 1 chamber measurements indicate growth. Engine TAD suggests not firing Engine 1 any more. 5. SEQ_1-5BA Note- question exists as to whether this should read "SEQ_1-5A" instead of "SEQ_1-5BA"; there may have been a typo on the test request sheet- will try to resolve, but if anyone knows for sure let me know)	
03-09-06	SEQ 3_17	A	SEQ_3-12C		54	0	11	10	270.0	0.00	4.41	1.61	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	Completed planned portion of profile. Manually called shutdown after T+4:20.	Profile 3_12a modified to remove Engine 1 from firing; called SEQ 3_17. Plan to repeat this sequence with purges reduced to 80 psi from 135 psi, as read on POJE2. After data review overnight and a telecon with Eric Hurlbert this morning, weighing in Aerojet recommendations, WSTF inputs, and Marshall inputs from the test team here, this is today's plan. Also rolled into this plan are the reality of limited test time constraints for pursuing resolution/fixing of Engine 1's shutdowns yesterday, and some lingering concerns, unknowns, and potential risks for Engine 1 due to its history of problems, and as of yet unexplained indication of combustion in the acoustic cavity. This plan also puts priority on getting reduced purge pressure tests completed (on E2 and E3 only) as a higher priority than pursuing engine 1's problems. MAKE TWO MODIFIED PROFILES & VALIDATE THEM AS FOLLOWS. RUN IN THE ORDER SHOWN: 1. Make a new version of 3_12a that eliminates Engine 1 from the profile, but no change to the valve timing from original profile. This profile will be used to run the reduced purge pressure tests. 2. Make a new version of 3_12a with a 30 ms lag on igniter fuel valve on Engine 1 only. Run this if time permits. LOX tank full, prepping for first firing. As a quick "feel good" with the newly modified version of the 3-12a profile (It deletes E1), we will first run about 2 pulse sets at normal purge pressure. Assuming that goes well, we will then attempt the full 25 minute profile at the first reduced purge pressure of 80 psia.	
03-09-06	SEQ 3_17	B	SEQ_3-12C		55	0	18	16	430.0	0.00	7.01	2.58	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	PCIGNE2 low in Limit Group 3	Suspect a bad transducer (off scale low). Plan to repeat profile. Tests 54 and 55 ran E1 & E2 with POJE2 purge levels of 126 and 76 psia. PCIGNE2 die during apparently normal igniter operation and lighting on the 18th E2 pulse.	
03-09-06	SEQ 3_17	C	SEQ_3-12C		56	0	1	1	13.0	0.00	0.17	0.16	Ambient temperature Ethanol & Ox temp (R) 204+0/-5R	PCIGNE2 high in Limit Group 3	POJE2 = 67-71 psia, Confirmed that transducer is bad (off-scale high, but same value as previous shutdown). Suspected that strain-type transducer may lose continuity when the igniter chamber is pressurized. Decided to stop testing engine 2 for remainder of testing.	
03-09-06	SEQ 4_18	B	SEQ_4-18A	5% .32 seconds	57	0	0	19	120.0	0.00	0.00	6.10	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown after 20 pulses.	POJE2 = 68 psia, Successfully completed 10 pulses with 20 psia and 10 pulses at zero psia purge, on E3 End of testing tonight. Completed 10 pulses on E3 as intended at ~40 psia purge press……some pulses not so pretty, but good enough to move into 20 psia run..in work If nothing horrendous comes of it, will run a zero psia after that Completed 10 pulses on E3 as intended at ~55 psia purge press……some pulses not so pretty, but good enough to move into 40 psia run..in work AND, we will leave the purge gas ON In order to keep running reduced purge pressures, We are considering running a profile that is only E3, "Firing Profile: SEQ_4-18A" which had been run before. It has 320 ms ON, 6.08 sec ON…188 pulses....and we would skip the 5 sec pre-burn., and not run for the entire 20 minutes. Engine TAD noted that data from pulse train looked a little funny (bat man ears).	
03-09-06	SEQ 4_18	C	SEQ_4-18A	5% .32 seconds	58	0	0	10	70.0	0.00	0.00	3.21	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown after 10 pulses.	POJE2 = 55 psia.	
03-09-06	SEQ 4_18	D	SEQ_4-18A	5% .32 seconds	59	0	0	10	70.0	0.00	0.00	3.21	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown after 10 pulses.	POJE2 = 42 psia	
03-09-06	SEQ 4_18	E	SEQ_4-18A	5% .32 seconds	60	0	0	10	70.0	0.00	0.00	3.21	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown after 10 pulses.	PPOJE2 = 21 psia	

Date	Filename		Profile Name	DC% EPW	Aerojet Test#	Actual # of Pulses			Test Time (Sec)	Total On Time (Sec)			Propellant conditions	Shutdown Rationale	Changes/Comments	Non-ignition?
						E1	E2	E3		E1	E2	E3				
03-09-06	SEQ 4_18	F	SEQ_4-18A	5% .32 seconds	61	0	0	10	70.0	0.00	0.00	3.21	Ambient temperature Ethanol & Ox temp (R) 184	Completed planned portion of profile. Manually called shutdown after 10 pulses.	POJE2 = 0 psia. Test profiles complete. Having a main Ox lead ahead of the igniter lighting may help sweep the ox manifold before fire exists in the chamber. However the time is short and may not guarantee that there is not an ignitable mixture in the ox manifolds if fuel was back driven. The main ox lead in conjunction with the igniter served to burn off residual propellant prior to main stage fuel arriving for the pulse. No hard starts were noted. On higher purge flow tests, there were instances where the pre-burning of residual propellant did not occur, resulting in slightly rougher starts.	

APPENDIX C: LO_2/LCH_4 COLD FLOW TEST MATRIX AND DATA

An LO_2 cold flow test on the APSTB LO_2 tank and feed system was conducted on October 13, 17, and 19, 2006. Each day, the orifice in the LO_2 TVS was changed per the Test Article Director's (TAD's) request. The same tests were then performed again. On October 13, 2007, the electrical, mechanical, control, and instrumentation setups were performed per task performance sheet (TPS) 4-LMM-06 0073. The test article was purged. LO_2 was loaded into the RCE manifold, and pressure was increased to 325 psia. Once the LO_2 manifold was loaded, the manifold control loop was activated with a maximum temperature of 204 R and a minimum temperature of 199 R. Stinger box vacuum pump operations were begun. Data was gathered on the manifold temperature control loop's performance without the TVS being active and without the MLI installed on the RCS LO_2 manifold. The E2 LO_2 igniter and main valves were cycled, and the temperature control loop was allowed to stabilize. The LO_2 TVS eductor was activated by opening the electronic control valve (ECV) that controlled the GN_2 motive gas. Data was gathered with the current TVS orifice (the October 13, 2007 test had a Lee 313k device installed), after which a heat leak liquid lock test was performed. These tests were repeated October 17, 2007, with a 0.07-mm orifice installed in the LO_2 TVS. On October 18, 2007, JSC engineers installed the MLI on the LO_2 RCS manifold, WSTF technicians installed a 0.06-mm orifice, and the tests were repeated.

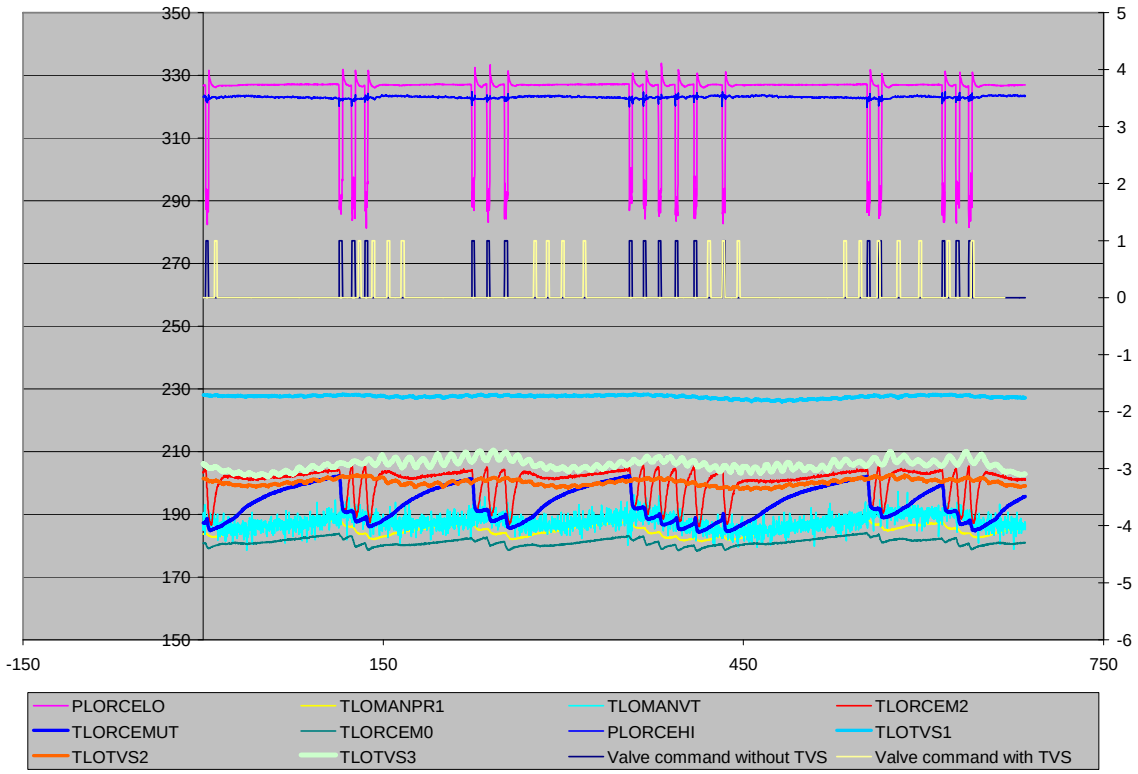


Figure C-1: October 13, 2007, LO_2 cold flow, TVS off, no MLI

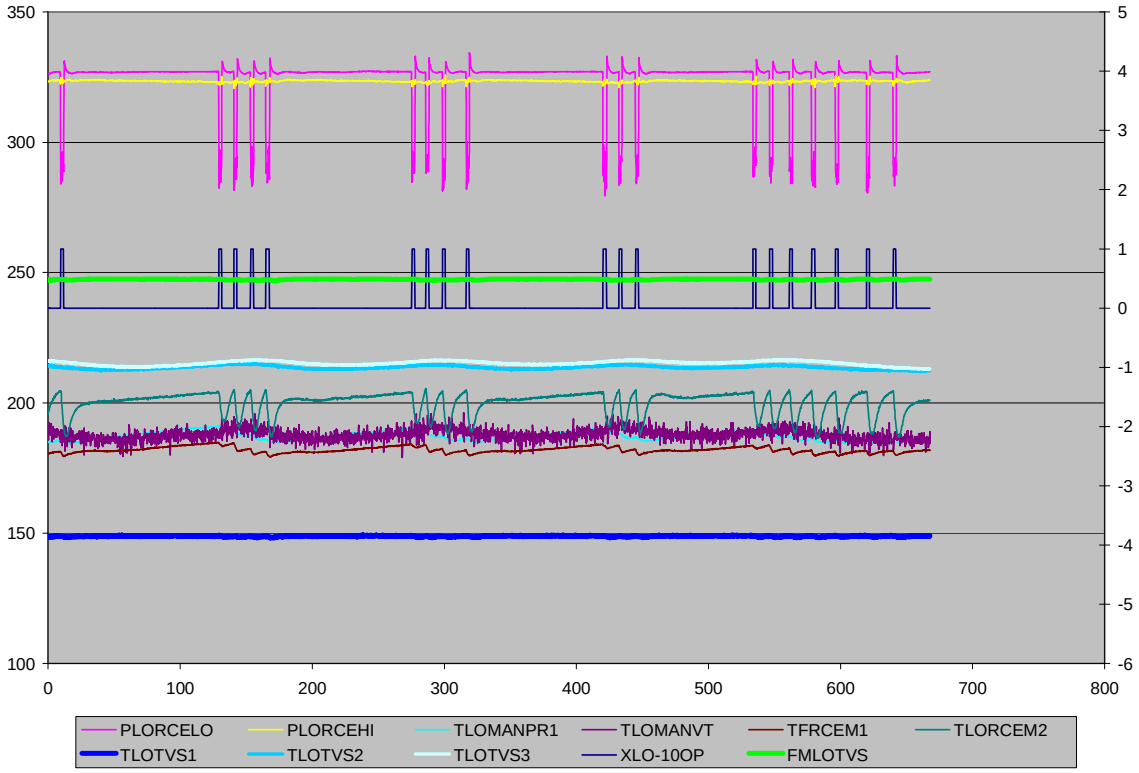


Figure C-2: October 13, 2007, LO_2 cold flow, TVS on (Lee 313K), no MLI

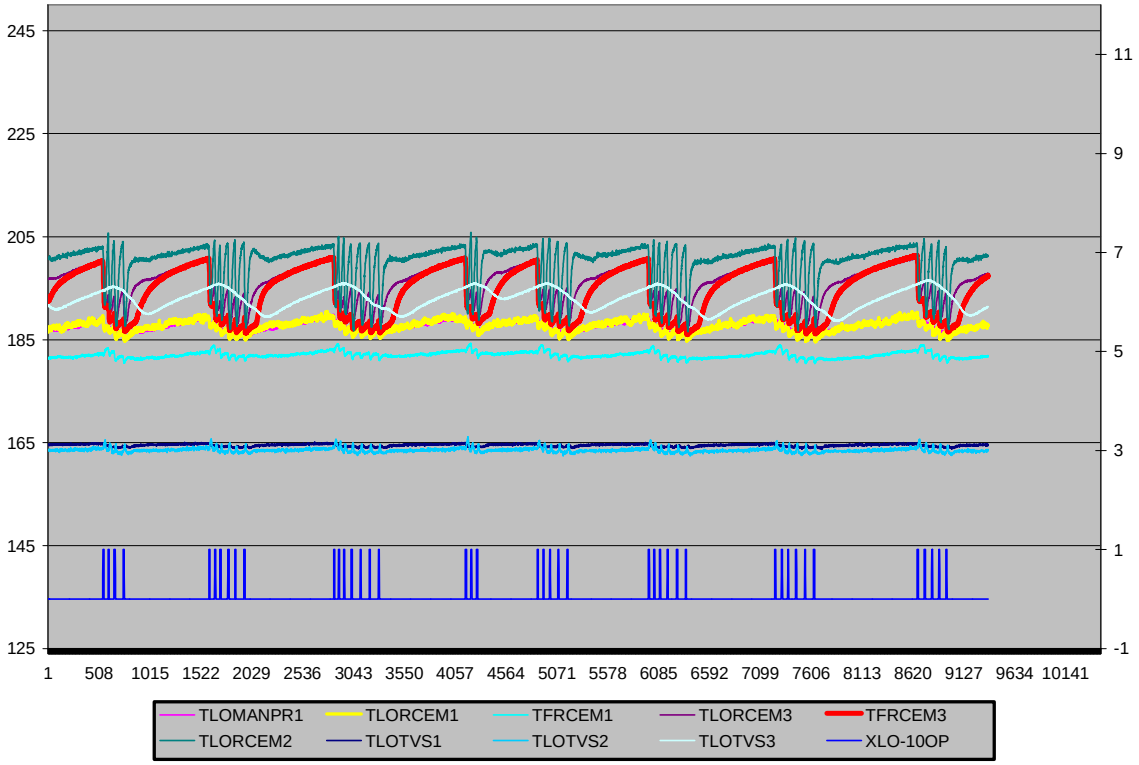


Figure C-3: October 17, 2007, LO_2 cold flow, TVS on (0.07-mm orifice), no MLI

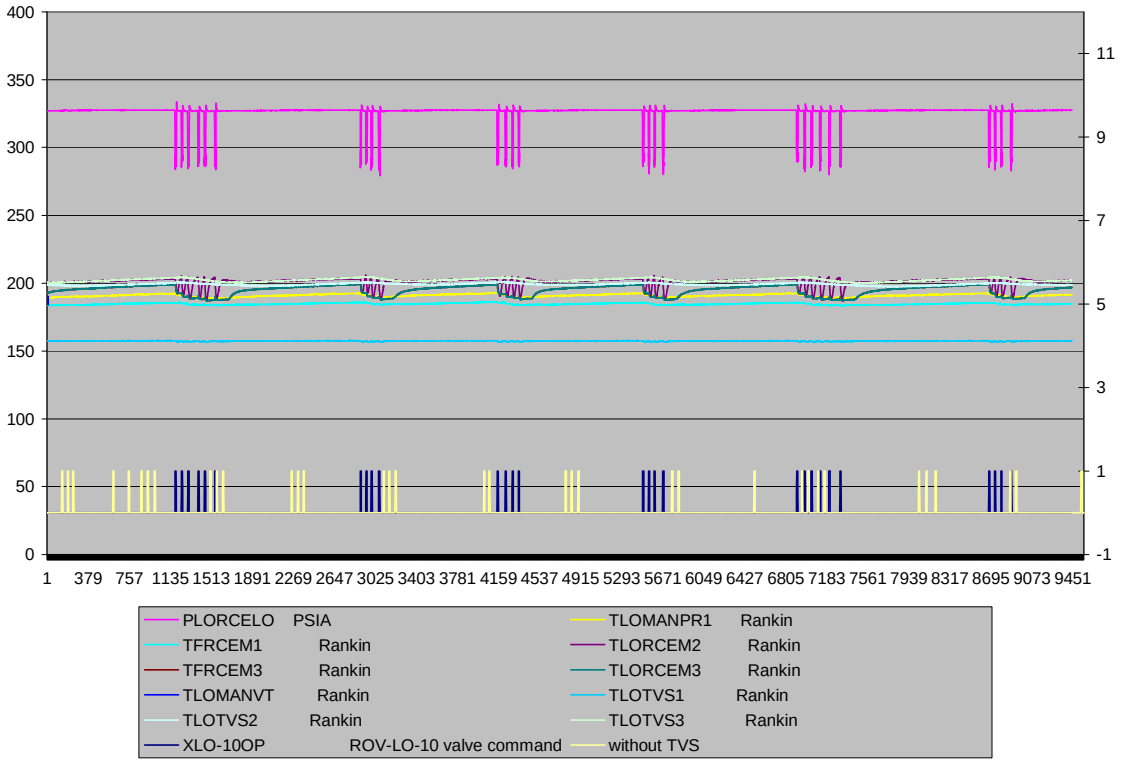


Figure C-4: October 19, 2007, LO_2 cold flow, TVS on (0.06-mm orifice), MLI on

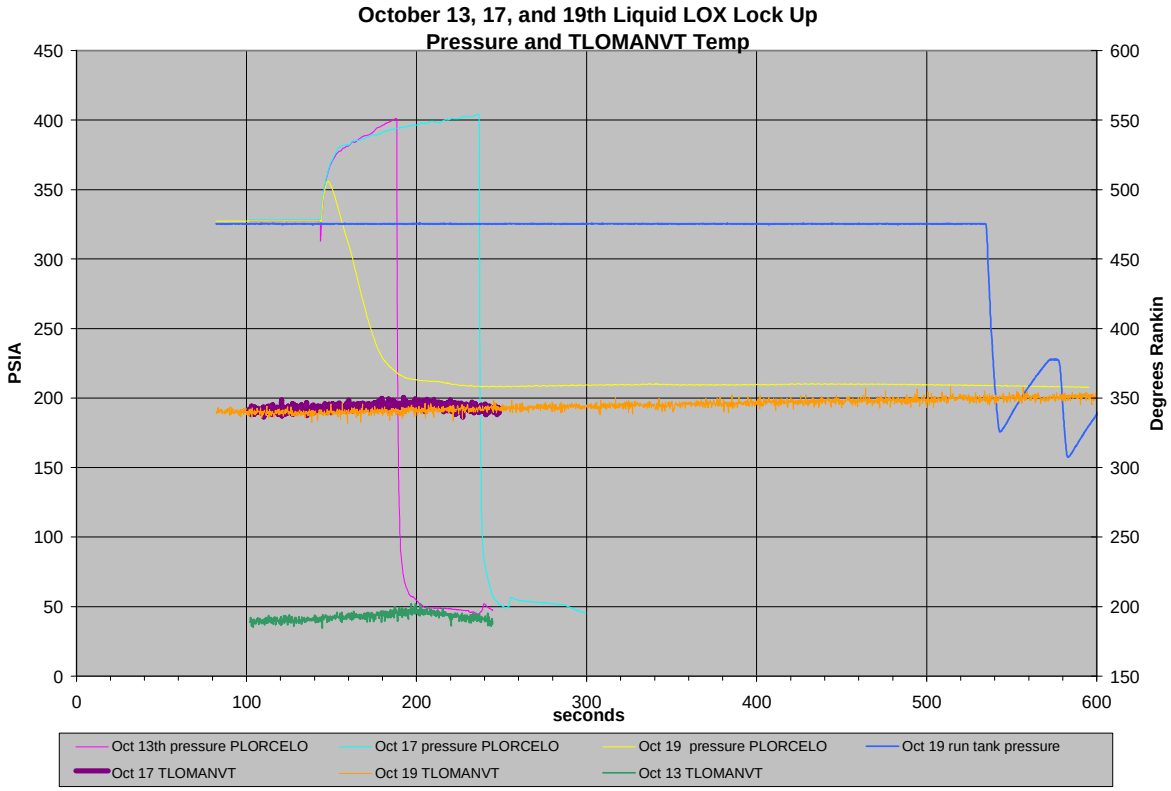


Figure C-5: October 13, 17, and 19, 2007, LO2 cold flow, liquid lock test

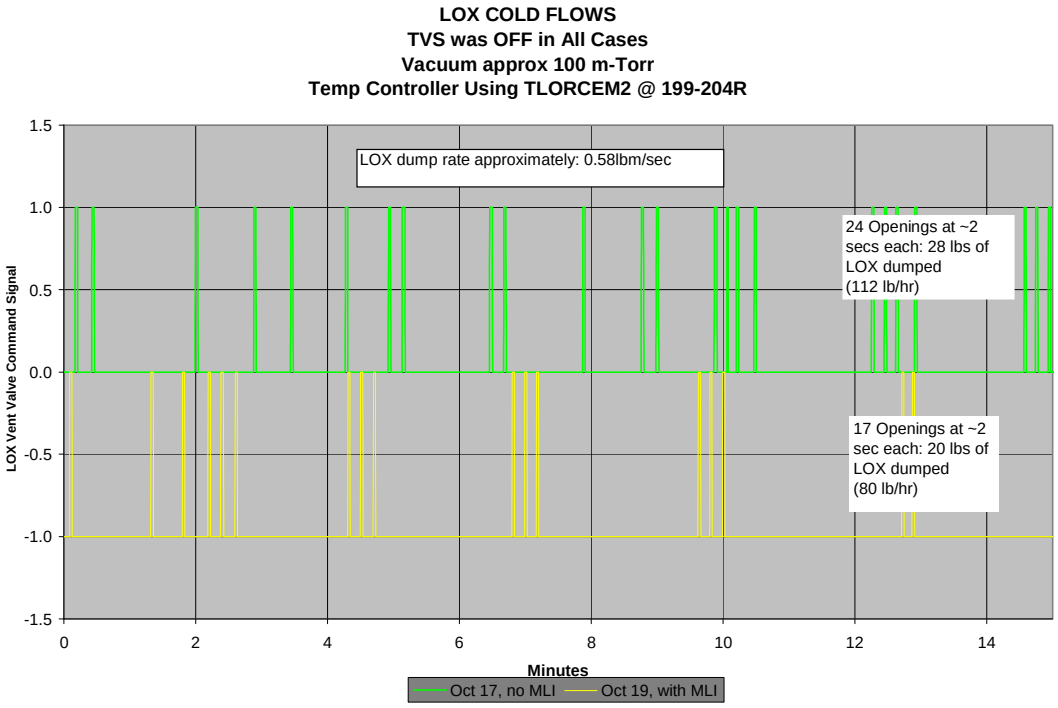


Figure C-6: LO_2 dump rate, TVS off, with and without MLI

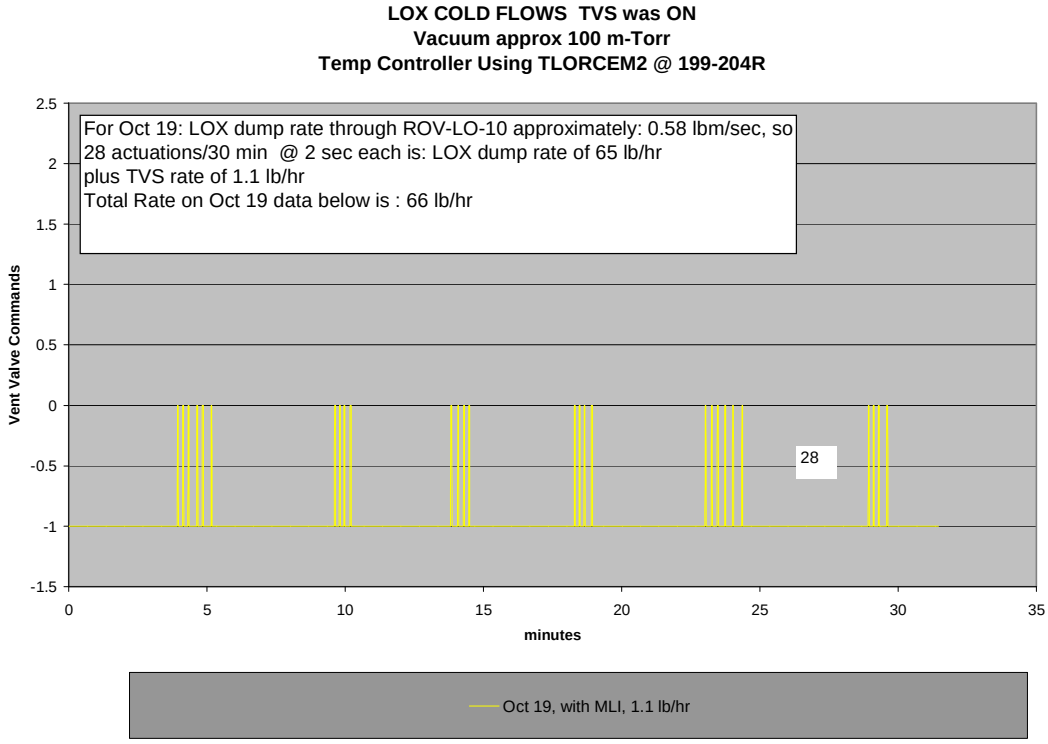


Figure C-7: LO_2 dump rate with TVS on and with MLI

C.1 LO_2 Cold Flow TVS and MLI Findings

The effectiveness of the TVS was measured by the time that the ROV-LO-10 was open when the manifold temperature control loop was activated and allowed to stabilize. The dump rate of LO_2 through the valve at test pressure is approximately 0.58 lb_m/secs. The test duration was 15 min. The vacuum level in the stinger box was approximately 100 mtorr. The temperature input for the temperature control loop was measurement TLORCEM2.

The test on October 17, 2006, was used as the control. The TVS was off, and there was no MLI on the RCS engine manifold. The LO-10 valve opened 24 times for approximately 2 sec each time. An estimated 28 lb of LO_2 was dumped.

The test on October 19, 2006, was the same test performed on October 17, but the MLI had been installed on the LO_2 manifold.

C.2 LO_2 Cold Flow Problems Encountered

APSTB Leaks – Leaks found during cold flow on the test article (October 13).

One leak was found on the 0.25-in. tee connecting PSV-LO-122 (LO_2 TVS safety relief valve). This leak was repaired by replacing the bulkhead tee with a swivel tee fitting, adding copper nose seals, and reapplying the proper torque.

Test Stand 401 Instrumentation – Test stand instrumentation recorded higher than anticipated flow rates during TVS LO_2 cold flow.

The original Hastings gas mass flowmeter was scaled for 1.5 lb/hr. TPS-LMM-06 0076 removed the original and replaced it with a 4.0 lb/hr scaled meter. The methane TVS flowmeter was also changed from a 0.75 lb/hr meter to a 2.0 lb/hr meter.

C.3 Methane Cold Flow

A cryogenic shock test was conducted on Test Stand 401's new methane supply system and the APSTB's methane tank and feed system on December 11, 2006, by introducing liquid nitrogen (LN_2) for the first time. WSTF provided approximately 1,300 gal of LN_2. Electrical and mechanical controls and instrumentation setups were performed per TPS 4-LMM-06 0089. The LN_2 dewar was brought up online, and liquid nitrogen was slowly transferred to the methane run tank after sampling operations confirmed cleanliness levels. Continuing with safe practices, all sections isolated were verified to have less than 10 psid across closed valves before opening to allow flow of the cryogen. LN_2 was loaded into the RCE manifold and into the modified flow simulator section. Pressure was increased to 125 psia. Mechanical technicians then used an oxygen meter to monitor the system for leaks of nitrogen by indications of low levels of oxygen. Once the fuel manifold was loaded with the LN_2, the manifold control loop was activated with a maximum temperature of 185 R and a minimum temperature of 180 R. The temperature control loop was allowed to stabilize. The fuel TVS eductor was activated by opening the ECV that controlled the GN_2 motive gas. The eductor in place was a FOX mini eductor (modified part number 611210-060-SS). With the eductor active, the TVS pressure dropped to 2.3 psia. TVS activation valve ROV-HC-123 was then opened to allow flow across the TVS. The pressure in the system stabilized at 2.4 psia. Leak checks continued throughout the TVS; engineers looked for obvious leaks and used the oxygen meter. Pressure in the fuel system was systematically increased in 50-psi increments, with leak checks performed at each pressure. Once the pressure reached 260 psia, the stinger box door was closed, and the checks continued to 360 psia. The manifold was viewed through the stinger box camera. The TVS performance recorded at the time showed a pressure of 4.7 to 5 psia and a flow rate of 0.870 lb_m/hr. The aft feed system, modified flow simulator, manifold, and TVS were then vented and purged.

The second part of the cold flow operation was the checkout of the methane blow down tank. TPS 4-LMM-06 0090 installed a temporary pressure indicator on the methane blow down tank so that the maximum pressure reached during the test could be observed. The APSTB methane run tank was topped off with LN_2, and a simulated emergency fuel dump was conducted. The APSTB methane run tank was 87% full with LN_2. The methane run tank pressure control loop was set to 80 psia. A dump path through the test stand's supply isolation and supply bleed valves was opened. The dump began with the opening of the test article's HC-09 valve.

The entire LN_2 contents, approximately 391 gal, were dumped in a little over 13 minutes. The frost line on the blow down tank indicated that approximately 200 gal had made its way to the blow down tank. The remaining LN_2 boiled off during the transfer. The highest pressure of 60 psig was seen in the blow down tank during the first half of the dump when boil off was at its highest as the LN_2 entered the relative warm dump system. After the entire contents were dumped an oscillation of 10–20 psig was observed in the blow down tank as the remaining LN_2 boiled off.

A post-cryo shock leak test was conducted on the liquid methane test article skid after the methane tank and feed system were exposed to LN2 under TPS 4-LMM-06 0091. This TPS used GHe from the pressure control loop to perform a leak check of the entire fuel system. The pressure was started at 50 psia and continued to 260 psia. After reaching 260 psia, the stinger box door was closed and secured. The leak check then continued to 360 psia. One small leak was found and repaired at a 0.25-in. connection on DPS-HC-20.

The methane system was loaded with LCH_4 just before the first hot-fire operation and engine valves cycled using WSJ PROP-401-0092 A. No problems were encountered. The test team continued directly into hot-fire operations.

C.4 Methane Cold Flow Problems Encountered

Test Stand 401 Leaks: Leaks Found During LN_2 Cryo Shock in TS 401(12/11) – Two small leaks were found on the 1-in. methane supply line between the feed through nozzle and filter F-4LM-LH101. These leaks were repaired by adding copper nose seals and reapplying the proper torque.

APSTB Leaks: Leaks Found During Cryo Shock on the Test Article (12/11) – One leak was found on the 0.25-in. tee connecting PSV-HC-122 (methane TVS safety relief valve). This leak was repaired by replacing the bulkhead tee with a swivel tee fitting, adding copper nose seals, and reapplying the proper torque.

Test Stand 401 Instrumentation: Incorrect Temperature Reading Compared to Run Tank Temperatures (12/11) – A resistive temperature device (RTD) probe, TT-4LM-LH106 (TMETEMP), was installed into the methane supply line incorrectly. The probe was inserted approximately only one-third of its length into the wetted area. This exposure to both cryo temperature and to ambient temperature created an average of the two temperatures, as much as a 120 R offset when the supply line was wetted with cryo. Discrepancy report DR-4-LMI-06 0022 was opened to remove the old RTD (ECN M899559) and install a new RTD (ECNM899561). The new RTD was installed by inserting the probe into the line until it bottomed out, then backing out 0.25 in. The Swagelok connection was then tightened per the manufacturer's instructions.

Test Stand 401 Instrumentation: Measurements TFMANVT and TOMANVT Did Not Track Between the Data Acquisition and Control System (DACS) GUI and the Control GUI (12/11) – DR-4-LMI-06 0025 was opened and used to make patch corrections and verify correlations between the measurements TFMANVT and TOMANVT in the DACS GUI and the temperature control GUI.

APPENDIX D: LO_2/LCH_4 HOT-FIRE TEST MATRIX AND DATA

Date	Profile Name	Run #	Attempt #	Completed		Pulse Count		Profile On Time	DC% EPW	Total on Time		Shutdown Rationale	Changes/Comments
				Yes	No	E2	E3			E2	E3		
1/18/2007	MSEQ_3-1	1	1		x	*				0.64		High PCIGNE2 (120)	Change limit group SIII-1-4 groups 2 and 3 high limits changed to 175.
1/18/2007	MSEQ_3-1	1	2		x	*				0		Low PCIGNE2	Non ignition. Reshimmed spark plug to 0.0585". Reattempt.
1/22/2007	MSEQ_3-1	1	3	x		1				0.5		completed profile	No change. Repeat profile 4 more times.
1/22/2007	MSEQ_3-1	1	4	x		1				0.5		completed profile	No change. Repeat profile 3 more times.
1/22/2007	MSEQ_3-1	1	5	x		1				0.5		completed profile	No change. Repeat profile 2 more times.
1/22/2007	MSEQ_3-1	1	6	x		1				0.5		completed profile	No change. Repeat profile 1 more time.
1/22/2007	MSEQ_3-1	1	7	x		1				0.5		completed profile	No change. Move on to SEQ 3_2.
1/22/2007	MSEQ_3-1	2	1	x		1				0.5		completed profile	TVS turned off to help maintain temps. No change. Ran test with fuel manifold temp 2 deg warmer than planned.
1/22/2007	MSEQ_3-1	3	1	x		1				0.5		completed profile	No change. Done for day.
1/23/2007	MSEQ_3-1	4*	1*									*profile not started	Methane drained from tank.
1/30/2007	MSEQ_3-1	4	1	x		1				0.5		completed profile	Proceed to 3_5.
1/30/2007	MSEQ_3-5	5	1	x		30			1% 160 ms	4.8		completed profile	Proceed to 3_6.
1/30/2007	MSEQ_3_6	6	1		x	24			1% 160 ms	3.84		Low PCIGNE2 (30) in limit group 2	Data review shows a 2 volt drop during 24th pulse. No other anomalies in temps and pressures. Continue with next sequence. Received permission from JSC to use a warmer control range (209-214R).
1/30/2007	MSEQ_3_7	7	1	x		31			1% 160 ms	4.96		Completed profile	Continue with next sequence.
1/30/2007	MSEQ_3_8	8	1		x	6				0.96		Low PCIGNE2 (30) in limit group 2	Quick look data shows a lower voltage during 6th pulse. Continue with next sequence.
1/30/2007	MSEQ_3_5	9	1		x	*				0		Low PCIGNE2 (30) in limit group 2	Quick look data shows a lower voltage during first pulse. Continue with next sequence.
1/30/2007	MSEQ_3_5	9	2		x	6				0.96		Low PCIGNE2 (30) in limit group 2	Quick look data shows a lower voltage during 6th pulse. Continue with next sequence.
1/30/2007	MSEQ_3_5	10	1		x	6				0.96		Low PCIGNE2 (38) in limit group 2	Quick look data shows a lower voltage during 6th pulse. Done for day. Data review and spark plug inspection tomorrow.
2/1/2007	MSEQ_3-5	9	3		x	27			1% 160 ms	4.16		Low PCIGNE2 (32) in limit group 2	Quick look data shows that voltage was nominal, but shutdown occurred during 27th pulse Continue with 3_10.

Date	Profile Name	Run #	Attempt #	Completed		Pulse Count		Profile On Time	DC% EPW	Total on Time		Shutdown Rationale	Changes/Comments
				Yes	No	E2	E3			E2	E3		
2/1/2007	MSEQ_3-5	10	2		x	2			1% 160 ms	0.256		Low PCIGNE2 (38) in limit group 2	Shutdown occurred during 2nd pulse. TAD and OD agreed to adjust the PCIGNE2 low cutoff in limit group 2 from 75 psi down to 25 psi. All other values remain the same. JSC requested that WSTF call a fire white if 3 consecutive non-ignitions occur.
2/1/2007	MSEQ_3-5	10	3		x	*			1% 160 ms	0		Manual hold due to 3 consecutive non-ignitions	Decided to modify profile MSEQ 3_5 rev 1. Timing on igniter initiation changed to -10 ms.
2/1/2007	MSEQ_3-5,rev3	10	4		x	29			1% 160 ms	4.598		High PCIGNE2 (178) in limit group 2	Reviewed quick look. PCIGNE2 increased during last few pulses. No change. TAD considered profile a success. Continue with next profile.
2/1/2007	MSEQ_3-5,rev3	11	1	x		30			1% 160 ms	4.8		Completed profile	Continue with next sequence.
2/1/2007	MSEQ_3-5,rev3	12	1	x		30			1% 160 ms	4.8		Completed profile	Done for day
2/28/2007	MSEQ_4-1	2	1		x	1						Low POJIGNE3 (200) in limit group 2	Changed low limit parameter in limit group 2 and 3 to 175 psia.
3/1/2007	MSEQ_4-1	2	2	x			1				0.5	Complete	
3/1/2007	MSEQ_4-1	1	1	x			1				0.5	Complete	
3/1/2007	MSEQ_4-1	1	2	x			1				0.5	Complete	Good igniter run
3/1/2007	MSEQ_4-1	3	1	x			1				0.5	Complete	Good igniter run
3/1/2007	MSEQ_4-1	3	2	x			1					No light	
3/1/2007	MSEQ_4-1	3	3	x			1					No light	
3/1/2007	MSEQ_4-1	4	1	x			1				0.5	Complete	
3/1/2007	MSEQ_4-1	4	2	x			1				0.5	Complete	
3/1/2007	MSEQ_4-1	5	1	x			1					No light	No light
3/1/2007	MSEQ_4-1	5	2	x			1					No light	No light
3/22/2007	mseq 4	3	4	x							0.5	Good ss	
3/22/2007	mseq 4	5	3	x			30				4.8	Profile complete	
3/23/2007	mseq 4	6	1	x			30				4.8	Complete	325 psia bot, 224 R fuel, 204 R LO2
3/23/2007	mseq 4	7	1		x							No light	325 fuel, 325 lo2 psia, 224 R fuel, 204 r Lox
3/23/2007	mseq 4	7	2		x							No light	Later in the day
3/23/2007	mseq 4	7	3		x							No light	Later in the day
3/23/2007	mseq 4	8	1	x			7				1.12	Complete 7 pulses	325 psia both, 214 fuel, 204 R Lo2, completed 7 pulses in 960 sec..
3/23/2007	mseq 4	9	1				16				2.56	Complete 16 pulses	Completed 16 pulses in 460 seconds.

Date	Profile Name	Run #	Attempt #	Completed		Pulse Count		Profile On Time	DC% EPW	Total on Time		Shutdown Rationale	Changes/Comments
				Yes	No	E2	E3			E2	E3		
3/23/2007	mseq 4	11	1				16				2.56	Complete 16 pulses	Completed 16 pulses in 460 seconds.
3/23/2007	mseq 4	11	2				16				2.56	Complete 16 pulses	375 psia both, 224 R fuel, 204 R LO2
3/23/2007	mseq 4	12	1				16				2.56	Complete 16 pulses	273 psia both, 224 R fuel, 204 R LO2
3/28/2007	MSEQ_4-6	6	2		x		1		100% 150 ms		0.128	High PCIGNE3 (200) in limit group 2	Ox manifold inlet at 375, fuel inlet at 325. Adjusted PCIGN redline to 225 from 175. Proceeded.
3/28/2007	MSEQ_4-6	6	3	x			38		5% 160 ms		6.08	Completed profile	Ox manifold inlet at 375, fuel inlet at 325. Proceeded to sequence 4_8.
3/28/2007	MSEQ_4-8	8	2	x			7				1.12	Completed profile	Ox manifold inlet at 375, fuel inlet at 325. Proceeded to sequence 4_11.
3/28/2007	MSEQ_4-5	11	2	x			30				4.8	Completed profile	Ox manifold inlet at 375, fuel inlet at 325. proceeded to sequence 4-12.
3/28/2007	MSEQ_4-5	12	2	x			30				30.16	Completed profile	Ox manifold inlet at 375, fuel inlet at 325. Non-ignition noted on 2nd pulse. Proceeded to sequence 4-7.
3/28/2007	MSEQ_4-7	7	4	x			31		25% 160 ms		4.96	Completed profile*	Shutdown on limit group 5, pfjign high on 31st pulse. Ox manifold inlet at 375, fuel inlet at 325. non-ignition on 2nd pulse. Repeat profile.
3/28/2007	MSEQ_4-7	7	5	x			31		25% 160 ms		4.96	Completed profile*	Shutdown on limit group 5, pfjign high on 31st pulse. Ox manifold inlet at 375, fuel inlet at 325. Non-ignition on 2nd pulse. Repeat profile.
3/30/2007	MSEQ_4-7	7	6		x		5				2.713	High PCIGNE3 (240) in limit group 2	Orifice removed from LO_2 Igniter. LO_2 manifold pressure reset to 375 psi. Adjusted upper limit on PCIGNE3 adjusted to 275 psi.
4/2/2007	MSEQ_4-6	6	4	x			38				6.08	Complete	
4/2/2007	MSEQ_4-8	8	3	x			7				1.12	Complete	
4/2/2007	MSEQ_4-9	9	2	x			29				4.64	Complete	29 pulses x 160 ms pulses at 1% DC, PLOTNK=325 psia, PETANK=325, 200R LO_2, 214R FU.
4/2/2007	MSEQ_4-11	11	4		x		3				0.38	High PCIGNE3 (250) in limit group 1	Adjusted upper limit on PCIGNE3 to 275 in limit group 1. Repeat.
4/2/2007	MSEQ_4-11	11	5		x		21				3.36	High PCIGNE3 (250) in limit group 1	375 psia LO_2 and methane, 160 ms at 1%
4/2/2007	MSEQ_4-12	12	3		x		29				4.64	Low PCIGN3, 70 psia	PLOTNK=275 psia, PETANK=275, 29 x 160 ms pulses at 1% DC
4/2/2007	MSEQ_4-10	10	1		x		2				0.32	High PCIGNE3 (250) in limit group 1	2 x 160 ms pulses at 1% DC, PLOTNK=325 psia, PETANK=325
4/2/2007	MSEQ_4-10	10	2		x		25				4	Low PCIGN3, 65 psia	25 x 160 ms pulses at 1% DC, PLOTNK=325 psia, PETANK=325,167 R Lox, 214 R LCH_4
4/4/2007	MSEQ_4-1	2	5	x	x		1				0.5	Complete	Igniter checkout
4/4/2007	MSEQ_5_1	2	1		x		1	2 s			0.226	Low PCAVE3 (12) in limit group 4	Adjusted lower limit on PCAVE3 to 5 in limit group 4.

Date	Profile Name	Run #	Attempt #	Completed		Pulse Count		Profile On Time	DC% EPW	Total on Time		Shutdown Rationale	Changes/Comments
				Yes	No	E2	E3			E2	E3		
4/4/2007	MSEQ_5-1	2	2		x		1	10 s			5	No shutdown, but PCAVE3 indicated no primary ignition, only igniter	PCAVE3 remained at 12 psi throughout 5 second burn. No main ignition. At shutdown, noted that igniter was firing. PCIGNE3 indicated the same. TADs decided to repeat profile with set pressures at 285 and 345 (LO_2 and LCH_4 respectively). EFCS to call fire white if engine does not light within 1 second. Previous lower set point in limit group 4 reset (35) for PCAVE3.
4/4/2007	MSEQ_5-1	2	3		x		1	2 s			0.226	Low PCAVE3 (12) in limit group 4	Done for day.
4/5/2007	MSEQ_5-5	9	1		x		1	2 s			0.16	Manual fire white call after 1 pulse for data review	TADs realized that valve timing was not written into the profile as they intended. Change made to profile mseq 5_5. Repeat.
4/5/2007	MSEQ_5-5	9	2		x		1				0.216	pcave3 low in limit group 4 (12)	Change tank sets to 325 and 345 (LO_2 /LCH_4) and repeat.
4/5/2007	MSEQ_5-5	9	3		x		1				0.225	pcave3 low in limit group 4 (13)	Change tank sets to 325 for both and repeat.
4/5/2007	MSEQ_5-5	9	4		x		1				0.226	pcave3 low in limit group 4 (13)	Lower tank pressures to 250. Maintain same temps.
4/5/2007	MSEQ_5-5	9	5		x		1				0.216	pcave3 low in limit group 4 (10)	Change tank pressures to 325 and 300 (LO_2 /LCH_4). Repeat.
4/5/2007	MSEQ_5-5	9	6		x		1				0.215	pcave3 low in limit group 4 (13)	Change tank pressure back to 300 for both. Lower LO_2 temp to 199–204 and methane temp to 219–224.
4/5/2007	MSEQ_5-5	9	7		x		1				0.216	pcave3 low in limit group 4 (13)	Lower fuel temp to 209–214. Pressures remain the same, as well as the fuel temp. Phantom flame observed on HSV.
4/5/2007	MSEQ_5-5	9	8		x		1				0.225	pcave3 low in limit group 4 (12)	Lower Lox temp to 168–173 and repeat.
4/5/2007	MSEQ_5-5	9	9		x		1				0.226	pcave3 and pcigne3 low in limit group 4 (11 and 53)	Same temps, change pressures to 325 LO_2 and 345 LCH_4. Repeat.
4/5/2007	MSEQ_5-5	9	10		x		1				0.25	Manual fire white call after 1 pulse for data review	Repeat.
4/5/2007	MSEQ_5-5	9	11		x		1				0.214	pcave3 and pcigne3 low in limit group 4 (12 & 63)	No change. Repeat.
4/5/2007	MSEQ_5-5	9	12		x		1				0.214	pcave3 and pcigne3 low in limit group 4 (12 & 63)	Increase temps on both manifolds by 15 °F [183–188 on LO_2 and 224–229 on LCH_4].

Date	Profile Name	Run #	Attempt #	Completed		Pulse Count		Profile On Time	DC% EPW	Total on Time		Shutdown Rationale	Changes/Comments
				Yes	No	E2	E3			E2	E3		
4/5/2007	MSEQ_5-5	9	13		x		1				0.215	pcave3 and pcigne3 low in limit group 4 (11 & 57)	Increase temps on both manifolds by 15 °F [198–203 on LO_2 and 224–229 on LCH_4].
4/5/2007	MSEQ_5-5	9	14		x		1				0.225	pcave3 and pcigne3 low in limit group 4 (11 & 57)	Done for day.
4/16/2007	MSEQ_5-5	9	15		x		1				0.25	Manual fire white call after 1 pulse for data review	Repeat. Countdown clock not functional.
4/16/2007	MSEQ_5-5	9	16		x		1				0.25	Manual fire white call after 1 pulse for data review	Aurora borealis
4/16/2007	MSEQ_5-5	9	17		x		1				0.25	Manual fire white call after 1 pulse for data review	Alt reduced to 92,300-ft.
4/16/2007	MSEQ_5-3	14	1		x		1				0.215	pcave3 and pcigne3 low in limit group 4 (11 & 55)	Weak spark. Repeat same profile.
4/16/2007	MSEQ_5-3	14	2	x			1				0.5	Completed profile	Repeat.
4/16/2007	MSEQ_5-3	14	3	x			1				0.5	Completed profile	Continue to 0.5 second pulse.
4/16/2007	MSEQ_5-2	15	1		x		1				0.226	pcave3 and pcigne3 low in limit group 4 (11 & 57)	Done for day.
4/18/2007	MSEQ_5-2	14	4		x		1				0	pcav low	LO_2 tank at 285 and FU @ 315
4/18/2007	MSEQ_5-2	15	2	x			1				2	Completed profile	LOX tank at 285 and FU @ 315
4/18/2007	MSEQ_5-2	15	3		x		1				0.5	Bad Pcav transducer	
4/18/2007	MSEQ_5-2	15	4		x		1				0.16	Ign it, low Pcav	
4/18/2007	MSEQ_5-2	15	5	x			1				3	Completed profile	
4/18/2007	MSEQ_5-2	16	1		x		1				0.16	Ign lit, low pcav	
4/18/2007	MSEQ_5-2	16	2		x		1				0.16	Ign, lit, low pcav	
4/19/2007	MSEQ_5-16	16	3	x			1		100% 3.5 s			Completed profile	LO_2 tank at 285 and FU @ 315
4/19/2007	MSEQ_5-1	1	1	x			1		100% 5 s			Completed profile	Using RLG 5-1
4/25/2007	MSEQ5	2	4		x		1				0.16	Ign lit, pcav low	Lox 285, FU@315, methane 240 R, LO_2 224 R
4/25/2007	mseq 7	2	1		x	1				0.16		No ignition, spark quench	
4/25/2007	mseq 7	1	1		x	1				0.16		No ignition, spark quench	Lox 285, FU@315, methane 240 R, LO_2 204 R
4/25/2007	mseq 5	1	2		x		1				0.16	Ign lit, pcav low	Lox 285, FU@315, methane 240 R, LO_2 204 R
4/25/2007	mseq 5	4	1		x		1				5	Completed profile	Lox 285, FU@315, methane 240 R, LO_2 170 R

Date	Profile Name	Run #	Attempt #	Completed		Pulse Count		Profile On Time	DC% EPW	Total on Time		Shutdown Rationale	Changes/Comments
				Yes	No	E2	E3			E2	E3		
4/25/2007	mseq 7	4	1		x	1				0.16		No ignition, spark quench	Lox 285, FU@315, methane 240 R, LO_2 170 R
4/25/2007	mseq 5	6	1		x		1		100% 140 ms		0.16	Ign lit, pcav low	Lox 285, FU@315, methane 204 R, LO_2 204 R
4/25/2007	mseq 5	6	2		x		1		100% 250 ms		0.16	Ign lit, pcav low	Lox 285, FU@315, methane 204 R, LO_2 170 R
4/25/2007	mseq 5	6	3		x		2		5% 250 ms		0.16	Redline too tight	LO_2 285, FU@315, Methane 204 R, LO_2 170 R
4/25/2007	mseq 5	6	4		x		2		5% 250 ms		0.32	Redline too tight, PFJ slow	LO_2 285, FU@315, methane 204 R, LO_2 170 R
4/25/2007	mseq 5	6	5		x		2		5% 250 ms		0.32	Redline too tight, PFJ slow	LO_2 285, FU@315, methane 204 R, LO_2 170 R
4/25/2007	mseq 5	6	6		x		15		5% 250 ms		4.8	Redline too tight, PFJ slow	LO_2 285, FU@315, methane 204 R, LO_2 170 R
4/25/2007	mseq 5	6	5		x		2				0.32	PFJ slow to bleed	LO_2 285, FU@315, methane 204 R, LO_2 170 R
4/25/2007	trial E23	1	1	x		1				0.6	0	Complete	50 ms igniter and main lead, LO_2 285, FU@315, methane 204 R, LO_2 170 R
4/27/2007	mseq 7	1	2		x	1				0		No ignition, spark quench	LO_2 315, FU@315, methane 240 R, LO_2 204 R
4/27/2007	trial 3A	1	1	x		1				0		No ignition, spark quench	50 ms igniter and main lead, LO_2 315, FU@315, methane 240 R, LO_2 204 R
4/27/2007	mseq 5	1	3	x			1				2	Good, but POJ redline	LO_2 315, FU@315, methane 240 R, LO_2 204 R
4/27/2007	mseq 5	4	2	x							4	Good, but POJ redline	LO_2 315, FU@315, methane 210 R, LO_2 170 R
4/27/2007	mseq 7	4	2		x	1				0		Igniter not lit	LO_2 315, FU@315, methane 210 R, LO_2 170 R
4/27/2007	trial 3a	1	2		x	1				0		Igniter not lit	50 ms igniter and main lead, LO_2 315, FU@315, methane 210 R, LO_2 170 R
4/27/2007	mseq 5	6	7	x			12		5% 250 ms		1.92	PFJ fail to bleed	LO_2 315, FU@315, methane 210 R, LO_2 204 R
4/27/2007	mseq 5	6	8	x			3		5% 250 ms		0.48	Low pcav?	LO_2 315, FU@315, methane 210 R, LO_2 204 R
5/3/2007	MSEQ_7-1a	3	1	x		1				5		Completed profile	
5/3/2007	MSEQ_5-1a	1	4		x		1				0.226	Low pcave3 in limit group 3	Proceed with similar profile, but adjusted LO_2 main valve timing to open with igniter valves (50 ms prior to main fuel).
5/3/2007	MSEQ_5-1b	1	1	x			1				5	Completed profile	Proceed with colder tank temps and nominal valve timing.
5/3/2007	MSEQ_5-1a	4	3		x		1				3.805	pcigne3 high in limit group 3	Although profile was incomplete, proceeded with same profile on engine 2.

Date	Profile Name	Run #	Attempt #	Completed		Pulse Count		Profile On Time	DC% EPW	Total on Time		Shutdown Rationale	Changes/Comments
				Yes	No	E2	E3			E2	E3		
5/3/2007	MSEQ_7-1a	4	3		x	1				0.065		pcigne2 low in limit group 2	Tank temp and pressures remain the same. Proceed with same basic profile, but accelerated LO_2 main valve timing.
5/3/2007	MSEQ_7_1b	1	1		x	1				0.075		pcigne2 low in limit group 2	Proceed with next profile on same engine.
5/3/2007	MSEQ_7-1d	1	1		x	1				0.064		pcigne2 low in limit group 2	Proceed with same test again.
5/3/2007	MS_Trial-E23	1	4		x	1				0.226		pcigne2 low in limit group 2	Move to engine 3, pulse test.
5/3/2007	MSEQ 5	6	9		x		15		5% 250 ms	3.672		pcave3 low in limit group 3 (3.7)	Done for day.
5/4/2007	MSEQ8	5	1		x	1	1			3	3	PCAV low	315, 315 meth, 204 LO_2, 240 meth Ign lit, mains lit, but valve driver failed to keep main valves open.
5/4/2007	Mseq 8	5	2		x	1	1			3	3	Valve driver dropout	350, 350 meth, 204 LO_2, 240 meth Ign lit, mains lit, but valve driver failed to keep main valves open.
5/4/2007	Mseq 8	7	1		x	1	1					E2 pc ign failed	350, 350 meth, 204 LO_2, 240 meth
5/4/2007	Mseq 8	7	2		x	1	1					E2 pc ign failed	350, 350 meth, 204 LO_2, 210 meth
5/4/2007	Mseq 8	7	3		x	1	1		E2&E3: 100% 3 s			Completed	315, 315 meth, 204 LO_2, 210 meth
5/4/2007	Mseq 8	7	4		x	1	1					Completed	315, 315 meth, 204 LO_2, 210 meth
5/4/2007	Mseq 8	7	5		x	1	1					Completed	315, 315 meth, 204 LO_2, 210 meth
5/4/2007	Mseq 8	7	6		x	1	1					Completed	315, 315 meth, 204 LO_2, 210 meth
5/4/2007	Mseq 8	7	7		x	1	1					Completed	315, 315 meth, 204 LO_2, 210 meth
5/4/2007	Mseq 8	7	8		x	1	1		E2&E3: 100% 3 s E3: 2.86 s			Completed, pc ign high	315, 315 meth, 170 LO_2, 210 meth
5/4/2007	mseq 7	6	2		x	4						3.5 pulse, then non-ign	315, 315 meth, 170 LO_2, 210 meth
5/4/2007	mseq 7	6	3		x	4						3.5 pulses, then non-ign	315, 315 meth, 170 LO_2, 210 meth
5/4/2007	mseq 7	6	4		x	4						2 pulse, then non-ign	350 LO_2, 315 meth, 170 LO_2, 210 meth

APPENDIX E: APSTB INSTRUMENTATION LIST

Seq	Meas ID	Description	Aerojet Nomenclature	Signal Location	Type of Transducer	Customer Supplied Transducer	Range	Signal Output	System Uncertainty (%FS)	Component ID	Data Frequency (HZ)
0	2nd Generation Controls										
1	TEST ARTICLE MEASUREMENTS										
2	EF126	Fire Red Command		Facility	Event		0, 1		N/A		1000
2	TEST ARTICLE VALVE COMMANDS										
3	TEST ARTICLE FEEDSYSTEM VALVE POSITION INDICATORS										
4	XHC-01CL	Aft Eth Feedline Iso valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-01	1000
4	XHC-01OP	Aft Eth Feedline Iso valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-01	1000
4	XHC-02CL	Eth Feedline Inlet Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-02	1000
4	XHC-02OP	Eth Feedline Inlet Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-02	1000
4	XHC-03CL	Eth 60ft Feedline Inlet Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-03	1000
4	XHC-03OP	Eth 60ft Feedline Inlet Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-03	1000
4	XHC-04CL	Eth 60ft Feedline Outlet Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-04	1000
4	XHC-04OP	Eth 60ft Feedline Outlet Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-04	1000
4	XHC-05CL	Eth 60ft Feedline Bypass Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-05	1000
4	XHC-05OP	Eth 60ft Feedline Bypass Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-05	1000
4	XHC-06CL	Eth Feedline Outlet Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-06	1000
4	XHC-06OP	Eth Feedline Outlet Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-06	1000
4	XHC-07CL	Eth Simulator Feedline Iso Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-07	1000
4	XHC-07OP	Eth Simulator Feedline Iso Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-07	1000
4	XHC-08CL	Eth Engine Feedline Iso Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-08	1000
4	XHC-08OP	Eth Engine Feedline Iso Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-08	1000
4	XHC-09CL	Eth Supply Feedline Iso Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-09	
4	XHC-09OP	Eth Supply Feedline Iso Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-HC-09	
4	XHC-10CL	Eth RCE Stinger Manifold Vent Close		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-HC-10	1000
4	XHC-10OP	Eth RCE Stinger Manifold Vent Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-HC-10	1000
4	XHC-11CL	Eth Simulator Manifold Vent Close		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-HC-11	1000
4	XHC-11OP	Eth Simulator Manifold Vent Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-HC-11	1000
4	XHC-13CL	Ethanol Hi-Pnt Bleed 1 Close		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-HC-13	1000
4	XHC-13OP	Ethanol Hi-Pnt Bleed 1 Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-HC-13	1000
4	XHC-14CL	Ethanol Hi-Pnt Bleed 2 Close		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-HC-14	1000
4	XHC-14OP	Ethanol Hi-Pnt Bleed 2 Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-HC-14	1000
4	XLO-01CL	Aft LOX Feedline Iso valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-01	1000
4	XLO-01OP	Aft LOX Feedline Iso valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-01	1000
4	XLO-02CL	LOX Feedline Inlet Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-02	1000
4	XLO-02OP	LOX Feedline Inlet Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-02	1000
4	XLO-03CL	LOX 60ft Feedline Inlet Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-03	1000
4	XLO-03OP	LOX 60ft Feedline Inlet Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-03	1000
4	XLO-04CL	LOX 60ft Feedline Outlet Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-04	1000
4	XLO-04OP	LOX 60ft Feedline Outlet Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-04	1000
4	XLO-05CL	LOX 60ft Feedline Bypass Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-05	1000
4	XLO-05OP	LOX 60ft Feedline Bypass Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-05	1000
4	XLO-06CL	LOX Feedline Outlet Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-06	1000
4	XLO-06OP	LOX Feedline Outlet Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-06	1000

Seq	Meas ID	Description	Aerojet Nomenclature	Signal Location	Type of Transducer	Customer Supplied Transducer	Range	Signal Output	System Uncertainty (%FS)	Component ID	Data Frequency (HZ)
4	XLO-07CL	LOX Simulator Feedline Iso Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-07	1000
4	XLO-07OP	LOX Simulator Feedline Iso Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-07	1000
4	XLO-08CL	LOX Engine Feedline Iso Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-08	1000
4	XLO-08OP	LOX Engine Feedline Iso Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-08	1000
4	XLO-09CL	LOX Supply Feedline Iso Valve Closed		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-09	
4	XLO-09OP	LOX Supply Feedline Iso Valve Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ROV-LO-09	
4	XLO-10CL	LOX RCE Stinger Manifold Vent Close		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-LO-10	1000
4	XLO-10OP	LOX RCE Stinger Manifold Vent Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-LO-10	1000
4	XLO-11CL	LOX Simulator Manifold Vent Close		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-LO-11	1000
4	XLO-11OP	LOX Simulator Manifold Vent Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-LO-11	1000
4	XLO-13CL	LOX Hi-Pnt Bleed 1 Close		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-LO-13	1000
4	XLO-13OP	LOX Hi-Pnt Bleed 1 Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-LO-13	1000
4	XLO-14CL	LOX Hi-Pnt Bleed 2 Close		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-LO-14	1000
4	XLO-14OP	LOX Hi-Pnt Bleed 2 Open		T/A Feed Sys	Event		0, 1	28VDC	N/A	ECV-LO-14	1000
4	XLO-68CL	LOX Tank Vent Iso Valve Closed			Event		0, 1	28VDC			
4	XLO-68OP	LOX Tank Vent Iso Valve Open			Event		0, 1	28VDC			
4	XHE-19CL	LOX Tank He Supply Iso Valve Closed			Event		0, 1	28VDC			
4	XHE-19OP	LOX Tank He Supply Iso Valve Open			Event		0, 1	28VDC			
4	XHC-60CL	Eth Tank Vent Iso Valve Closed			Event		0, 1	28VDC			
4	XHC-60OP	Eth Tank Vent Iso Valve Open			Event		0, 1	28VDC			
4	XHE-20CL	Eth Tank He Supply Iso Valve Closed			Event		0, 1	28VDC			
4	XHE-20OP	Eth Tank He Supply Iso Valve Open			Event		0, 1	28VDC			
4	XHC-71CL	Eth Forward Feedline Purge Valve Closed			Event		0, 1	28VDC			
4	XHC-71OP	Eth Forward Feedline Purge Valve Open			Event		0, 1	28VDC			
4	XHC-72CL	Eth Manifold Purge Valve Closed			Event		0, 1	28VDC			
4	XHC-72OP	Eth Manifold Purge Valve Open			Event		0, 1	28VDC			
4	XLO-79CL	LOX Forward Feedline Purge Valve Closed			Event		0, 1	28VDC			
4	XLO-79OP	LOX Forward Feedline Purge Valve Open			Event		0, 1	28VDC			
4	XLO-80CL	LOX Manifold Purge Valve Closed			Event		0, 1	28VDC			
4	XLO-80OP	LOX Manifold Purge Valve Open			Event		0, 1	28VDC			
6	TEST ARTICLE SIMULATOR VALVE POSITION INDICATORS										
7	XHC-S1CL	Eth Simulator Valve 1 Close		T/A Sim1	Event		0, 1	28VDC	N/A	ROV-HC-S1	1000
7	XHC-S1OP	Eth Simulator Valve 1 Open		T/A Sim1	Event		0, 1	28VDC	N/A	ROV-HC-S1	1000
7	XHC-S2CL	Eth Simulator Valve 2 Close		T/A Sim2	Event		0, 1	28VDC	N/A	ROV-HC-S2	1000
7	XHC-S2OP	Eth Simulator Valve 2 Open		T/A Sim2	Event		0, 1	28VDC	N/A	ROV-HC-S2	1000
7	XHC-S3CL	Eth Simulator Valve 3 Close		T/A Sim3	Event		0, 1	28VDC	N/A	ROV-HC-S3	1000
7	XHC-S3OP	Eth Simulator Valve 3 Open		T/A Sim3	Event		0, 1	28VDC	N/A	ROV-HC-S3	1000
7	XLO-S1CL	LOX Simulator Valve 1 Close		T/A Sim1	Event		0, 1	28VDC	N/A	ROV-LO-S1	1000
7	XLO-S1OP	LOX Simulator Valve 1 Open		T/A Sim1	Event		0, 1	28VDC	N/A	ROV-LO-S1	1000
7	XLO-S2CL	LOX Simulator Valve 2 Close		T/A Sim2	Event		0, 1	28VDC	N/A	ROV-LO-S2	1000
7	XLO-S2OP	LOX Simulator Valve 2 Open		T/A Sim2	Event		0, 1	28VDC	N/A	ROV-LO-S2	1000
7	XLO-S3CL	LOX Simulator Valve 3 Close		T/A Sim3	Event		0, 1	28VDC	N/A	ROV-LO-S3	1000
7	XLO-S3OP	LOX Simulator Valve 3 Open		T/A Sim3	Event		0, 1	28VDC	N/A	ROV-LO-S3	1000
8	TEST ARTICLE FEED-SYSTEM INSTRUMENTATION										
9	Test Article Propellant Tank Pressures										
10	PETATANK	Ethanol Tank Pressure		T/A Feed Sys	Cryo Taber		0-500 psia	BR	1	PT-HC-15	1000

Seq	Meas ID	Description	Aerojet Nomenclature	Signal Location	Type of Transducer	Customer Supplied Transducer	Range	Signal Output	System Uncertainty (%FS)	Component ID	Data Frequency (HZ)
10	PETFEED1	Ethanol Feedline Pressure 1		T/A Feed Sys	Cryo Taber		0-500 psia	BR	1	PT-HC-24	
10	PETFEED2	Ethanol Feedline Pressure 2		T/A Feed Sys	Cryo Taber		0-500 psia	BR	1	PT-HC-25	
10	PLOFEED1	LOX Feedline Pressure 1		T/A Feed Sys	Cryo Taber		0-500 psia	BR	1	PT-LO-24	
10	PLOFEED2	LOX Feedline Pressure 2		T/A Feed Sys	Cryo Taber		0-500 psia	BR	1	PT-LO-25	
10	PLOTATANK	LOX Tank Pressure		T/A Feed Sys	Cryo Taber		0-500 psia	BR	1	PT-LO-15	100
11	Test Article Propellant Tank Temperatures										
12	TETTNKB	Ethanol Tank Bulk Temp (Bottom)		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-HC-18	10
12	TETTNKM	Ethanol Tank Bulk Temp (Mid)		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-HC-17	10
12	TETTNKT	Ethanol Tank Bulk Temp (Top)		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-HC-16	10
12	TLOTNKB	LOX Tank Bulk Temp (Bottom)		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-LO-18	10
12	TLOTNKM	LOX Tank Bulk Temp (Mid)		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-LO-17	10
12	TLOTNKT	LOX Tank Bulk Temp (Top)		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-LO-16	10
13	Test Article Propellant Tank Liquid Level Sensors										
14	DPETTNK	Ethanol Tank Delta-P Sensor		T/A Feed Sys	Delta P	X	0 - 3 LBS		1	DPT-HC-22	1000
14	DPLOTNK	LOX Tank Delta-P Sensor		T/A Feed Sys	Delta P	X	0 - 3 LBS		1	DPT-LO-22	1000
14	XLSET0	Ethanol tank level sensor (0%)		T/A Feed Sys	Diff P-Switch	X	event		N/A	DPS-HC-55	1000
14	XLSET100	Ethanol Tank Level Sensor (at Max fill)		T/A Feed Sys	Diff P-Switch	X	event		N/A	DPS-HC-19	1000
14	XLSET5	Ethanol Liquid Level Depletion Sensor (at 5%)		T/A Feed Sys	Diff P-Switch	X	event		N/A	DPS-HC-21	1000
14	XLSET95	Ethanol Tank Level Sensor (at 95% fill)		T/A Feed Sys	Diff P-Switch	X	event		N/A	DPS-HC-20	1000
14	XLSLO0	LOX tank level sensor (0%)		T/A Feed Sys	Diff P-Switch	X	event		N/A	DPS-LO-43	1000
14	XLSLO100	LOX Tank Level Sensor (at Max fill)		T/A Feed Sys	Diff P-Switch	X	event		N/A	DPS-LO-19	1000
14	XLSLO5	LOX Liquid Level Depletion Sensor (at 5%)		T/A Feed Sys	Diff P-Switch	X	event		N/A	DPS-LO-21	1000
14	XLSLO95	LOX Tank Level Sensor (at 95% fill)		T/A Feed Sys	Diff P-Switch	X	event		N/A	DPS-LO-20	1000
15	Accumulator Instrumentation										
16	LETBELLOW	Ethanol Bellows Displacement		T/A Feed Sys	LVT	X	0-100%	0-5V	1	LLS-HC-23	
16	LLOBELLOW	LOX Bellows Displacement		T/A Feed Sys	LVT	X	0-100%	0-5V	1	LLS-LO-23	
16	PETACUL	Ethanol Accumulator Ullage Pressure		T/A Feed Sys	Cryo Taber		0 -500 psia	BR	1	PT-HE-04	1000
16	PLOACUL	LOX Accumulator Ullage Pressure		T/A Feed Sys	Cryo Taber		0 -500 psia	BR	1	PT-HE-01	1000
16	TETACOUT	Ethanol Accumulator Outlet Temperature		T/A Feed Sys	RTD	???	140 -600 R	100 ohm	1	TT-HC-28	0.10
16	TETACUL	Ethanol Accumulator Ullage Ghe Temp		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-HE-05	0.10
16	TLOACOUT	LOX Accumulator Outlet Temp		T/A Feed Sys	RTD	???	140 -600 R	100 ohm	1	TT-LO-28	0.10
16	TLOACSK	LOX Accumulator Ullage Skin Temperature		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-LO-26	0.10
16	TLOACUL	LOX Accumulator Ullage Ghe Temp		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-HE-02	0.10
17	RCE Stinger Manifold Pressures										
18	PETRCEHI	Ethanol RCE Manifold Pressure - high freq		Stinger	ST560		0-2000 psia	BR	1	PT-HC-30	5000
18	PETRCELO	Ethanol RCE Manifold Pressure - low freq	PFVI, PFVV	Stinger	Cryo Taber		0 -500 psia	BR	1	PT-HC-29	1000
18	PLORCEHI	LOX RCE Manifold Pressure - high freq		Stinger	ST560		0-2000 psia	BR	1	PT-LO-30	5000
18	PLORCELO	LOX RCE Manifold Pressure - low freq	POVI, POVV	Stinger	Cryo Taber		0 -500 psia	BR	1	PT-LO-29	1000
19	RCE Stinger Box Measurements										
20	LKETSBOX	Ethanol sensor (leakage within stinger box)		Test Stand	TBD		TBD		?		
20	LKLOSBOX	LOX sensor (leakage within stinger box)		Test Stand	TBD		TBD		?		
20	PSBOXHI	Stinger Box Pressure		Stinger	STJE		0-15 psia		1	PT-VA-01	
20	PSBOXLO	Stinger Box Vacuum		Stinger	Hastings		0 - 1E-3 torr		1	VT-VA-02	
21	LOX Feedsystem Temperatures										
22	TLOVJ1	LOX Feedsystem Temperature 1		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-LO-52	0.10
22	TLOVJ2	LOX Feedsystem Temperature 2		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-LO-53	0.10

Seq	Meas ID	Description	Aerojet Nomenclature	Signal Location	Type of Transducer	Customer Supplied Transducer	Range	Signal Output	System Uncertainty (%FS)	Component ID	Data Frequency (HZ)
22	TLOVJ3	LOX Feedsystem Temperature 3		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-LO-54	0.10
22	TLOVJ4	LOX Feedsystem Temperature 4		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-LO-55	0.10
22	TLOVJ5	LOX Feedsystem Temperature 5		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-LO-56	0.10
22	TLOVJ6	LOX Feedsystem Temperature 6		T/A Feed Sys	RTD	X	140 -600 R	100 ohm	1	TT-LO-57	0.10
23	Ethanol Feedsystem Temperatures										
24	TETSIM	Ethanol Simulator Manifold Temperature		T/A Sim	RTD		500 - 600 R	500 ohm	1	TT-HC-26	
24	TETVJ1	Ethanol Feedsystem Temperature 1		T/A Feed Sys	RTD	X	500 - 600 R	100 ohm	1	TT-HC-43	0.10
24	TETVJ2	Ethanol Feedsystem Temperature 2		T/A Feed Sys	RTD	X	500 - 600 R	100 ohm	1	TT-HC-44	0.10
24	TETVJ3	Ethanol Feedsystem Temperature 3		T/A Feed Sys	RTD	X	500 - 600 R	100 ohm	1	TT-HC-45	0.10
24	TETVJ4	Ethanol Feedsystem Temperature 4		T/A Feed Sys	RTD	X	500 - 600 R	100 ohm	1	TT-HC-49	
24	TETVJ5	Ethanol Feedsystem Temperature 5		T/A Feed Sys	RTD	X	500 - 600 R	100 ohm	1	TT-HC-50	
24	TETVJ6	Ethanol Feedsystem Temperature 6		T/A Feed Sys	RTD	X	500 - 600 R	100 ohm	1	TT-HC-51	
25	LOX Feedsystem VJ Annulus Pressure										
26	PLOVJ1	LOX Tank VJ Annulus Pressure		T/A Feed Sys	Hastings	X	0 - 1E-3 torr		1		0.10
26	PLOVJ2	LOX Feedline VJ Annulus Pressure 2		T/A Feed Sys	Hastings	X	0 - 1E-3 torr		1		0.10
26	PLOVJ3	LOX Accumulator VJ Annulus Pressure		T/A Feed Sys	Hastings	X	0 - 1E-3 torr		1		0.10
26	PLOVJ4	LOX Feedline VJ Annulus Pressure 4		T/A Feed Sys	Hastings	X	0 - 1E-3 torr		1		0.10
27	ENGINE 1										
28	ENGINE INSTRUMENTATION										
29	ACCLE1	Acceleration - E1		Stinger	Endevco		0 - 100 G	Pc/g	8		20K
29	IETPVE1	Primary Ethanol valve current - E1		Bunker	Current Sensor		0 - 5 amps	0-5V	1		1000
29	IETVVE1	Igniter Ethanol valve current - E1		Bunker	Current Sensor		0 - 5 amps	0-5V	1		1000
29	ILOPVE1	Primary LOX valve current - E1		Bunker	Current Sensor		0 - 5 amps	0-5V	1		1000
29	ILOVVE1	Igniter LOX valve current - E1		Bunker	Current Sensor		0 - 5 amps	0-5V	1		1000
29	MSPARKE1	Spark monitor - E1		Bunker	Exciter	X	TBD		1		TBD
29	PCAVE1	Primary Chamber Press - E1 (0-300)	PCAV	T/A - E1	GP50		0 -300 psia		1		400
29	PCAVLOE1	Primary Chamber Press - E1 (0-30)	PCAV	T/A - E1	GP50		0 -30 psia		1		400
29	PCIGNE1	Igniter Chamber Pressure - E1	PCIGN	Stinger	STJE		0 -500 psia		1		TBD
29	PFJE1	LOX primary, injector manifold pressure - E1	PFJ	Stinger	Cryo Taber		0 -500 psia	BR	1		TBD
29	PFJIGNE1	LOX Igniter, valve outlet pressure - E1	PFJIGN	Stinger	Cryo Taber		0 -500 psia	BR	1		
29	POJE1	LOX primary, injector manifold pressure - E1	POJ	Stinger	Cryo Taber		0 -500 psia	BR	1		TBD
29	POJIGNE1	LOX Igniter, valve outlet pressure - E1	POJIGN	Stinger	Cryo Taber		0 -500 psia	BR	1		
29	TETPVSE1	Ethanol Primary Valve Seal Vent Temp-E1		Stinger	TC		500 - 600 R	0-5V DF	1	TT-HC-56	
29	TFJE1	Ethanol Primary Valve Outlet Temp-E1	TFJ	Stinger	TC		500 - 600 R	0-5V DF	1		1000
29	TFJIGNE1	Ethanol Igniter Valve Outlet Temp - E1	TFJIGN	Stinger	TC		500 - 600 R	0-5V DF	1		1000
29	TFVE1	Ethanol RCE Stinger Manifold Temp 1	TFV, TFVV	Stinger	Diode		500 - 600 R	500 ohm	1	TT-HC-40	10
29	TINJECTE1	Injector Temp - E1		Stinger	TC		140 -750 R	Conomic	1		1000
29	TLOPOUTE1	LOX Primary Valve Outlet Temp-E1	TOJ	Stinger	TC		140 - 600 R	Conomic	1		1000
29	TLOPVSE1	LOX Primary Valve Seal Vent Temp-E1		Stinger	TC		140 - 600 R	Conomic	1	TT-LO-38	
29	TLORCEM1	LOX RCE Stinger Manifold Temp 1		Stinger	Diode		140 - 600 R	500 ohm	1	TT-LO-40	10
29	TOJIGNE1	LOX Igniter Valve Outlet Temp - E1	TOJIGN	Stinger	TC		140 - 600 R	Conomic	1		1000
29	TOVE1	LOX Primary Inlet Manifold Temp-E1	TOV	Stinger	Diode		140 - 600 R	500 ohm	1	TT-LO-44	10
29	TOVVE1	LOX Igniter Inlet Manifold Temp - E1	TOVV	Stinger	Diode		140 - 600 R	500 ohm	1	TT-LO-45	10
29	VEXTRE1	Spark Exciter Voltage - E1		Stinger	Exciter		0 - 28 VDC		1		1000
30	Engine 1 - Temperatures (Welded Thermocouples)										
31	TCHAMB1E1	Chamber temperature #1 - E1	TBD	T/A - E1	TC	X	0 - 2300 deg F	0-5V DF	1		10

Seq	Meas ID	Description	Aerojet Nomenclature	Signal Location	Type of Transducer	Customer Supplied Transducer	Range	Signal Output	System Uncertainty (%FS)	Component ID	Data Frequency (HZ)
31	TCHAMB2E1	Chamber temperature #2 - E1	TBD	T/A - E1	TC	X	0 - 2300 deg F	0-5V DF	1		10
31	TCHAMB3E1	Chamber temperature #3 - E1	TBD	T/A - E1	TC	X	0 - 2300 deg F	0-5V DF	1		10
31	TCHAMB4E1	Chamber temperature #4 - E1	TBD	T/A - E1	TC	X	0 - 2300 deg F	0-5V DF	1		10
31	TCHAMB5E1	Chamber temperature #5 - E1	TBD	T/A - E1	TC	X	0 - 2300 deg F	0-5V DF	1		10
31	TCHAMB6E1	Chamber temperature #6 - E1	TBD	T/A - E1	TC	X	0 - 2300 deg F	0-5V DF	1		10
31	TCHAMB7E1	Chamber temperature #7 - E1	TBD	T/A - E1	TC	X	0 - 2300 deg F	0-5V DF	1		10
31	TCHAMB8E1	Chamber temperature #8 - E1	TBD	T/A - E1	TC	X	0 - 2300 deg F	0-5V DF	1		10
31	TFVPSOLE1	Ethanol Primary Solenoid valve temp - E1	TFVPSOL	Stinger	TC		140 - 750 R	0-5V DF	1		10
31	TFVVSOLE1	Ethanol Igniter Solenoid valve temp. - E1	TFVVSOL	Stinger	TC		140 - 750 R	0-5V DF	1		10
31	TOVPSOLE1	LOX Primary Solenoid valve temp - E1	TOVPSOL	Stinger	TC		140 - 750 R	Conomic	1		10
31	TOVVSOLE1	LOX Igniter Solenoid valve temp - E1	TOVVSOL	Stinger	TC		140 - 750 R	Conomic	1		10
32	ENGINE 2										10
33	ENGINE INSTRUMENTATION										10
34	ACCLE2	Acceleration - E2		Stinger	Endevco		0 - 100 G	Pc/g	8		10
34	IETPVE2	Primary Ethanol valve current - E2		Bunker	Current Sensor		0 - 5 amps	0-5V	1		10
34	IETVVE2	Igniter Ethanol valve current - E2		Bunker	Current Sensor		0 - 5 amps	0-5V	1		10
34	ILOPVE2	Primary LOX valve current - E2		Bunker	Current Sensor		0 - 5 amps	0-5V	1		10
34	ILOVVE2	Igniter LOX valve current - E2		Bunker	Current Sensor		0 - 5 amps	0-5V	1		10
34	MSPARKE2	Spark monitor - E2		Bunker	Exciter	X	TBD		1		10
34	PCAVE2	Primary Chamber Press - E2 (0-300)	PCAV	T/A - E2	GP50		0 -300 psia		1		10
34	PCAVLOE2	Primary Chamber Press - E2 (0-30)	PCAV	T/A - E2	GP50		0 -30 psia		1		10
34	PCIGNE2	Igniter Chamber Pressure - E2	PCIGN	Stinger	STJE		0 -500 psia		1		
34	PFJE2	LOX primary, injector manifold pressure - E2	PFJ	Stinger	Cryo Taber		0 -500 psia	BR	1		10
34	PFJIGNE2	LOX Igniter, valve outlet pressure - E2	PFJIGN	Stinger	Cryo Taber		0 -500 psia	BR	1		10
34	POJE2	LOX primary, injector manifold pressure - E2	POJ	Stinger	Cryo Taber		0 -500 psia	BR	1		10
34	POJIGNE2	LOX Igniter, valve outlet pressure - E2	POJIGN	Stinger	Cryo Taber		0 -500 psia	BR	1		10
34	TETPVSE2	Ethanol Primary Valve Seal Vent Temp-E2		Stinger	TC		500 - 600 R	0-5V DF	1	TT-HC-57	
34	TFJE2	Ethanol Primary Valve Outlet Temp-E2	TFJ	Stinger	TC		500 - 600 R	0-5V DF	1		
34	TFJIGNE2	Ethanol Igniter Valve Outlet Temp - E2	TFJIGN	Stinger	TC		500 - 600 R	0-5V DF	1		1000
34	TFVE2	Ethanol RCE Stinger Manifold Temp 2	TFV, TFVV	Stinger	Diode		500 - 600 R	500 ohm	1	TT-HC-41	20K
34	TINJECTE2	Injector Temp - E2		Stinger	TC		140 -750 R	Conomic	1		1000
34	TLOPOUTE2	LOX Primary Valve Outlet Temp-E2	TOJ	Stinger	TC		140 - 600 R	Conomic	1		1000
34	TLOPVSE2	LOX Primary Valve Seal Vent Temp-E2		Stinger	TC		140 - 600 R	Conomic	1	TT-LO-46	TBD
34	TLORCEM2	LOX RCE Stinger Manifold Temp 2		Stinger	Diode		140 - 600 R	500 ohm	1	TT-LO-41	400
34	TOJIGNE2	LOX Igniter Valve Outlet Temp - E2	TOJIGN	Stinger	TC		140 - 600 R	Conomic	1		TBD
34	TOVE2	LOX Primary Inlet Manifold Temp-E2	TOV	Stinger	Diode		140 - 600 R	500 ohm	1	TT-LO-47	1000
34	TOVVE2	LOX Igniter Inlet Manifold Temp - E2	TOVV	Stinger	Diode		140 - 600 R	500 ohm	1	TT-LO-48	400
34	VEXTRE2	Spark Exciter Voltage - E2		Stinger	Exciter		0 - 28 VDC		1		TBD
35	Engine 2 - Temperatures (Welded Thermocouples)										
36	TCHAMB1E2	Chamber temperature #1 - E2	TBD	T/A - E2	TC	X	0 - 2300 deg F	0-5V DF	1		TBD
36	TCHAMB2E2	Chamber temperature #2 - E2	TBD	T/A - E2	TC	X	0 - 2300 deg F	0-5V DF	1		
36	TCHAMB3E2	Chamber temperature #3 - E2	TBD	T/A - E2	TC	X	0 - 2300 deg F	0-5V DF	1		1000
36	TCHAMB4E2	Chamber temperature #4 - E2	TBD	T/A - E2	TC	X	0 - 2300 deg F	0-5V DF	1		
36	TCHAMB5E2	Chamber temperature #5 - E2	TBD	T/A - E2	TC	X	0 - 2300 deg F	0-5V DF	1		1000
36	TCHAMB6E2	Chamber temperature #6 - E2	TBD	T/A - E2	TC	X	0 - 2300 deg F	0-5V DF	1		
36	TCHAMB7E2	Chamber temperature #7 - E2	TBD	T/A - E2	TC	X	0 - 2300 deg F	0-5V DF	1		10

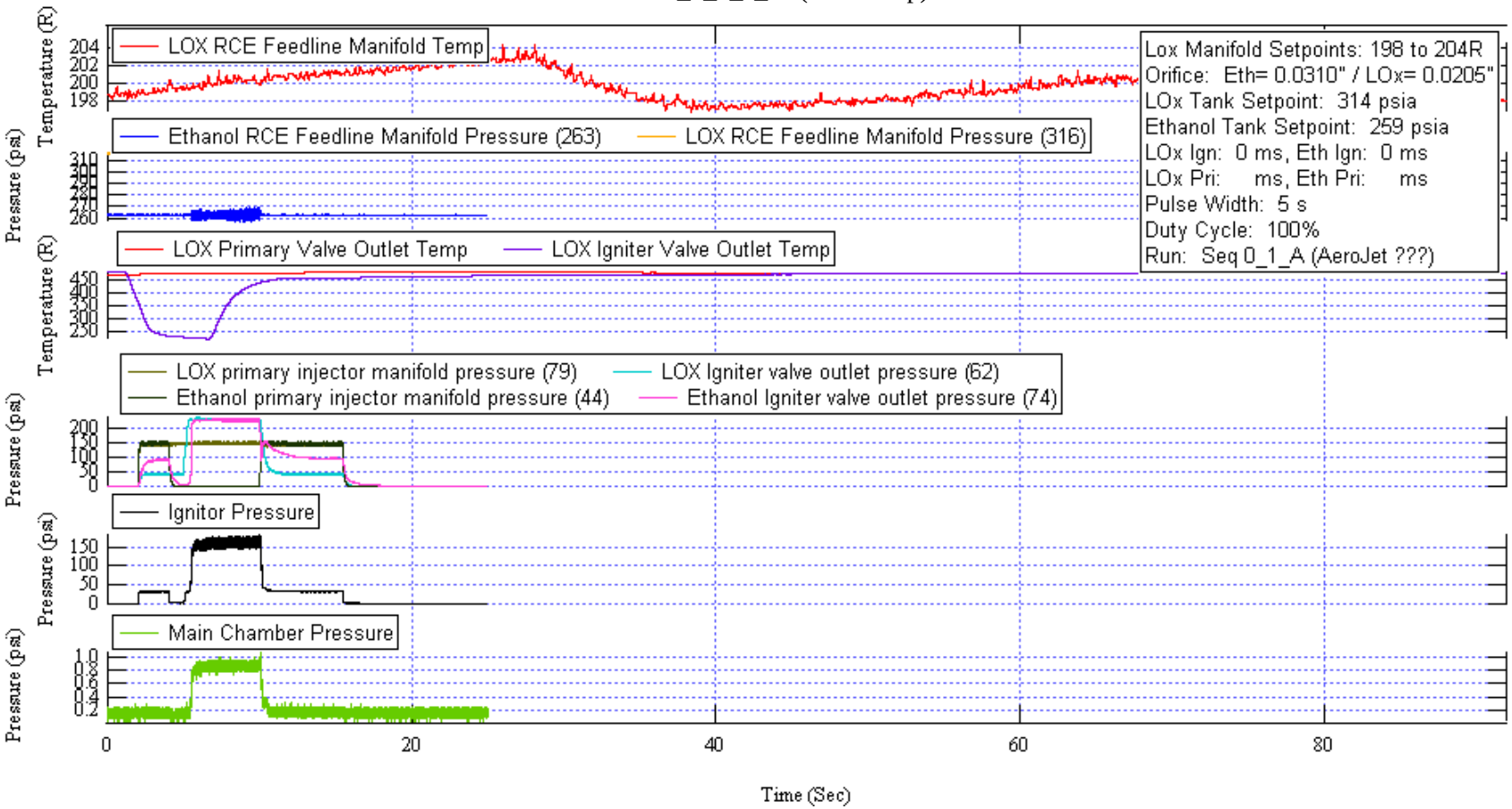
Seq	Meas ID	Description	Aerojet Nomenclature	Signal Location	Type of Transducer	Customer Supplied Transducer	Range	Signal Output	System Uncertainty (%FS)	Component ID	Data Frequency (HZ)
36	TCHAMB8E2	Chamber temperature #8 - E2	TBD	T/A - E2	TC	X	0 - 2300 deg F	0-5V DF	1		10
36	TFVPSOLE2	Ethanol Primary Solenoid valve temp - E2	TFVPSOL	Stinger	TC		140 - 750 R	0-5V DF	1		10
36	TFVVSOLE2	Ethanol Igniter Solenoid valve temp. - E2	TFVVSOL	Stinger	TC		140 - 750 R	0-5V DF	1		1000
36	TOVPSOLE2	LOX Primary Solenoid valve temp - E2	TOVPSOL	Stinger	TC		140 - 750 R	Conomic	1		1000
36	TOVVSOLE2	LOX Igniter Solenoid valve temp - E2	TOVVSOL	Stinger	TC		140 - 750 R	Conomic	1		10
37	ENGINE 3										1000
38	ENGINE INSTRUMENTATION										1000
39	ACCLE3	Acceleration - E3		Stinger	Endevco		0 - 100 G	Pc/g	8		
39	IETPVE3	Primary Ethanol valve current - E3		Bunker	Current Sensor		0 - 5 amps	0-5V	1		
39	IETVVE3	Igniter Ethanol valve current - E3		Bunker	Current Sensor		0 - 5 amps	0-5V	1		10
39	ILOPVE3	Primary LOX valve current - E3		Bunker	Current Sensor		0 - 5 amps	0-5V	1		10
39	ILOVVE3	Igniter LOX valve current - E3		Bunker	Current Sensor		0 - 5 amps	0-5V	1		10
39	MSPARKE3	Spark monitor - E3		Bunker	Exciter	X	TBD		1		10
39	PCAVE3	Primary Chamber Press - E3 (0-300)	PCAV	T/A - E3	GP50		0 -300 psia		1		10
39	PCAVLOE3	Primary Chamber Press - E3 (0-30)	PCAV	T/A - E3	GP50		0 -30 psia		1		10
39	PCIGNE3	Igniter Chamber Pressure - E3	PCIGN	Stinger	STJE		0 -500 psia		1		10
39	PFJE3	LOX primary, injector manifold pressure - E3	PFJ	Stinger	Cryo Taber		0 -500 psia	BR	1		10
39	PFJIGNE3	LOX Igniter, valve outlet pressure - E3	PFJIGN	Stinger	Cryo Taber		0 -500 psia	BR	1		10
39	POJE3	LOX primary, injector manifold pressure - E3	POJ	Stinger	Cryo Taber		0 -500 psia	BR	1		10
39	POJIGNE3	LOX Igniter, valve outlet pressure - E3	POJIGN	Stinger	Cryo Taber		0 -500 psia	BR	1		10
39	TETPVSE3	Ethanol Primary Valve Seal Vent Temp-E3		Stinger	TC		500 - 600 R	0-5V DF	1	TT-HC-58	10
39	TFJE3	Ethanol Primary Valve Outlet Temp-E3	TFJ	Stinger	TC		500 - 600 R	0-5V DF	1		10
39	TFJIGNE3	Ethanol Igniter Valve Outlet Temp - E3	TFJIGN	Stinger	TC		500 - 600 R	0-5V DF	1		10
39	TFVE3	Ethanol RCE Stinger Manifold Temp 3	TFV, TFVV	Stinger	Diode		500 - 600 R	500 ohm	1	TT-HC-42	10
39	TINJECTE3	Injector Temp - E3		Stinger	TC		140 -750 R	Conomic	1		10
39	TLOPOUTE3	LOX Primary Valve Outlet Temp-E3	TOJ	Stinger	TC		140 - 600 R	Conomic	1		10
39	TLOPVSE3	LOX Primary Valve Seal Vent Temp-E3		Stinger	TC		140 - 600 R	Conomic	1	TT-LO-49	10
39	TLORCEM3	LOX RCE Stinger Manifold Temp 3		Stinger	Diode		140 - 600 R	500 ohm	1	TT-LO-42	10
39	TOJIGNE3	LOX Igniter Valve Outlet Temp - E3	TOJIGN	Stinger	TC		140 - 600 R	Conomic	1		
39	TOVE3	LOX Primary Inlet Manifold Temp-E3	TOV	Stinger	Diode		140 - 600 R	500 ohm	1	TT-LO-50	10
39	TOVVE3	LOX Igniter Inlet Manifold Temp - E3	TOVV	Stinger	Diode		140 - 600 R	500 ohm	1	TT-LO-51	10
39	VEXTRE3	Spark Exciter Voltage - E3		Stinger	-		0 - 28 VDC		1		10
40	Engine 3 - Temperatures (Welded Thermocouples)										10
41	TCHAMB1E3	Chamber temperature #1 - E3	TBD	T/A - E3	TC	X	0 - 2300 deg F	0-5V DF	1		10
41	TCHAMB2E3	Chamber temperature #2 - E3	TBD	T/A - E3	TC	X	0 - 2300 deg F	0-5V DF	1		10
41	TCHAMB3E3	Chamber temperature #3 - E3	TBD	T/A - E3	TC	X	0 - 2300 deg F	0-5V DF	1		
41	TCHAMB4E3	Chamber temperature #4 - E3	TBD	T/A - E3	TC	X	0 - 2300 deg F	0-5V DF	1		
41	TCHAMB5E3	Chamber temperature #5 - E3	TBD	T/A - E3	TC	X	0 - 2300 deg F	0-5V DF	1		1000
41	TCHAMB6E3	Chamber temperature #6 - E3	TBD	T/A - E3	TC	X	0 - 2300 deg F	0-5V DF	1		TBD
41	TCHAMB7E3	Chamber temperature #7 - E3	TBD	T/A - E3	TC	X	0 - 2300 deg F	0-5V DF	1		400
41	TCHAMB8E3	Chamber temperature #8 - E3	TBD	T/A - E3	TC	X	0 - 2300 deg F	0-5V DF	1		400
41	TFVPSOLE3	Ethanol Primary Solenoid valve temp - E3	TFVPSOL	Stinger	TC		140 - 750 R	0-5V DF	1		20K
41	TFVVSOLE3	Ethanol Igniter Solenoid valve temp. - E3	TFVVSOL	Stinger	TC		140 - 750 R	0-5V DF	1		1000
41	TOVPSOLE3	LOX Primary Solenoid valve temp - E3	TOVPSOL	Stinger	TC		140 - 750 R	Conomic	1		1000
41	TOVVSOLE3	LOX Igniter Solenoid valve temp - E3	TOVVSOL	Stinger	TC		140 - 750 R	Conomic	1		1000
42	SIMULATOR 1										TBD

Seq	Meas ID	Description	Aerojet Nomenclature	Signal Location	Type of Transducer	Customer Supplied Transducer	Range	Signal Output	System Uncertainty (%FS)	Component ID	Data Frequency (HZ)
43	PETVINS1	Ethanol Simulator Valve Inlet Pressure - S1		T/A Sim1	Cryo Taber		0 -500 psia	BR	1	PT-HC-52	TBD
43	PLOVINS1	LOX Simulator Valve Inlet Pressure - S1		T/A Sim1	Cryo Taber		0 -500 psia	BR	1	PT-LO-64	TBD
43	TLOVINS1	LOX Simulator Valve Inlet Temp - S1		T/A Sim1	RTD		140 - 600 R	500 ohm	1	TT-LO-58	
44	SIMULATOR 2										TBD
45	PETVINS2	Ethanol Simulator Valve Inlet Pressure - S2		T/A Sim2	Cryo Taber		0 -500 psia	BR	1	PT-HC-53	
45	PLOVINS2	LOX Simulator Valve Inlet Pressure -S2		T/A Sim2	Cryo Taber		0 -500 psia	BR	1	PT-LO-65	1000
45	TLOVINS2	LOX Primary Venturi Inlet Temp-S2		T/A Sim2	RTD		140 - 600 R	500 ohm	1	TT-LO-59	
46	SIMULATOR 3										10
47	PETVINS3	Ethanol Simulator Valve Inlet Pressure - S3		T/A Sim3	Cryo Taber		0 -500 psia	BR	1	PT-HC-54	1000
47	PLOVINS3	LOX Simulator Valve Inlet Pressure -S3		T/A Sim3	Cryo Taber		0 -500 psia	BR	1	PT-LO-66	1000
47	TLOVINS3	LOX Primary Venturi Inlet Temp-S3		T/A Sim3	RTD		140 - 600 R	500 ohm	1	TT-LO-60	10
48	FACILITY MEASUREMENTS										1000
49	PECELL10	Test Stand Chamber Pressure		Test Stand	Baratron		0 - 10 Torr		1		
49	PECELL100	Test Stand Chamber Pressure		Test Stand	Baratron		0 - 100 Torr		1		10
49	PECELL1000	Test Stand Chamber Pressure		Test Stand	Baratron		0 - 1000 Torr		1		10
49	TCELL	Test Stand Chamber Temperature		Test Stand	TC		0 -200 °F	0-5V DF	1		1000
52	Ethanol Instrumentation Measurements										1000
53	PETSTORE	Ethanol Storage Tank Low Point Pressure		Facility	STJE		0 - 1000 psia		1	PT-4HC-BM070	
53	PETSUPPLY	Ethanol Supply Pressure		Facility	STJE		0 - 1000 psia		1	PT-4HC-BM139	
53	PETTANK	Ethanol Storage Tank Ullage Pressure		Facility	STJE		0 - 1000 psia		1	PT-4HC-BM086	10
53	QETSUPPLY	Ethanol Supply Calculated Flowrate		Facility	Comp Meas		7 lbm/s		1	Note: this will be a calculated measurement from a DPT across a venturi	10
53	TETTANK	Ethanol Storage Tank Bulk Propellant Temperature		Facility	RTD		140 - 600 R	100 ohm	1	TT-4HC-BM127	10
53	TETTEMP	Ethanol Supply Temperature		Facility	TC		140 - 600 R	???	1	TT-4HC-BM140	10
54	LOX Instrumentation Measurements										10
55	LLOLOWLEV	LOX Low Level Alarm Sensor		Facility	Delta P-Switch				1		10
55	PLOSTLPT	LOX Storage Tank Low Pt Pressure		Facility	STJE		0 - 1000 psia		1		10
55	PLOSTVJ	LOX Storage Tank Vacuum Jacket Pressure		Facility	STJE		0 -30 psia		1		10
55	PLOSUPPLY	LOX Supply Pressure		Facility	STJE		0 - 1000 psia		1	PT-4LO-BN112	10
55	PLOTANK	LOX Storage Tank Pressure		Facility	STJE		0 - 1000 psia		1	PT-4LO-BN008	10
55	PLOTKLEVEL	LOX Storage Level Sensor		Facility	STJE		0-10 psid		1	DPT-4LO-BN014	10
55	PLOTKVACJK	LOX Vacuum Jacket Pressure		Facility	STJE		0-1000 torr		1	PT-4VA-BN041	10
55	QLOSUPPLY	LOX Supply Mass Flowrate		Facility	Comp Meas		8 lbm/s		1	Note: this will be a calculated measurement from a DPT across a venturi	10
55	TLOTEMP	LOX Supply Temperature		Facility	RTD		140 - 600 R	500 ohm	1	TT-4LO-BN113	10
56	Ethanol Controls Commands and Talkbacks										10
57	KETDMP_CL	Ethanol Dump Valve close		Facility			Event		N/A		10
57	KETDMP_OPEN	Ethanol Dump Valve open		Facility			Event		N/A		10
57	KETRTN	Ethanol Return Valve		Facility			Event		N/A		10
57	KETRUNTANK	Ethanol Run Tank Pressuration Command		Facility			Event		N/A		10
57	KETSUP_ISO	Ethanol Supply Isolation Command		Facility			Event		N/A		10

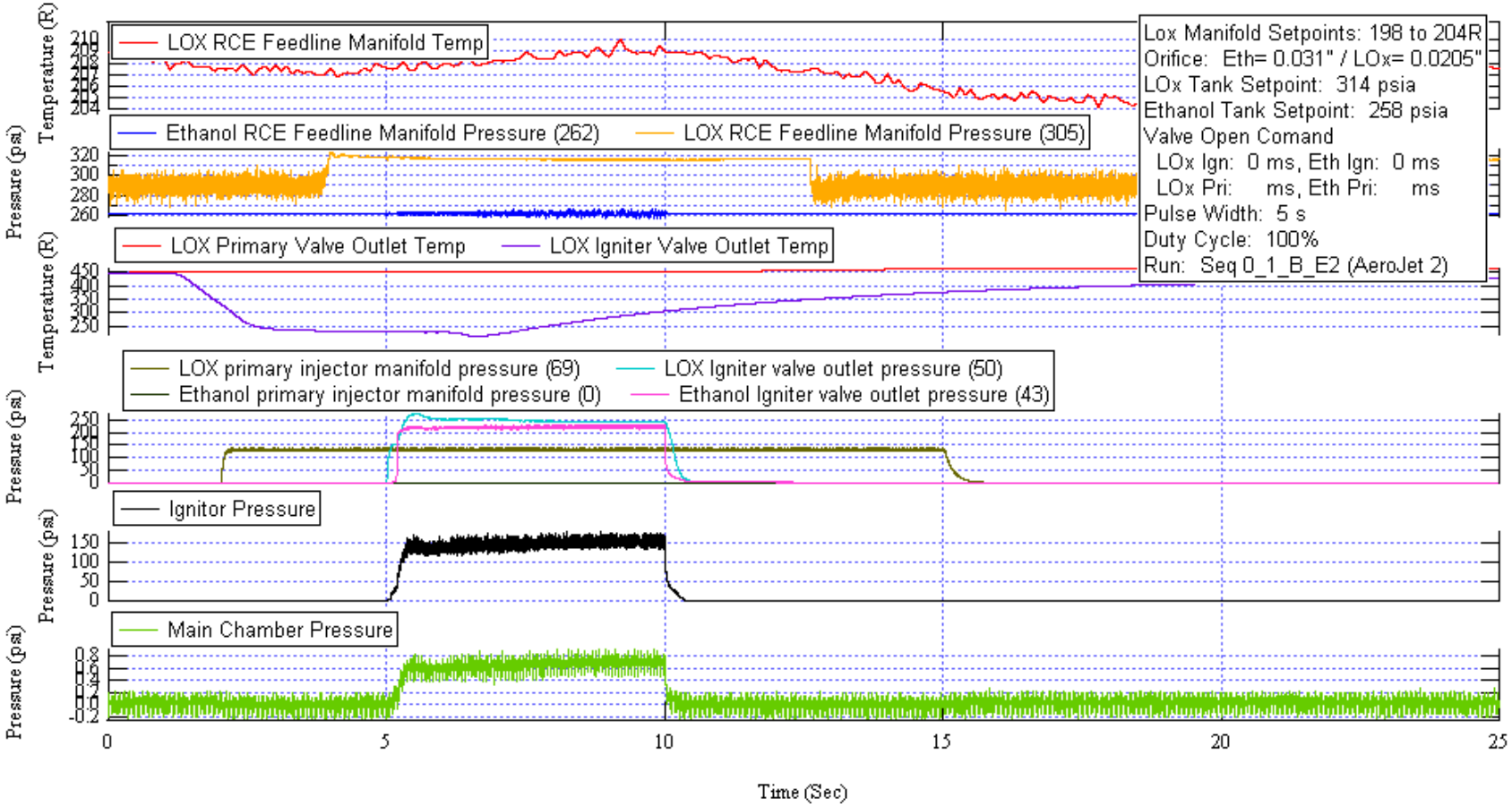
Seq	Meas ID	Description	Aerojet Nomenclature	Signal Location	Type of Transducer	Customer Supplied Transducer	Range	Signal Output	System Uncertainty (%FS)	Component ID	Data Frequency (HZ)
57	KETTNK	Ethanol Storage Tank Pressuration Command		Facility			Event		N/A		10
57	KETTNKISO	Ethanol Storage Tank Pressuration Iso Command		Facility			Event		N/A		10
57	KETTNKOUT	Ethanol Storage Tank Outlet Command		Facility			Event		N/A		
57	KETTRIM	Ethanol Trim Vent Command		Facility			Event		N/A		10
57	KETVENT	Ethanol Storage Tank Vent Command		Facility			Event		N/A		10
57	KETVENT_ISO	Ethanol Vent Isolation Command		Facility			Event		N/A		10
57	XETRTN_CL	Ethanol Return close		Facility			Event		N/A		10
57	XETRTN_OPEN	Ethanol Return open		Facility			Event		N/A		10
57	XETSUP_CL	Ethanol Supply Isolation Closed		Facility			Event		N/A		
57	XETSUP_OPEN	Ethanol Supply Isolation Open		Facility			Event		N/A		
57	XETVENT_CL	Ethanol Vent Isolation Closed		Facility			Event		N/A		
57	XETVENT_OPEN	Ethanol Vent Isolation Open		Facility			Event		N/A		10
58	LOX Controls Commands and Talkbacks										
59	KLOOUT	LOX Storage Tank Outlet Command		Facility			Event		N/A		
59	KLOSUP_BLED	LOX Supply Bleed Command		Facility			Event		N/A		
59	KLOSUP_ISO	LOX Supply Isolation Command		Facility			Event		N/A		10
59	KLOTNK	LOX Storage Tank Pressuration Command		Facility			Event		N/A		
59	KLOTNKISO	LOX Storage Tank Isolation Command		Facility			Event		N/A		
59	KLOTNKISO	LOX Storage Tank Pressuration Iso Command		Facility			Event		N/A		
59	KLOTRIM	LOX Trim Vent Command		Facility			Event		N/A		10
59	KLOVENT	LOX Storage Tank Vent Command		Facility			Event		N/A		
59	KLOVENT_ISO	LOX Vent Isolation Command		Facility			Event		N/A		
59	XLOSUP_BLED	LOX Supply Bleed Open		Facility			Event		N/A		
59	XLOSUP_BLED	LOX Supply Bleed Closed		Facility			Event		N/A		
59	XLOSUP_CL	LOX Supply Isolation Closed		Facility			Event		N/A		
59	XLOSUP_OPEN	LOX Supply Isolation Open		Facility			Event		N/A		
59	XLOVENT_CL	LOX Vent Isolation Closed		Facility			Event		N/A		
59	XLOVENT_OPEN	LOX Vent Isolation Open		Facility			Event		N/A		

APPENDIX F: WSTF LO_2/ETHANOL TEST PLOTS

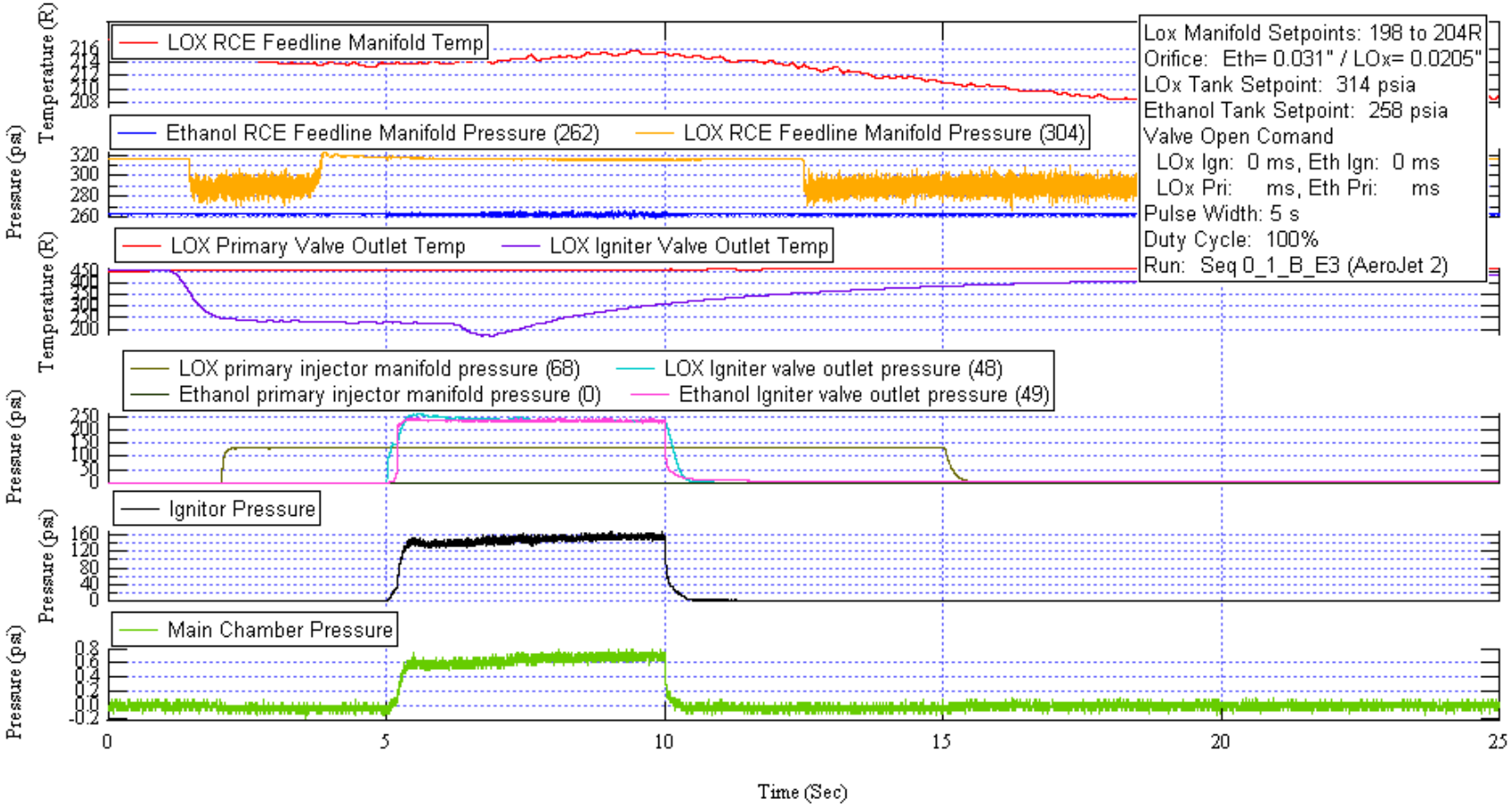
01146_0_1_a_e1 (fixed temp)



01146_0_1_b_e1 (fixed temp)



01146_0_1_c_e1 (fixed temp)



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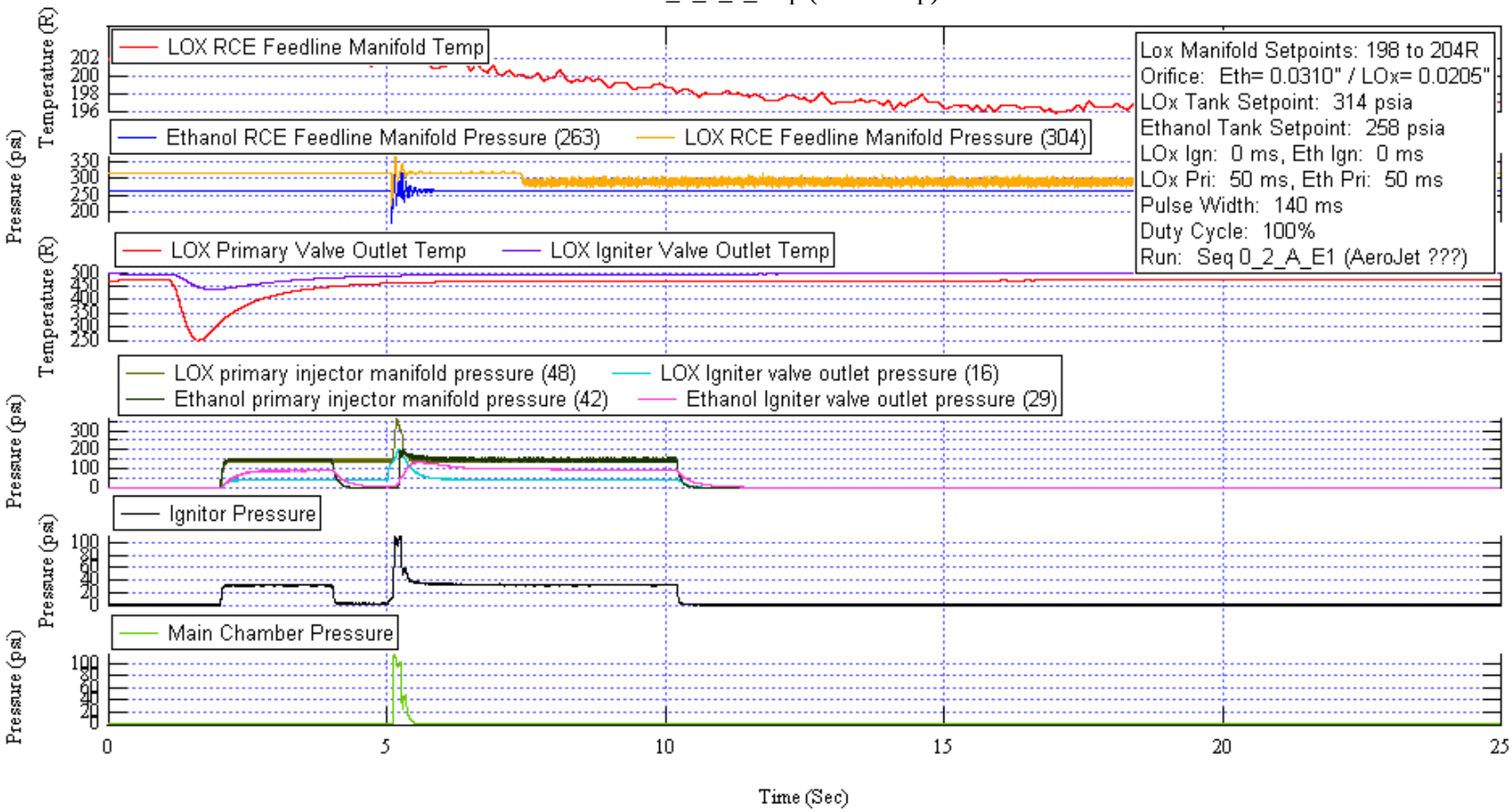

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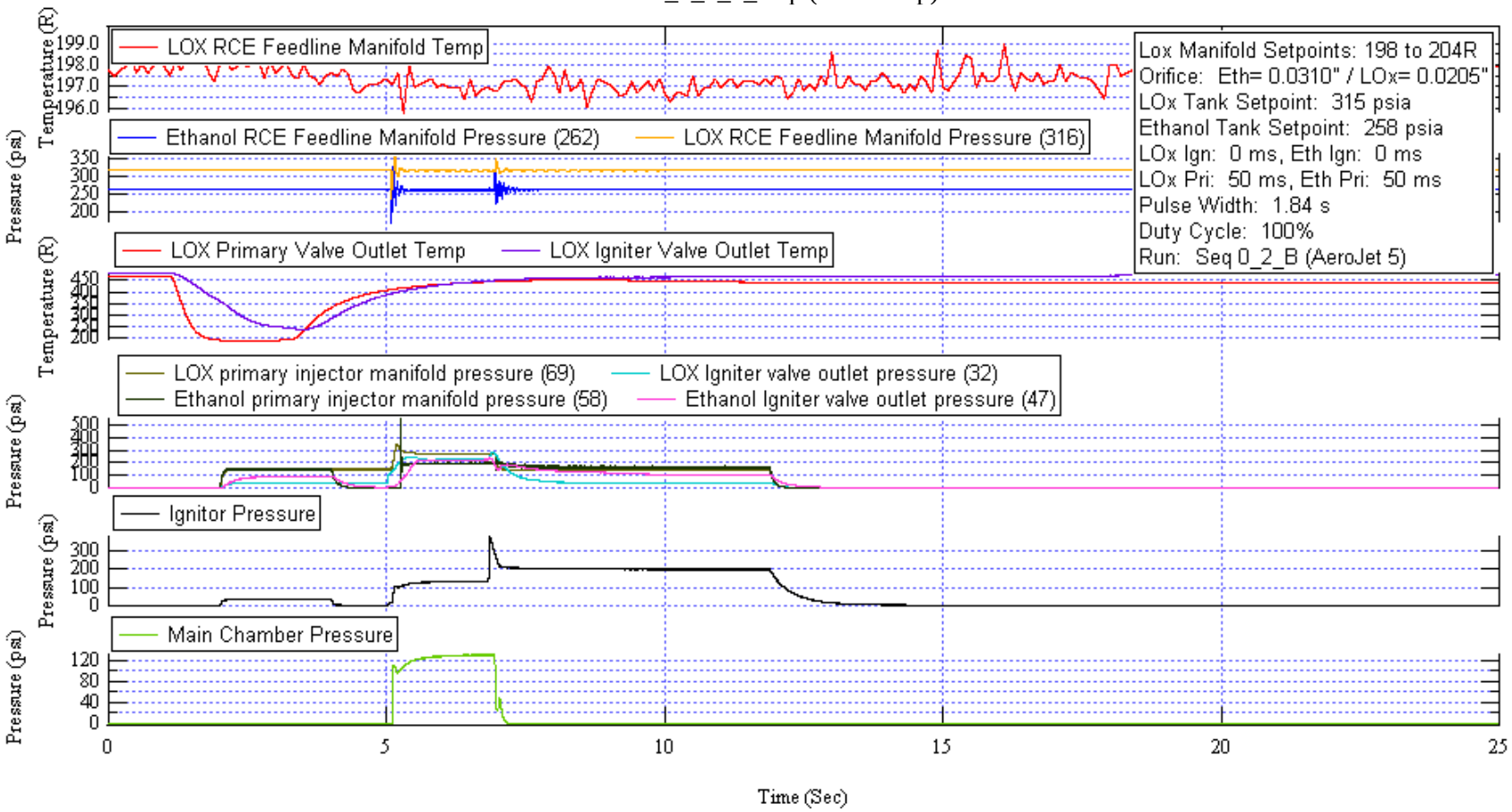

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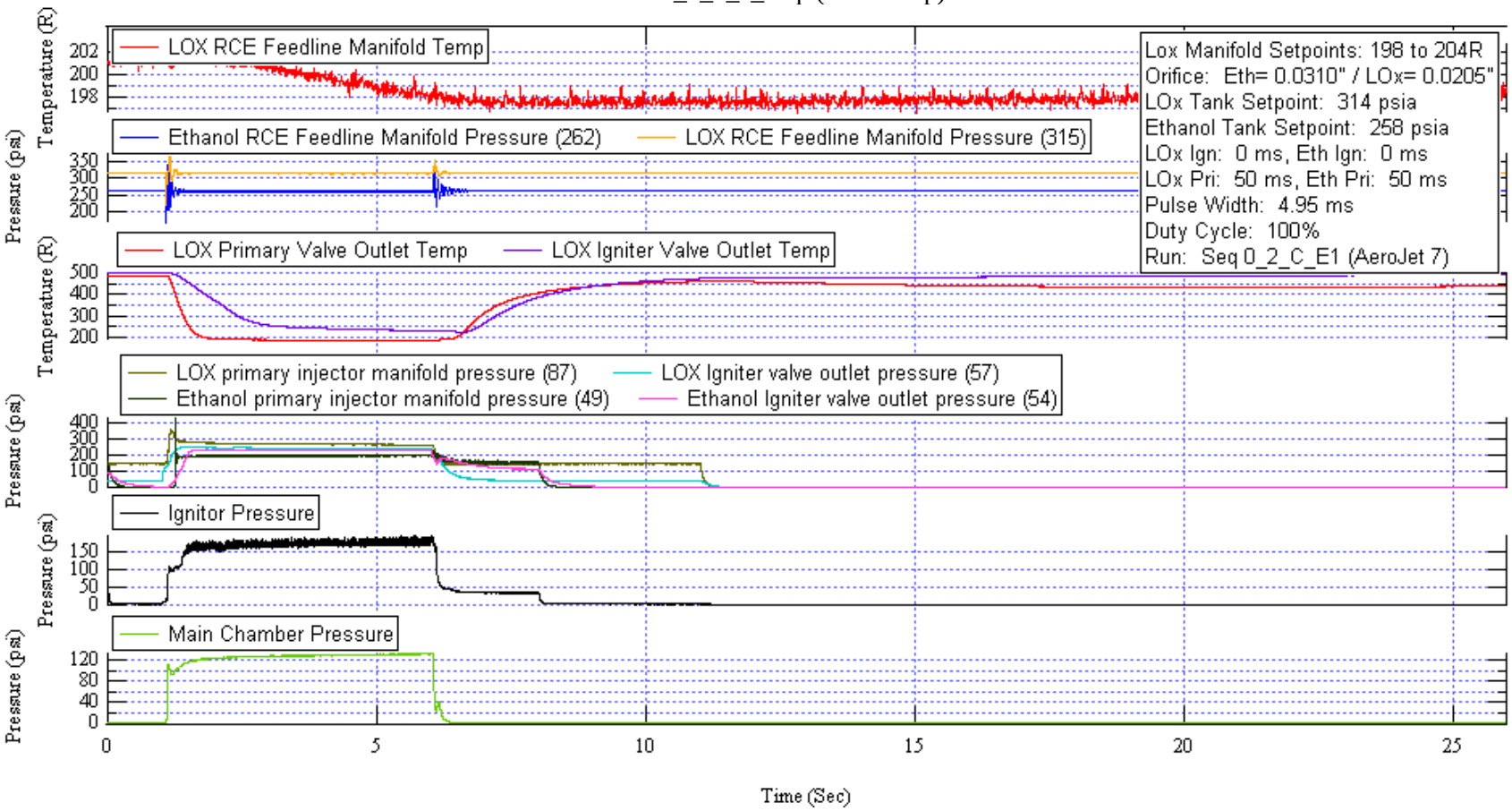

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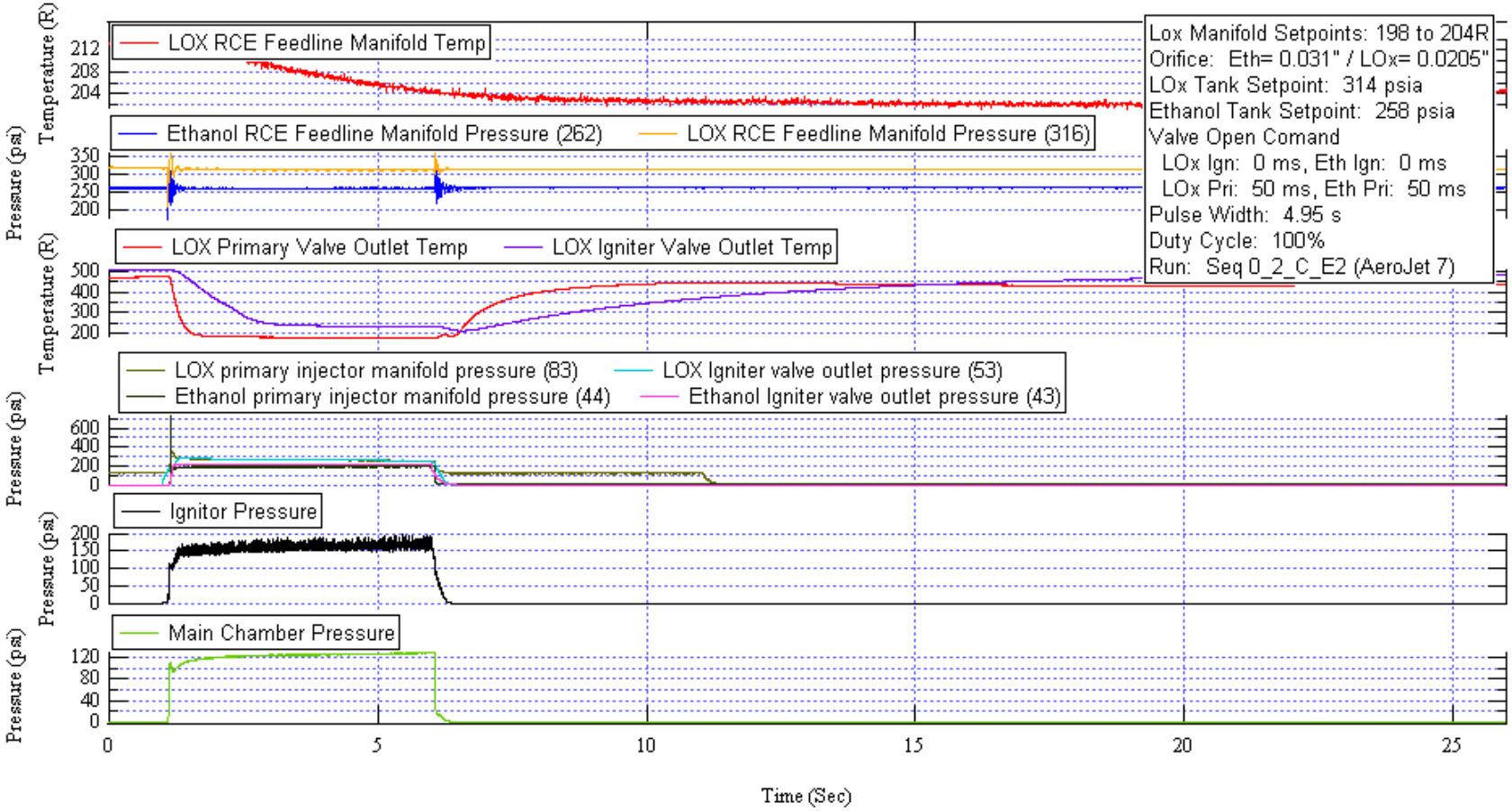

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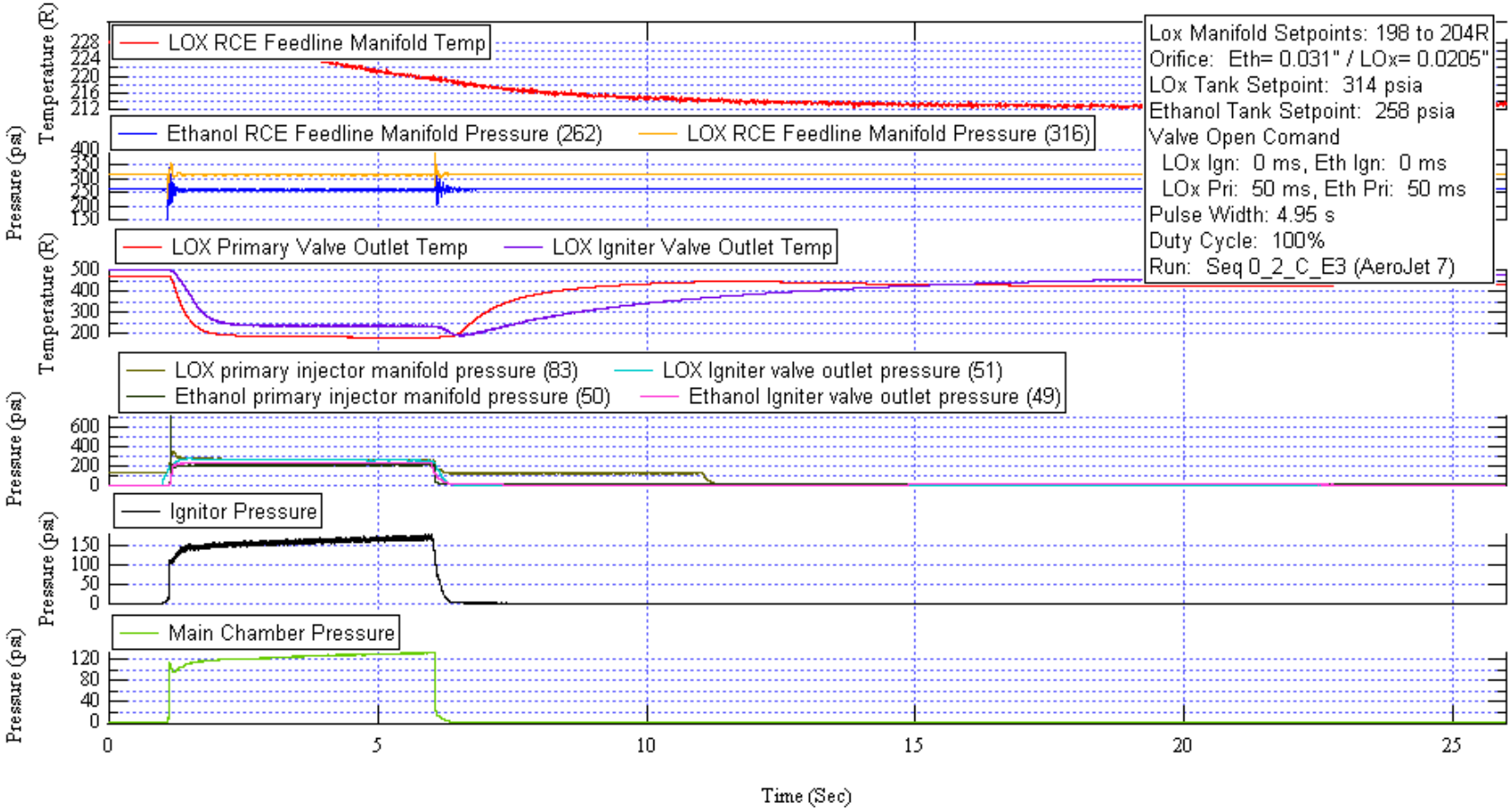

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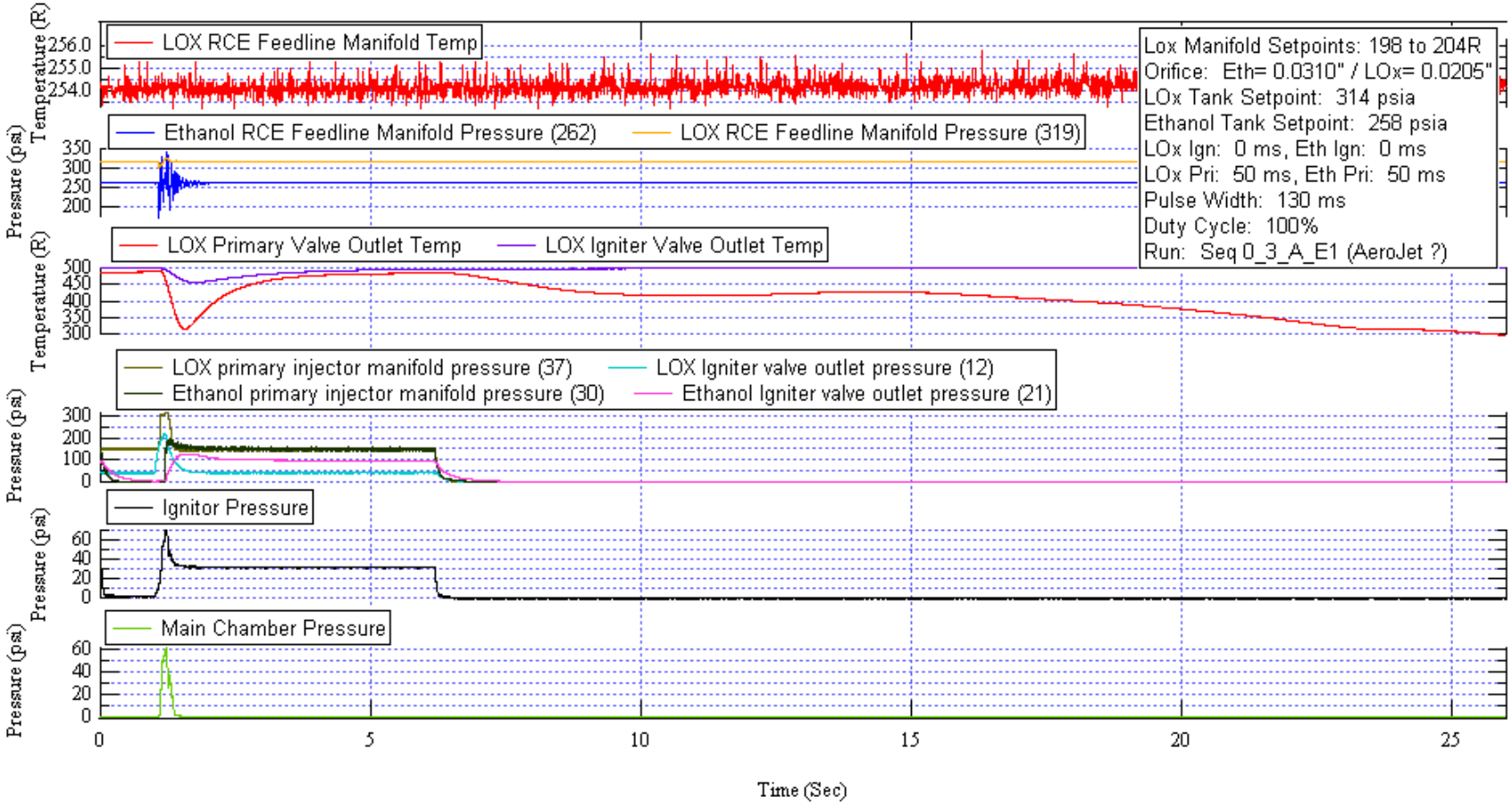

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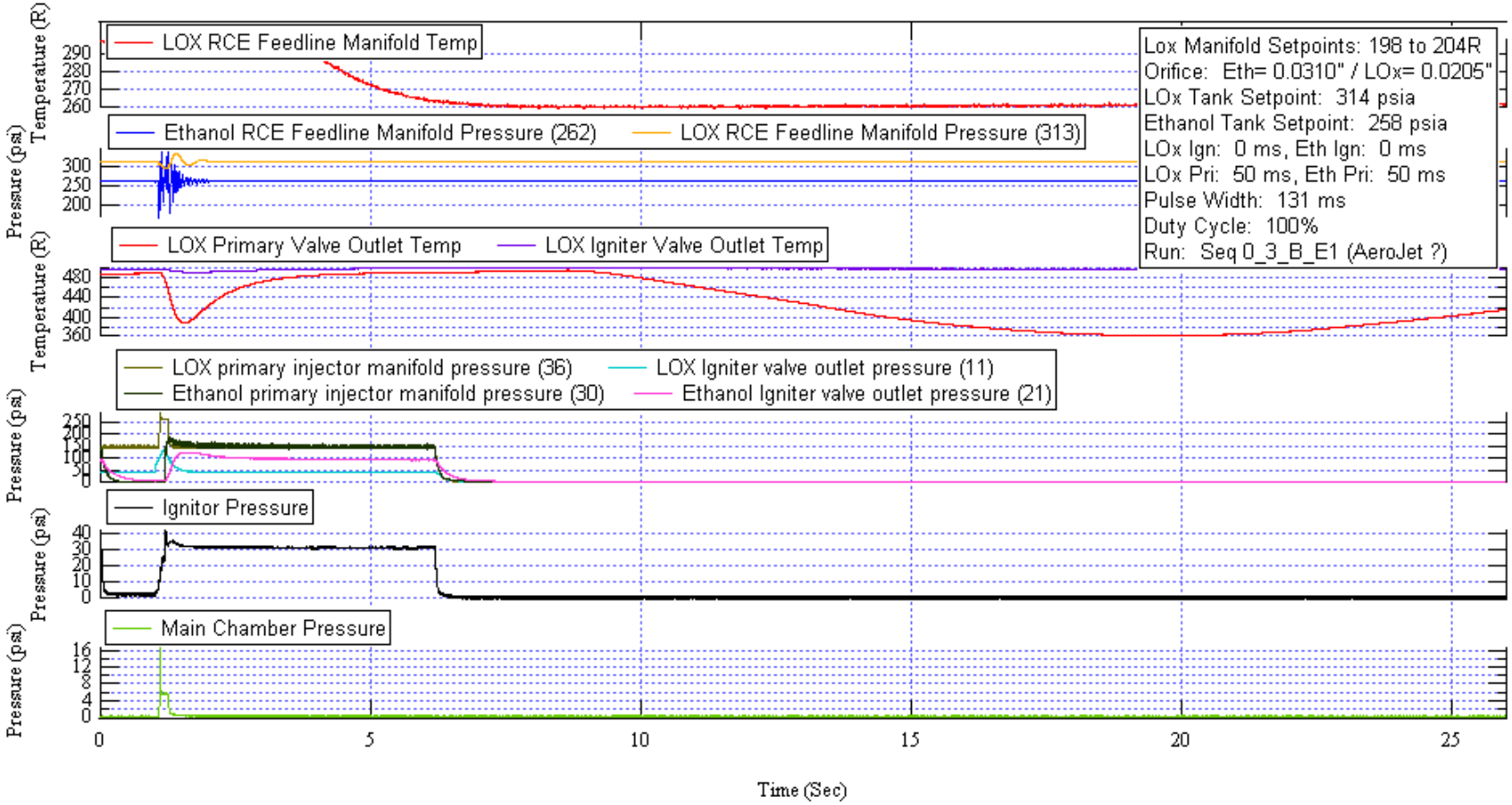

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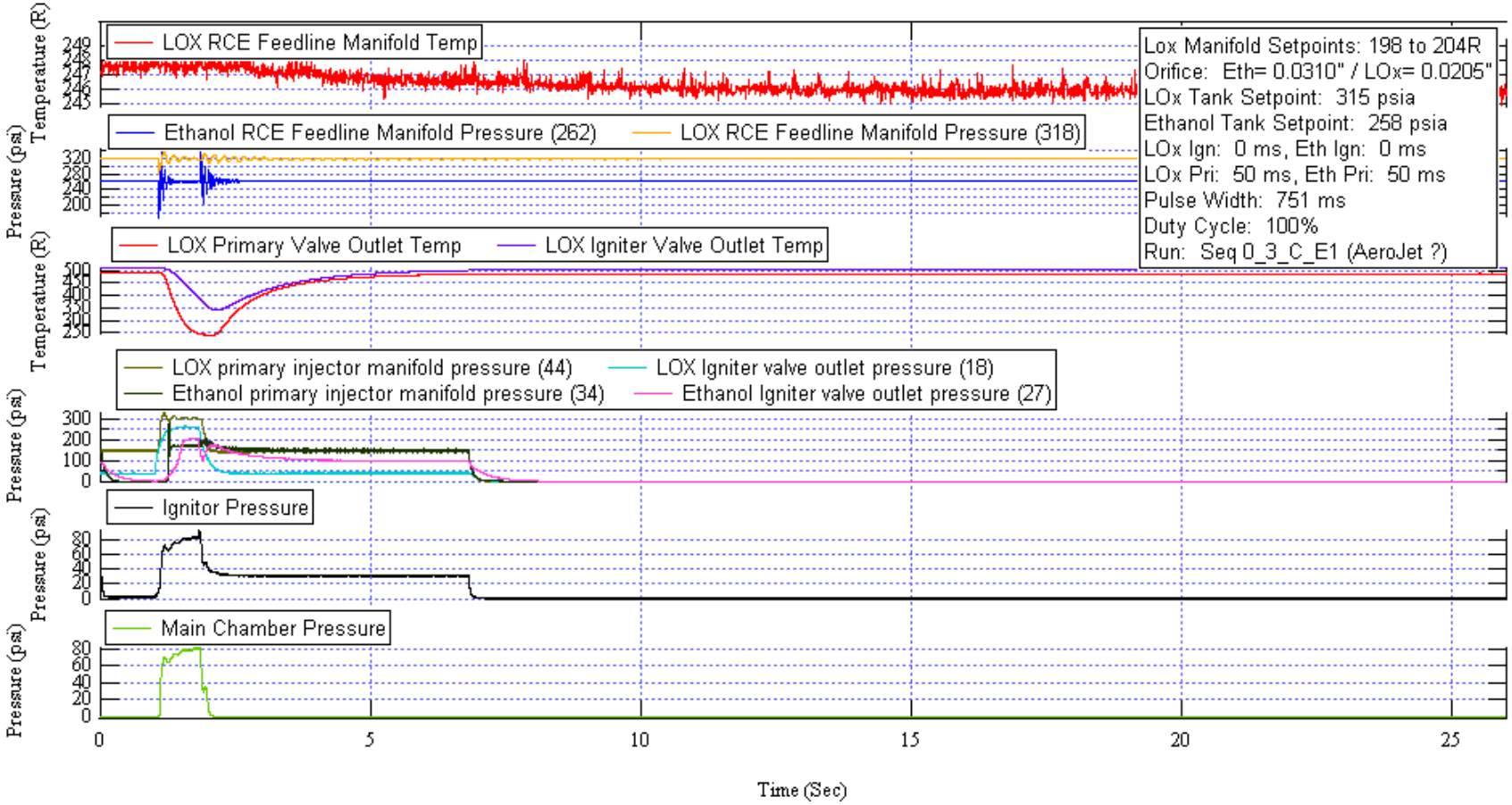

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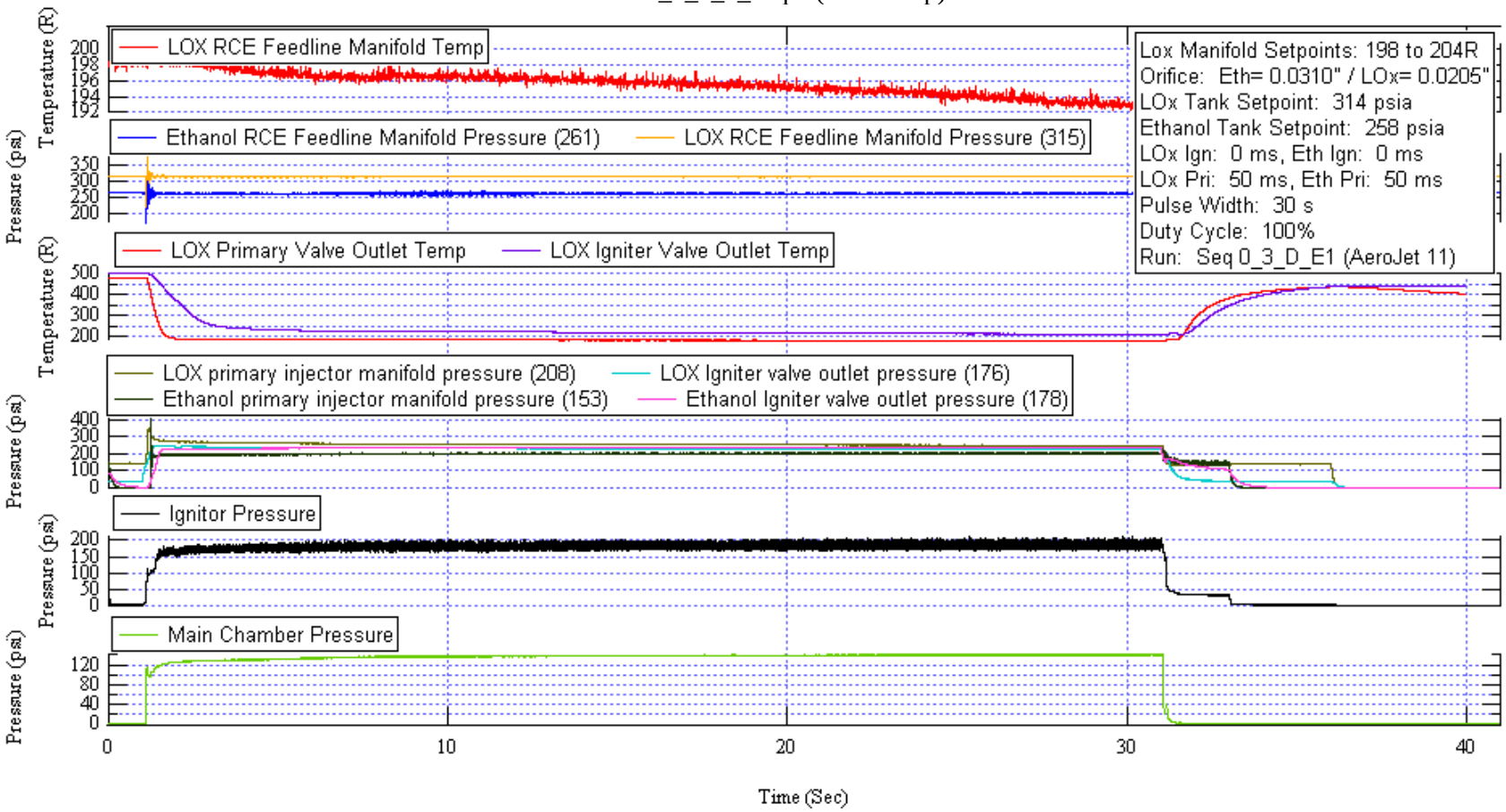

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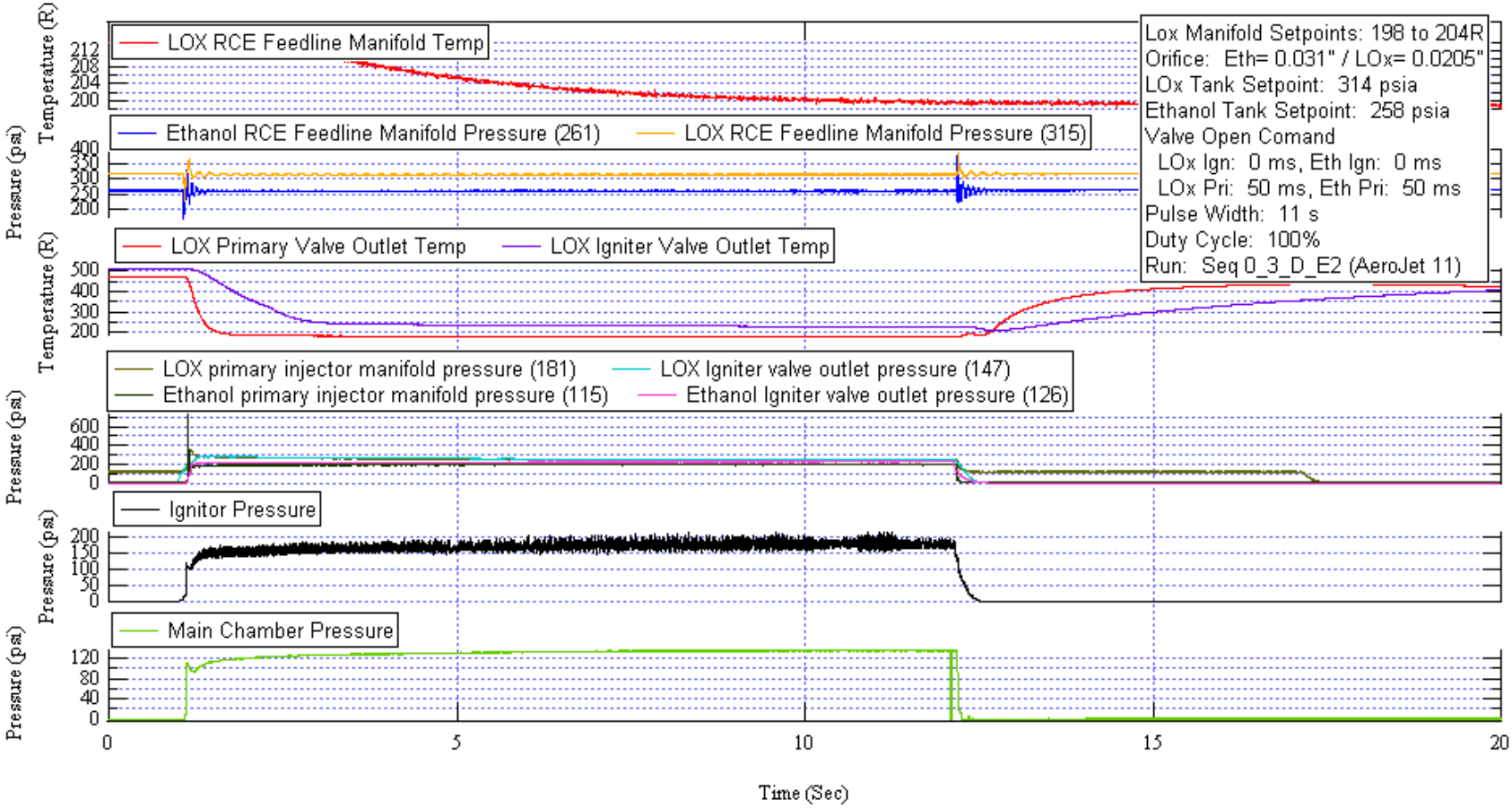

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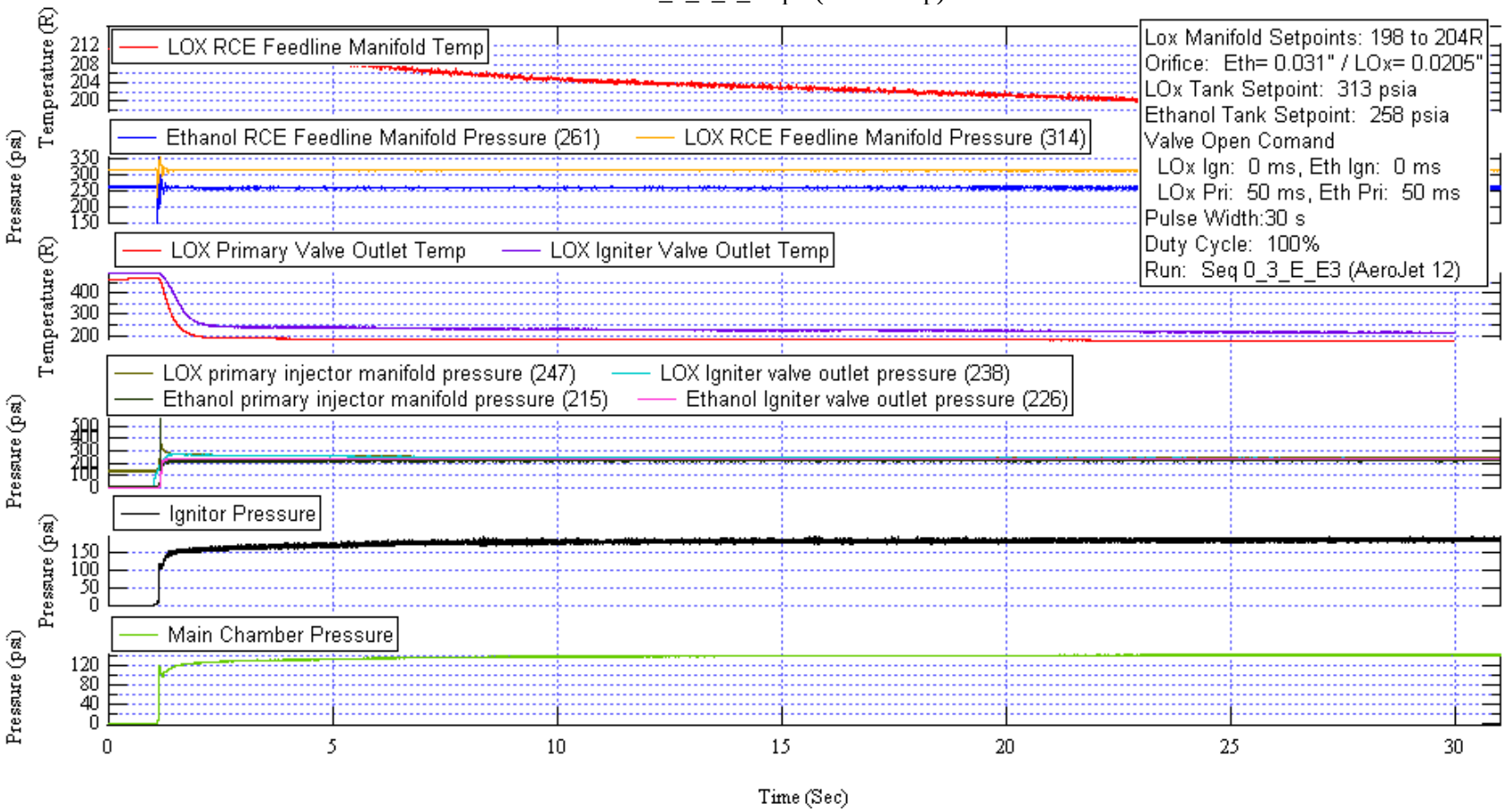

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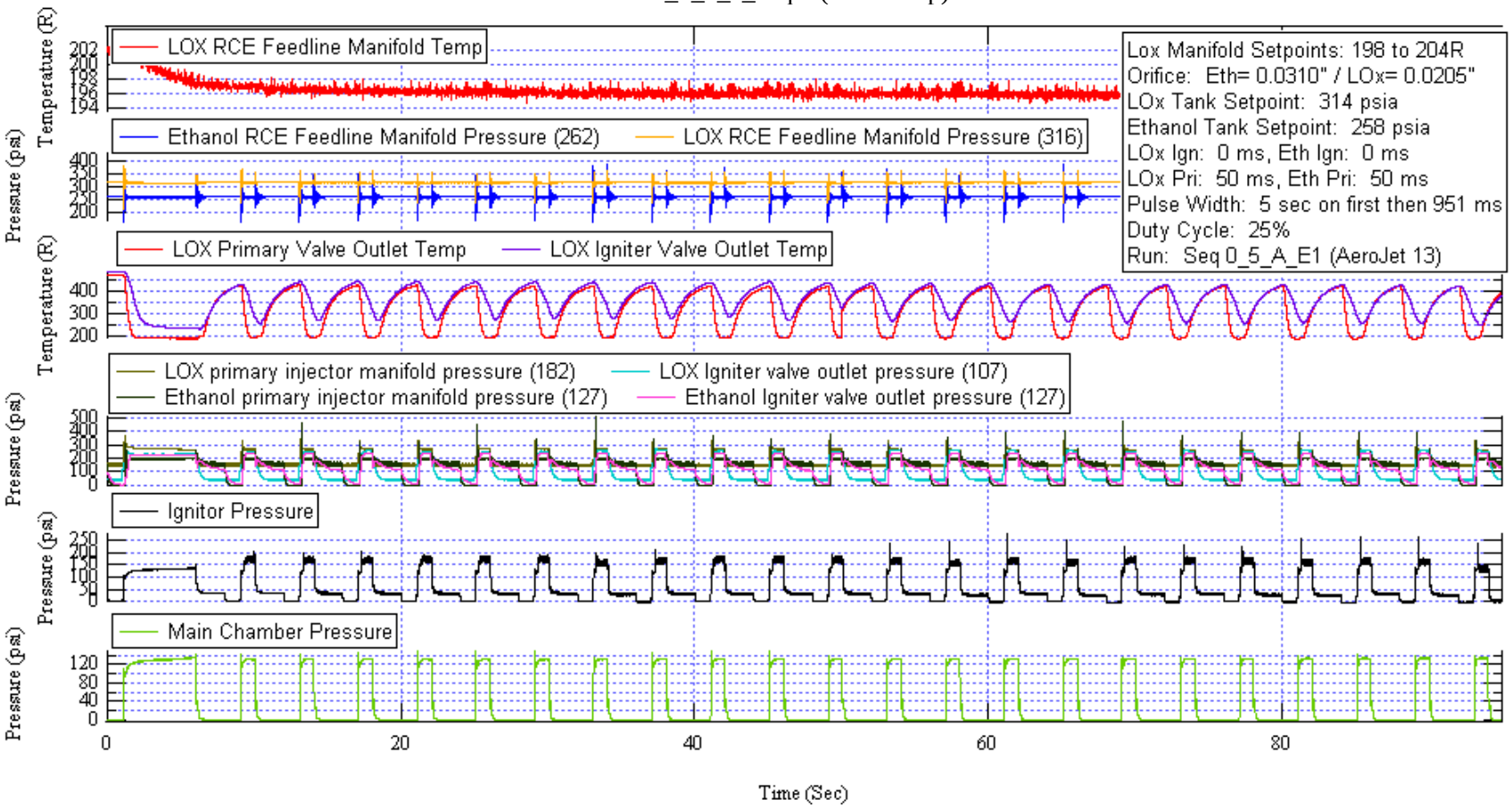

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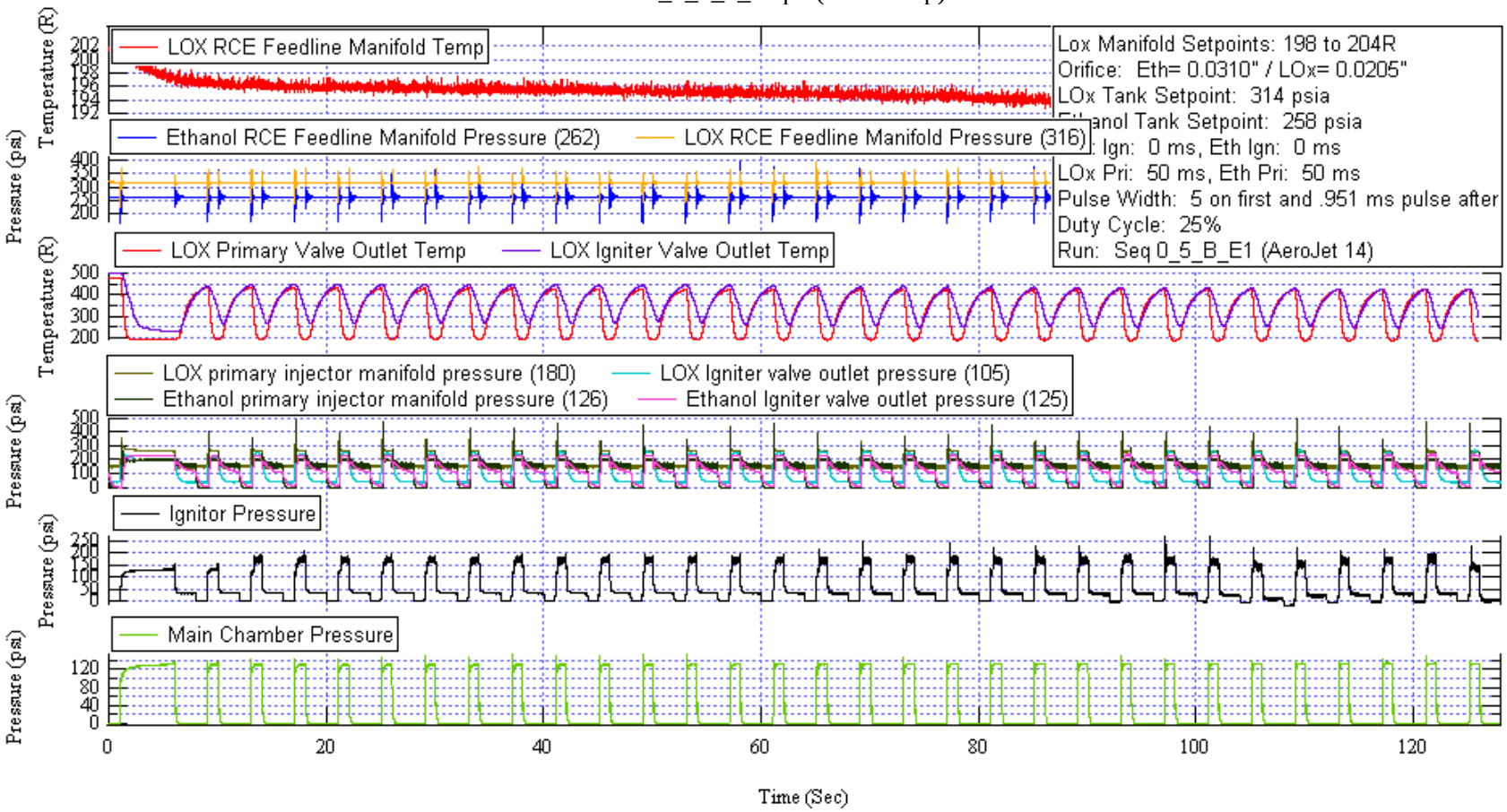

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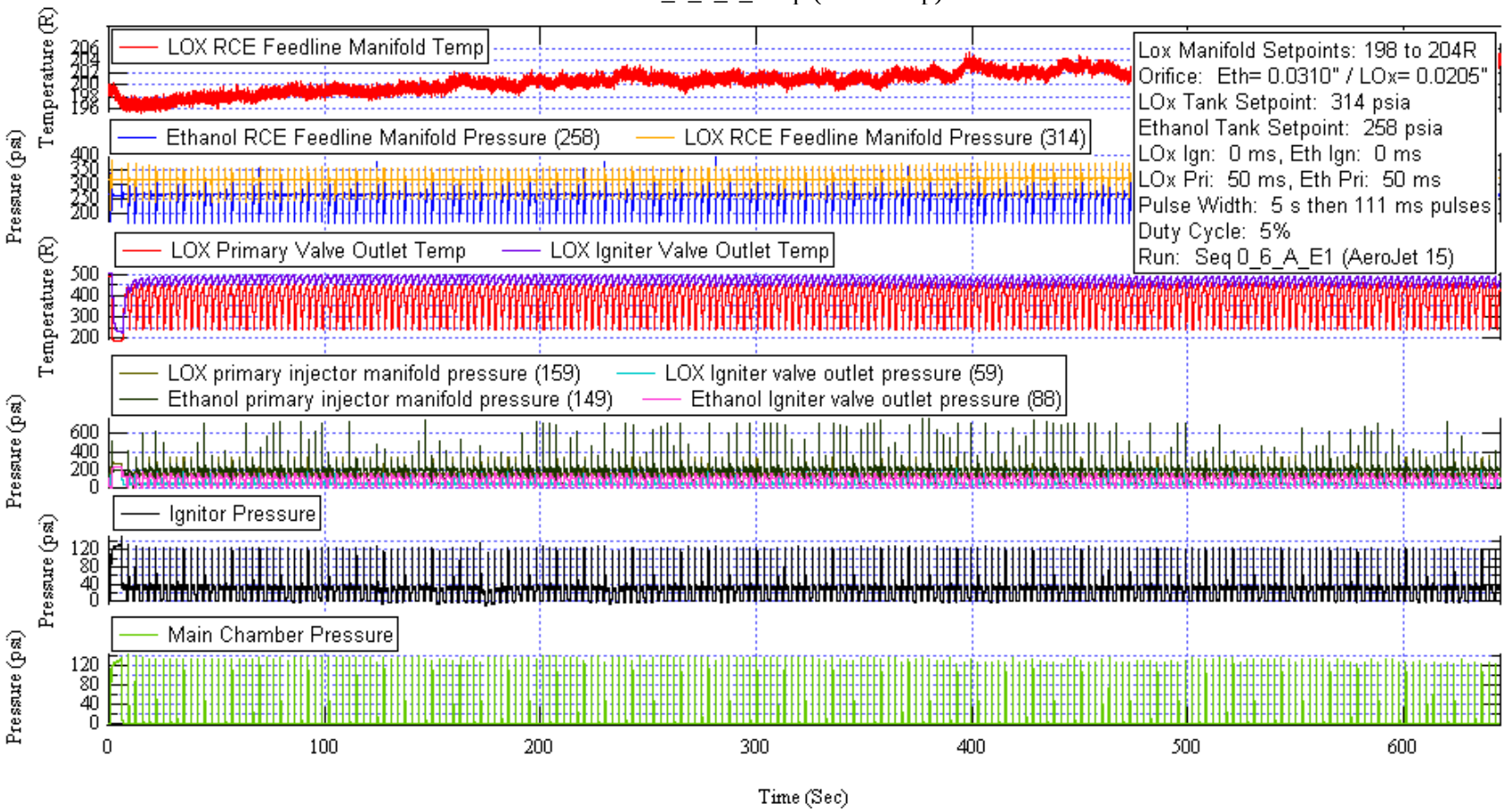

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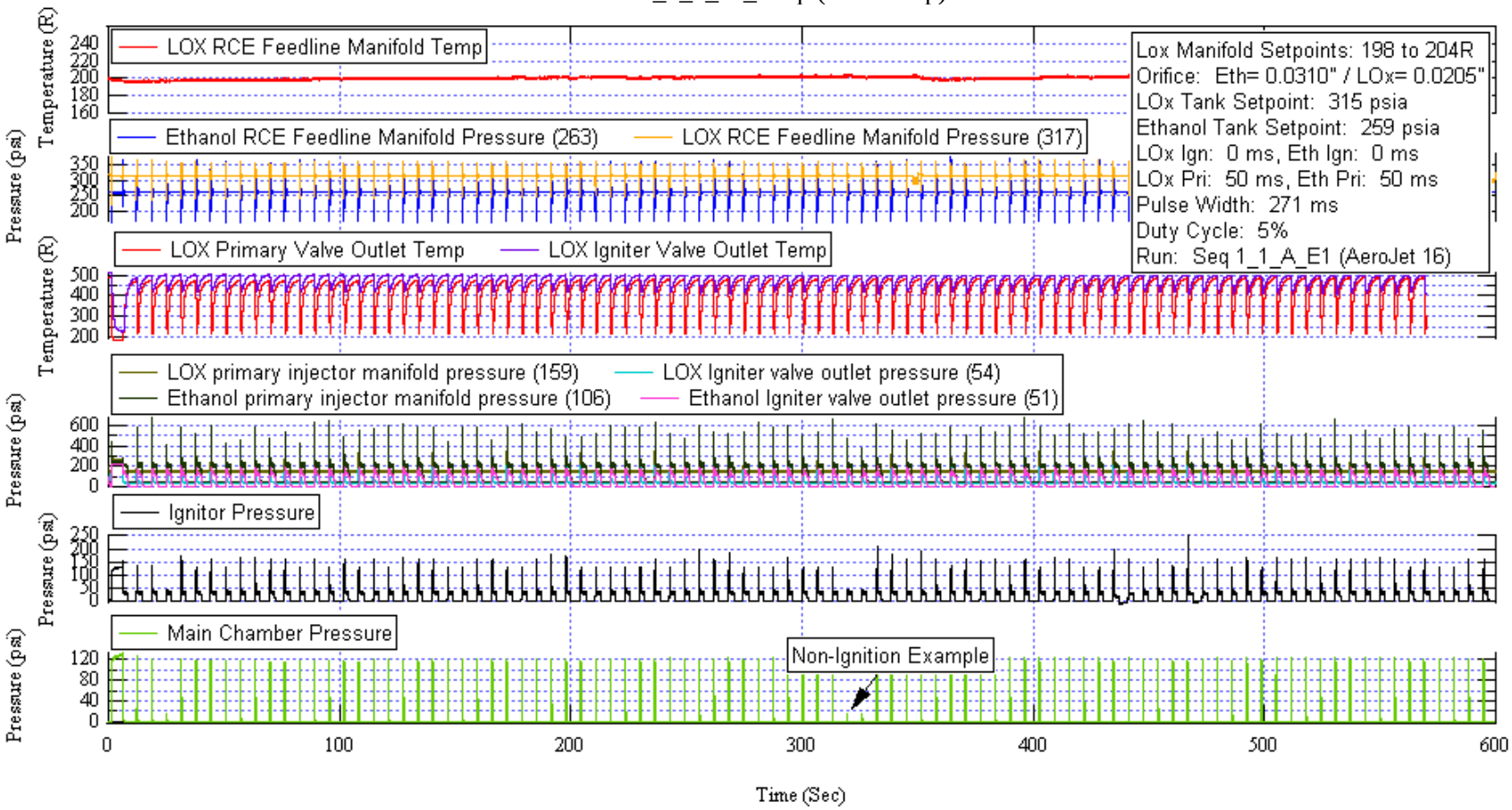

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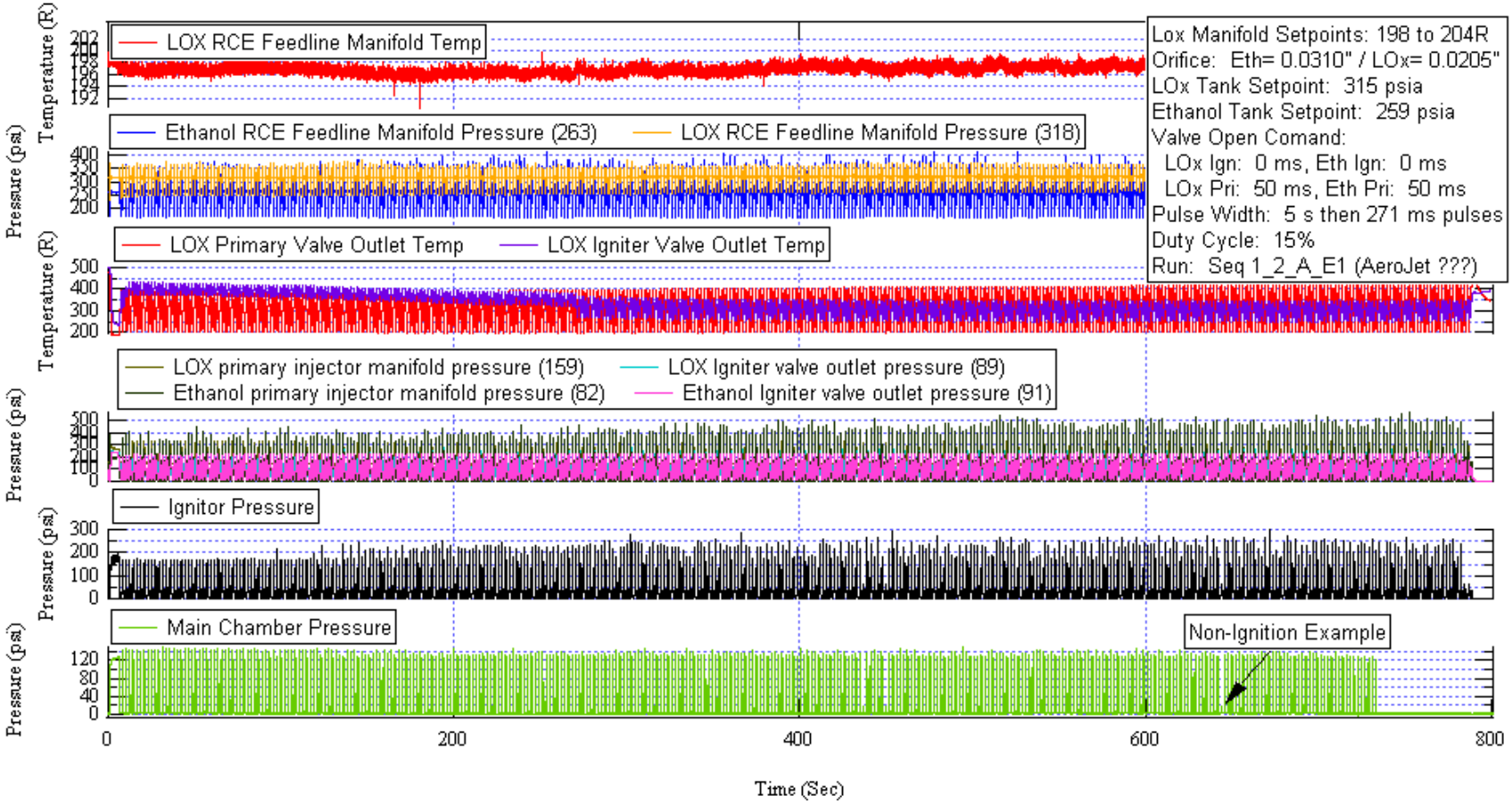

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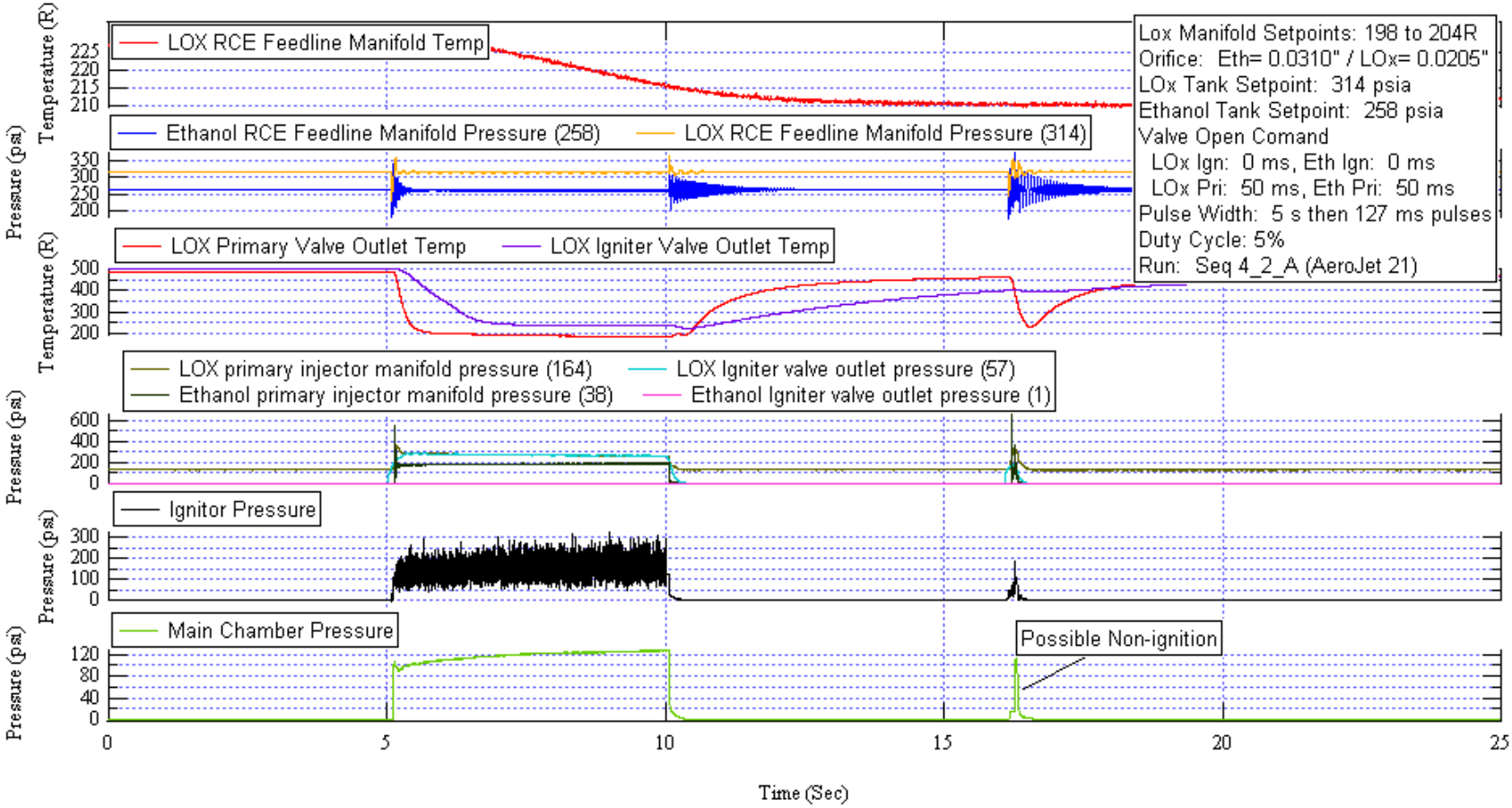

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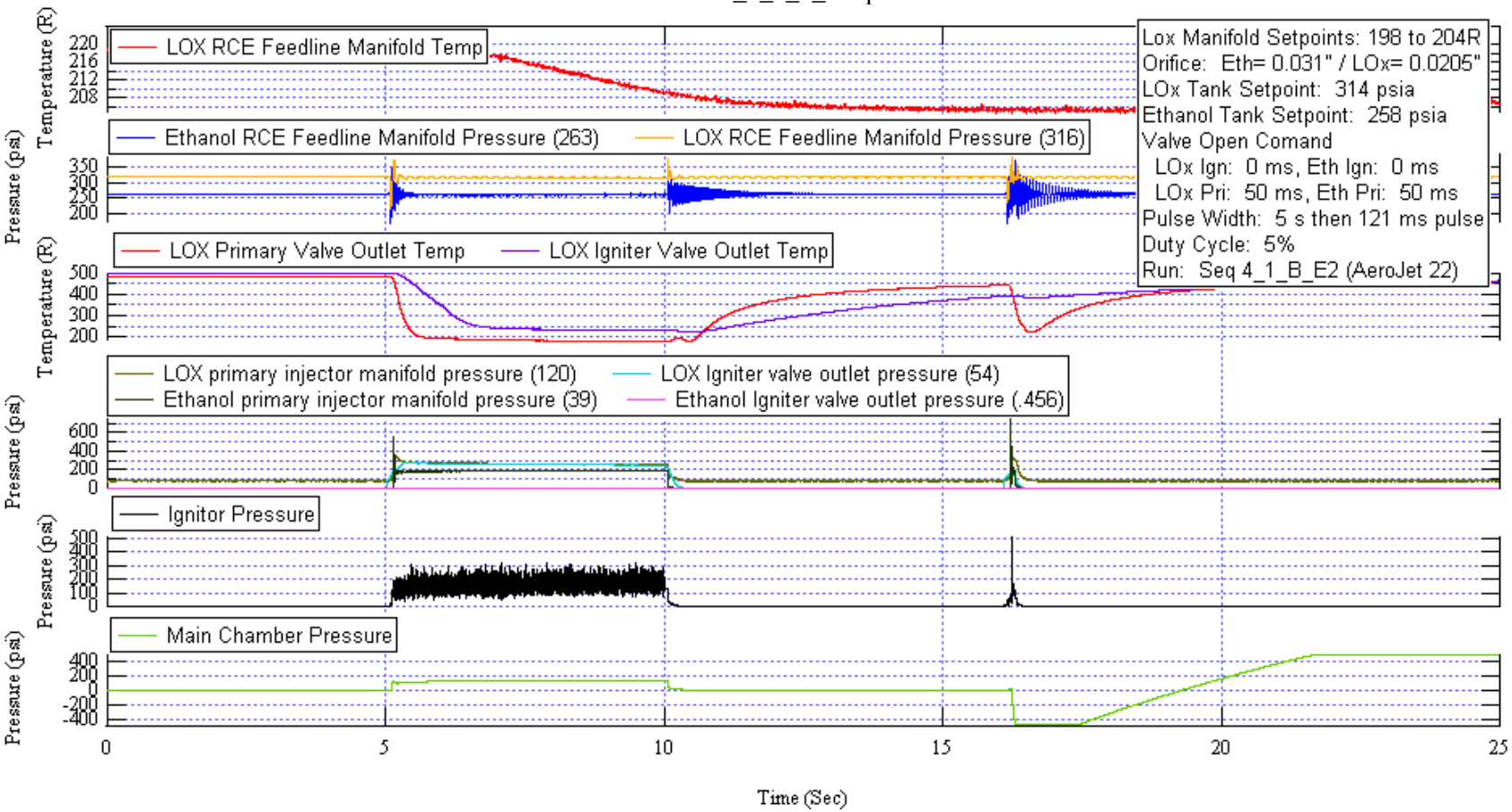

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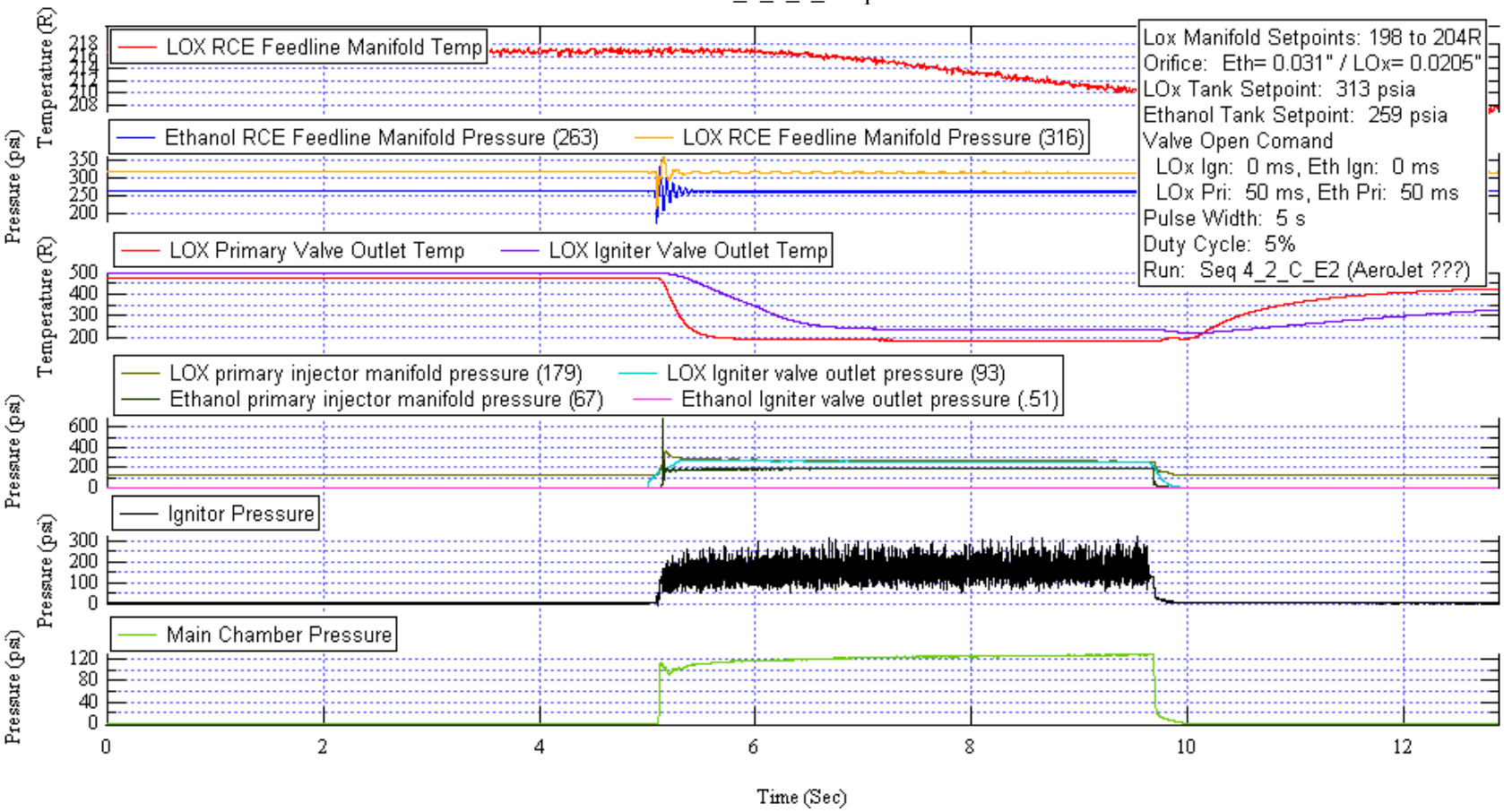

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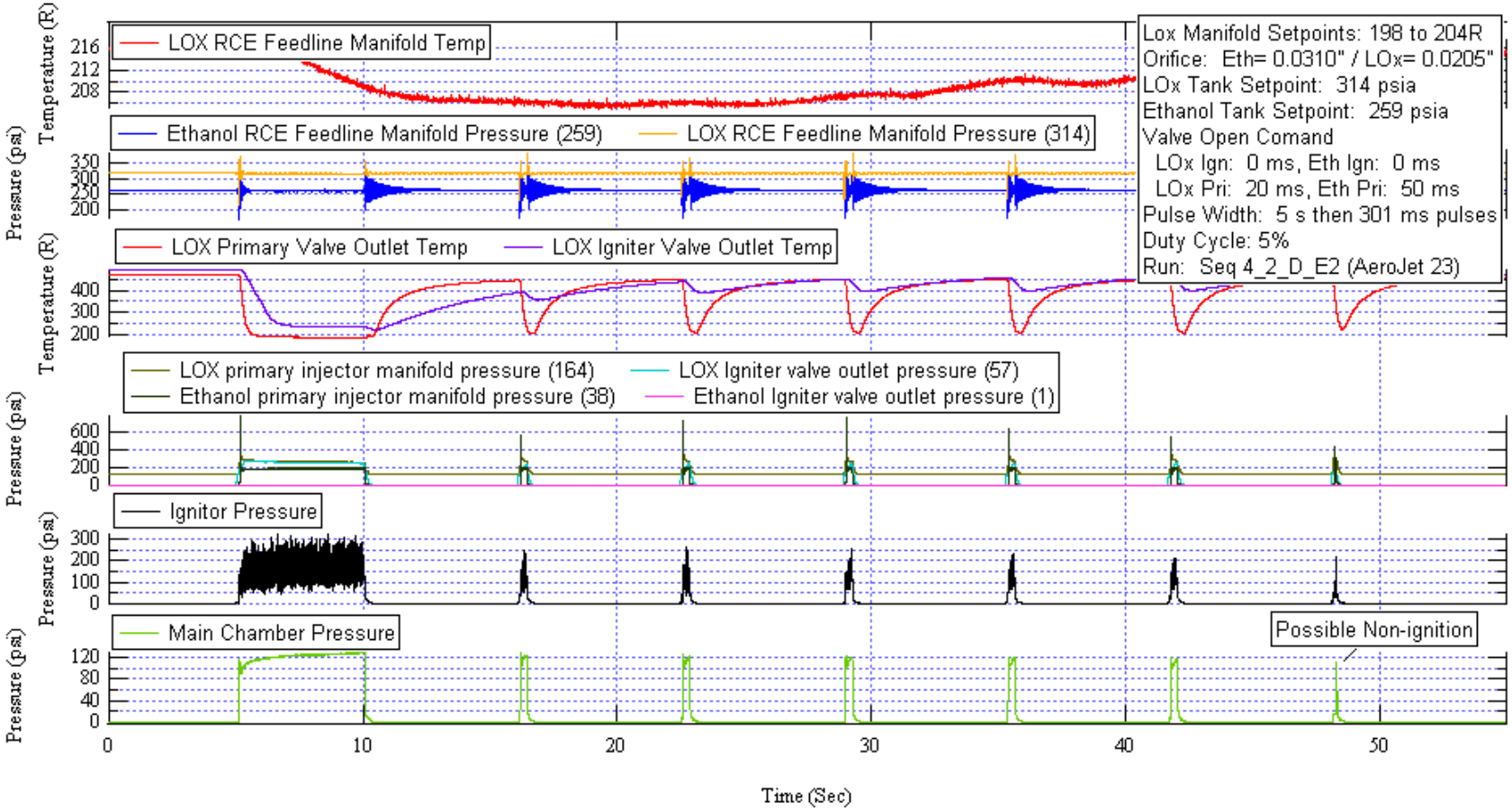

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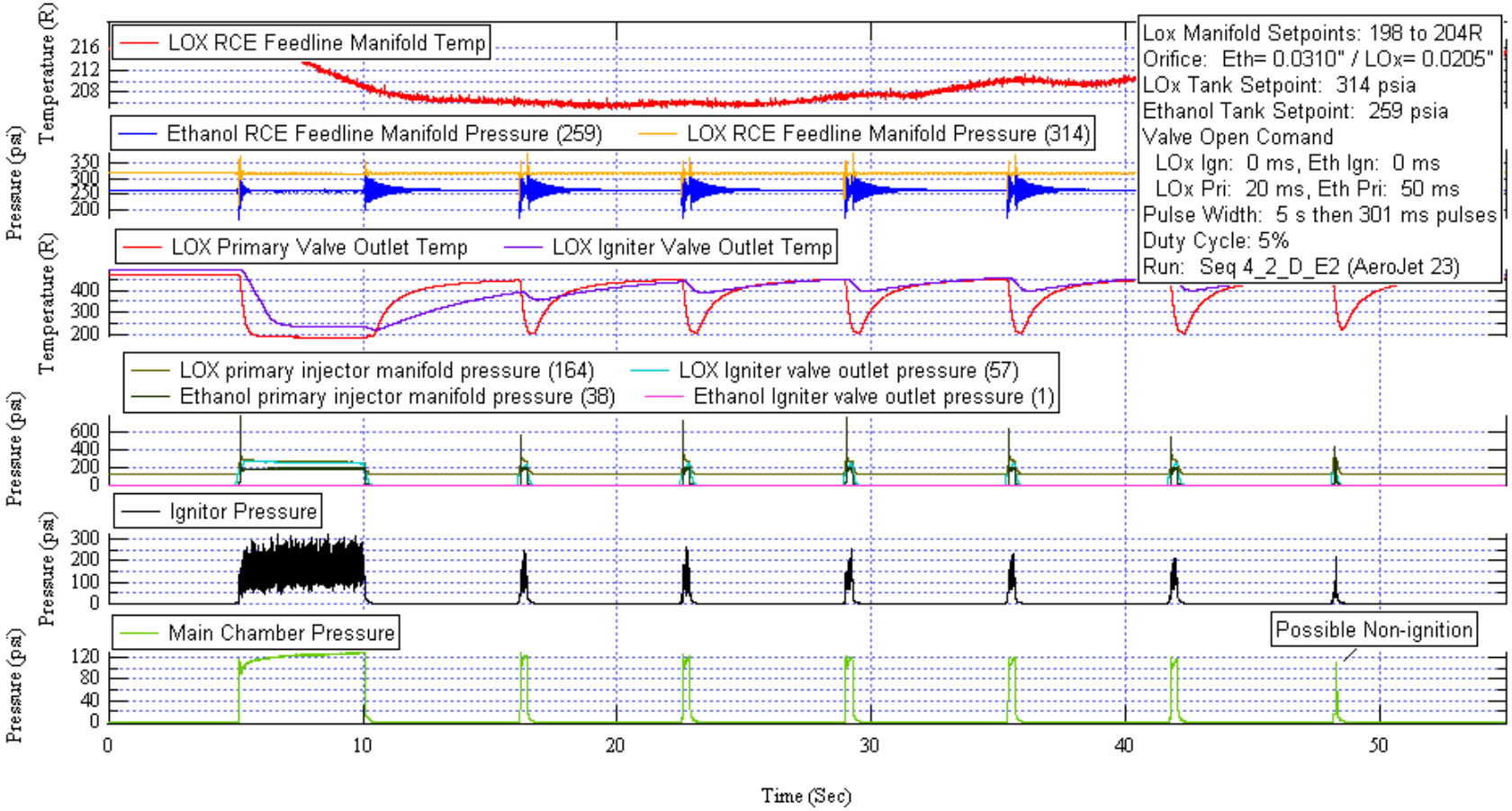

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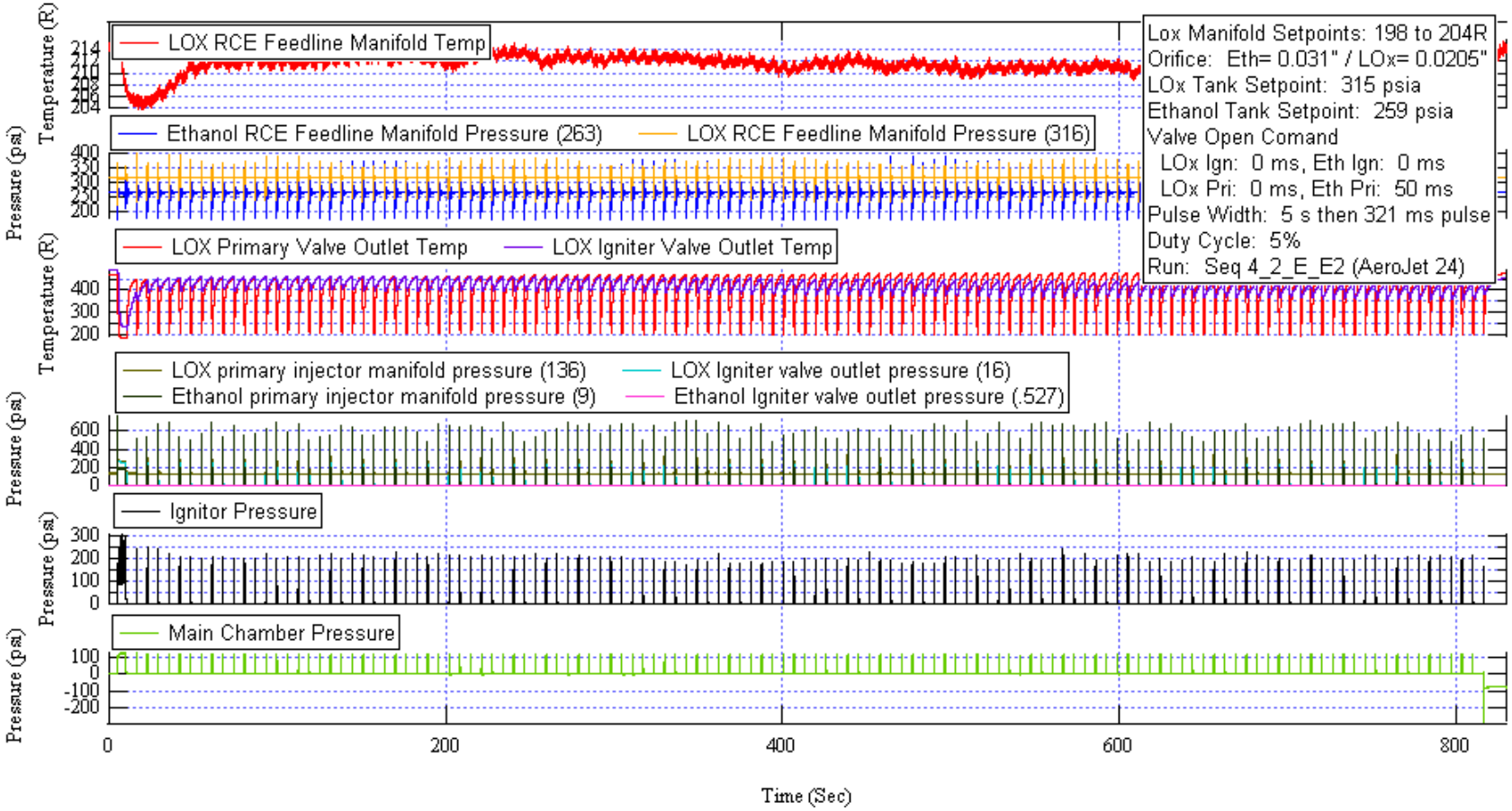

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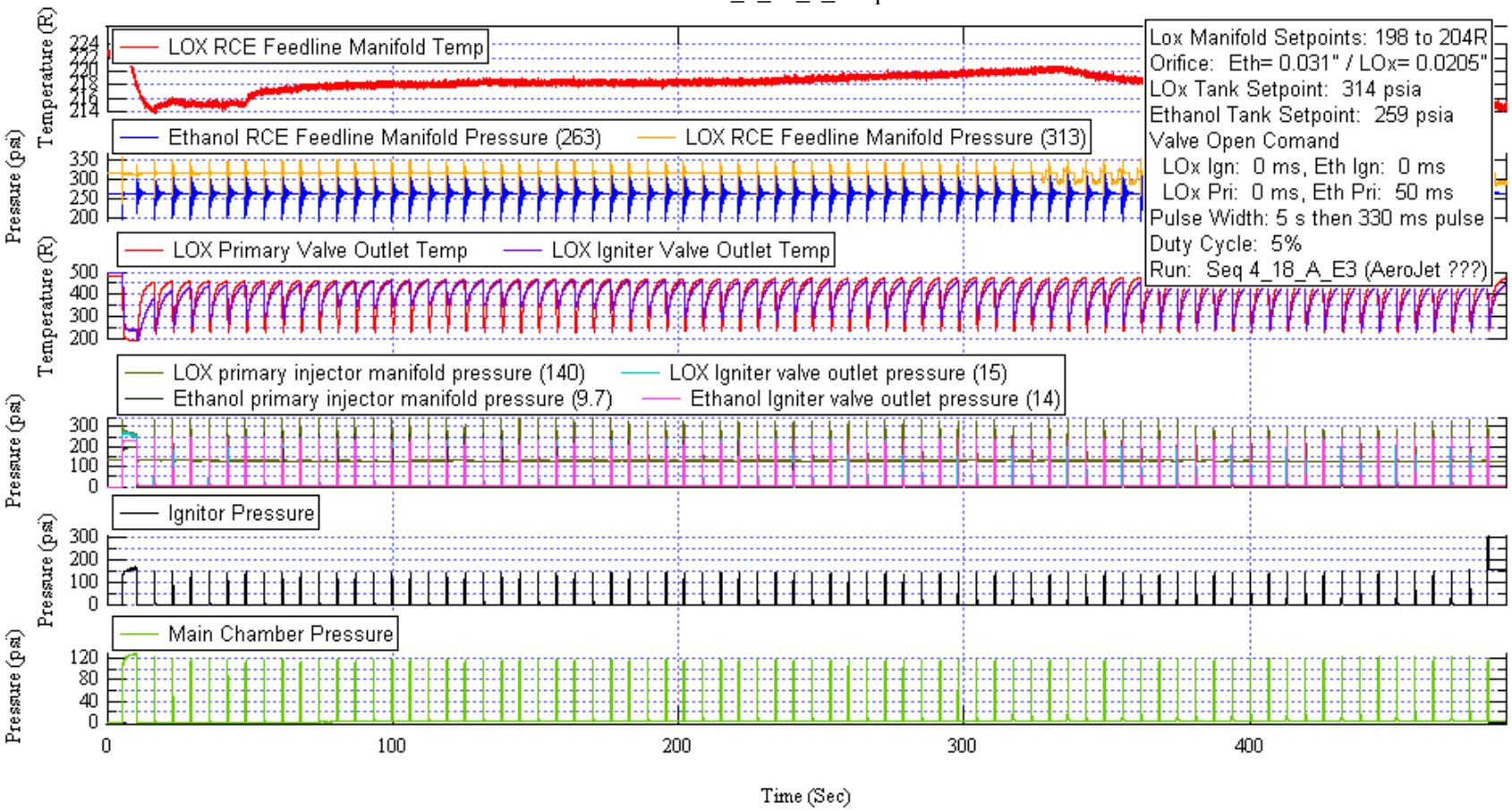

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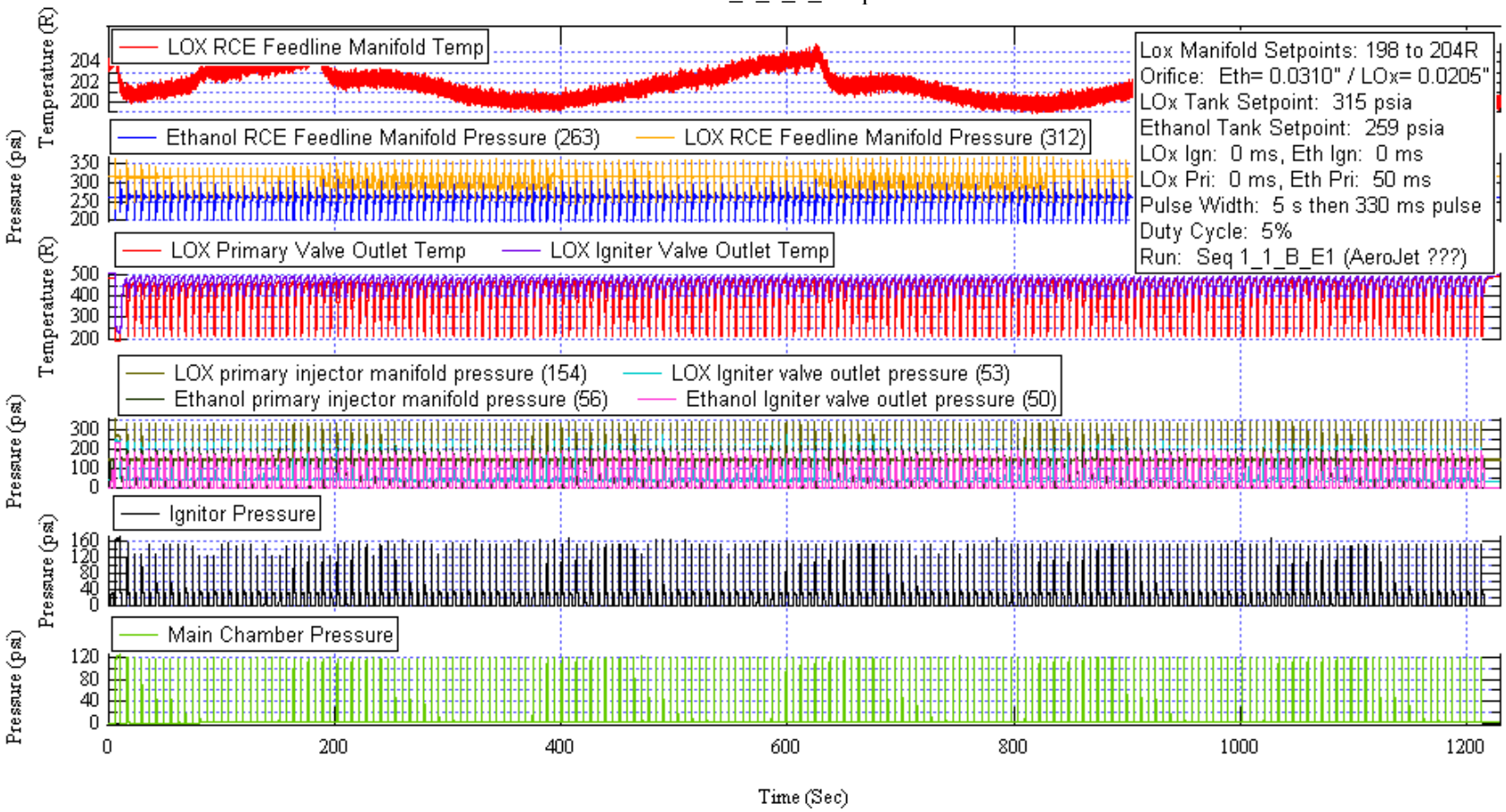

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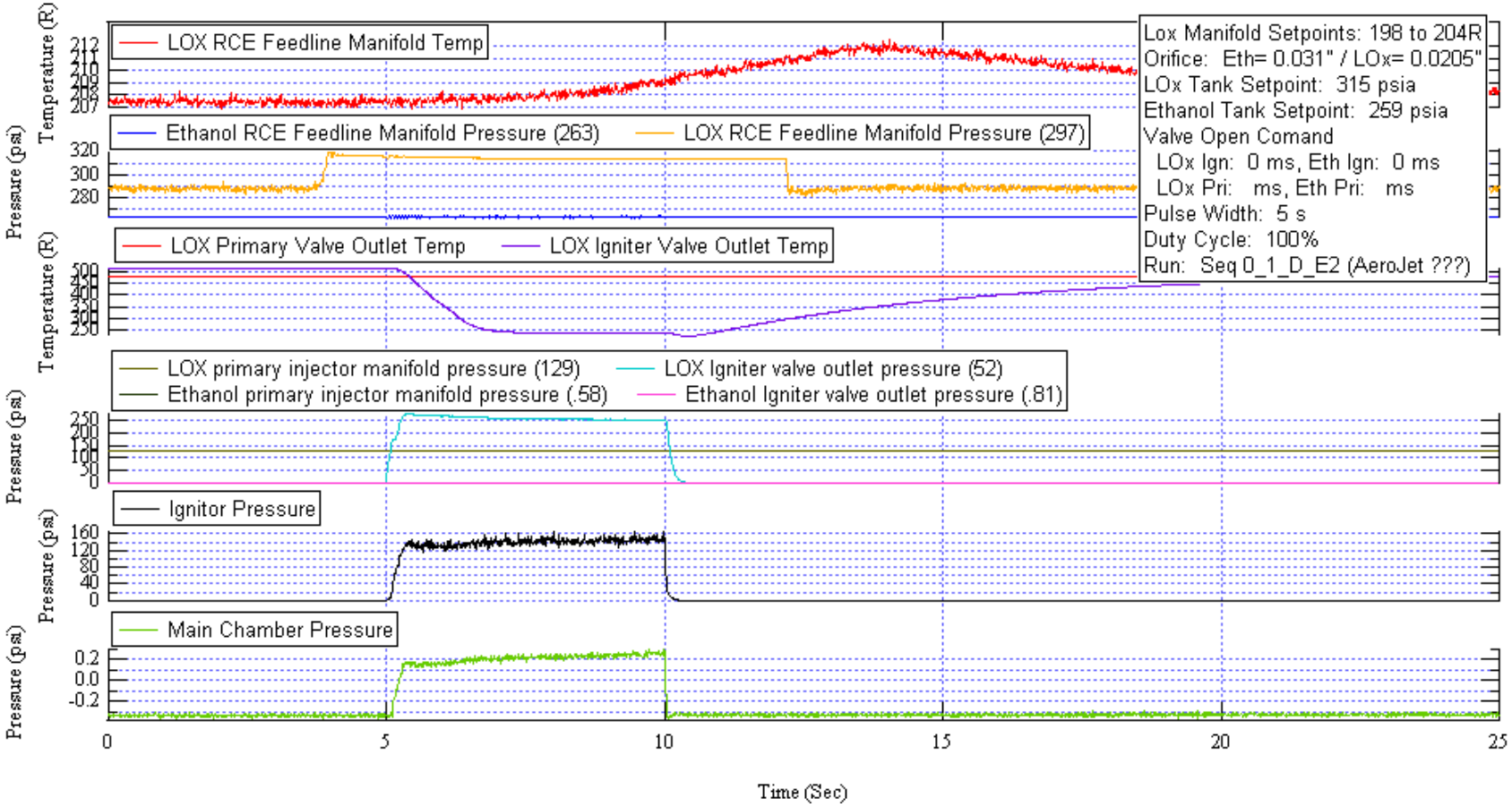

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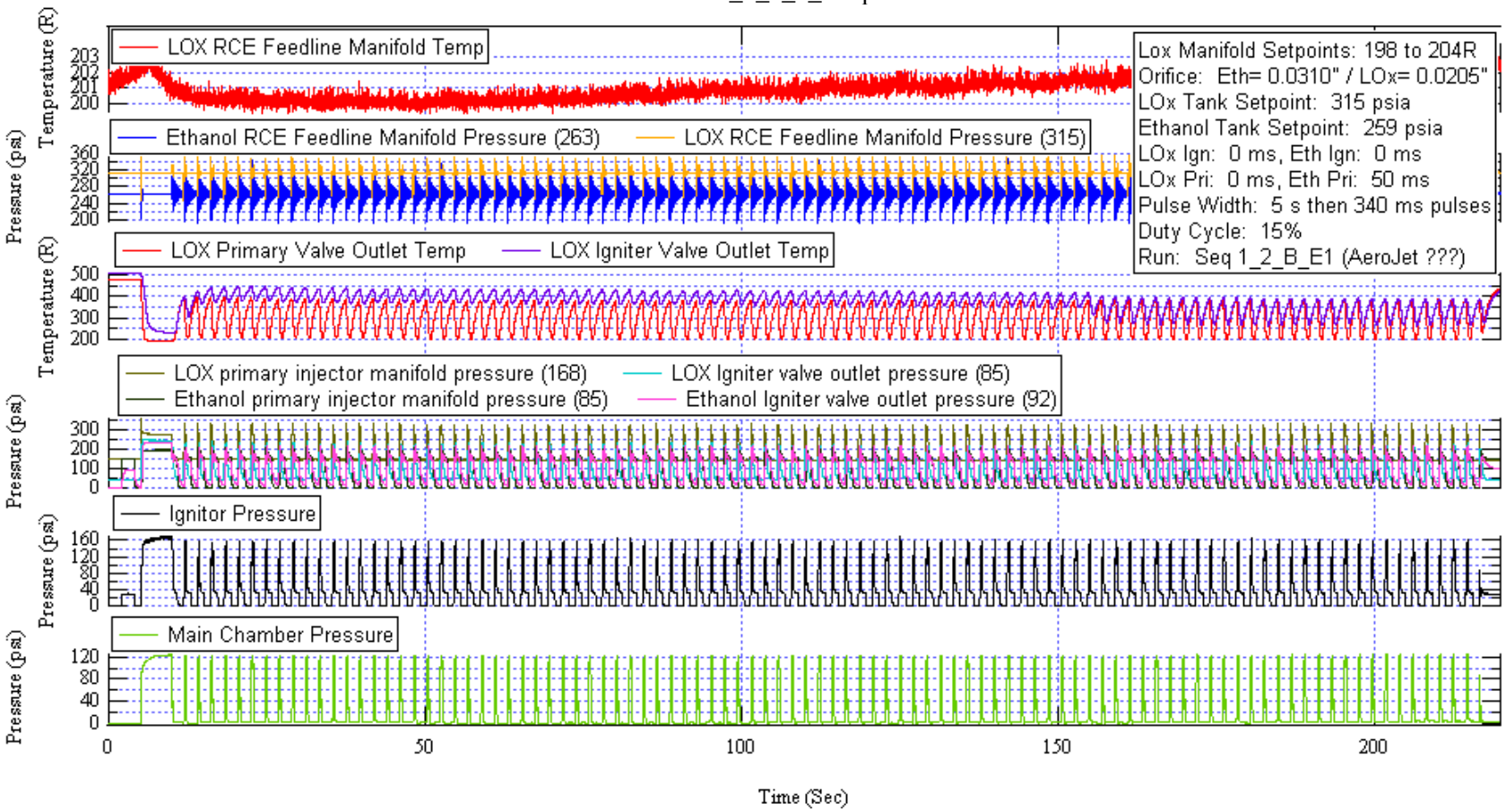

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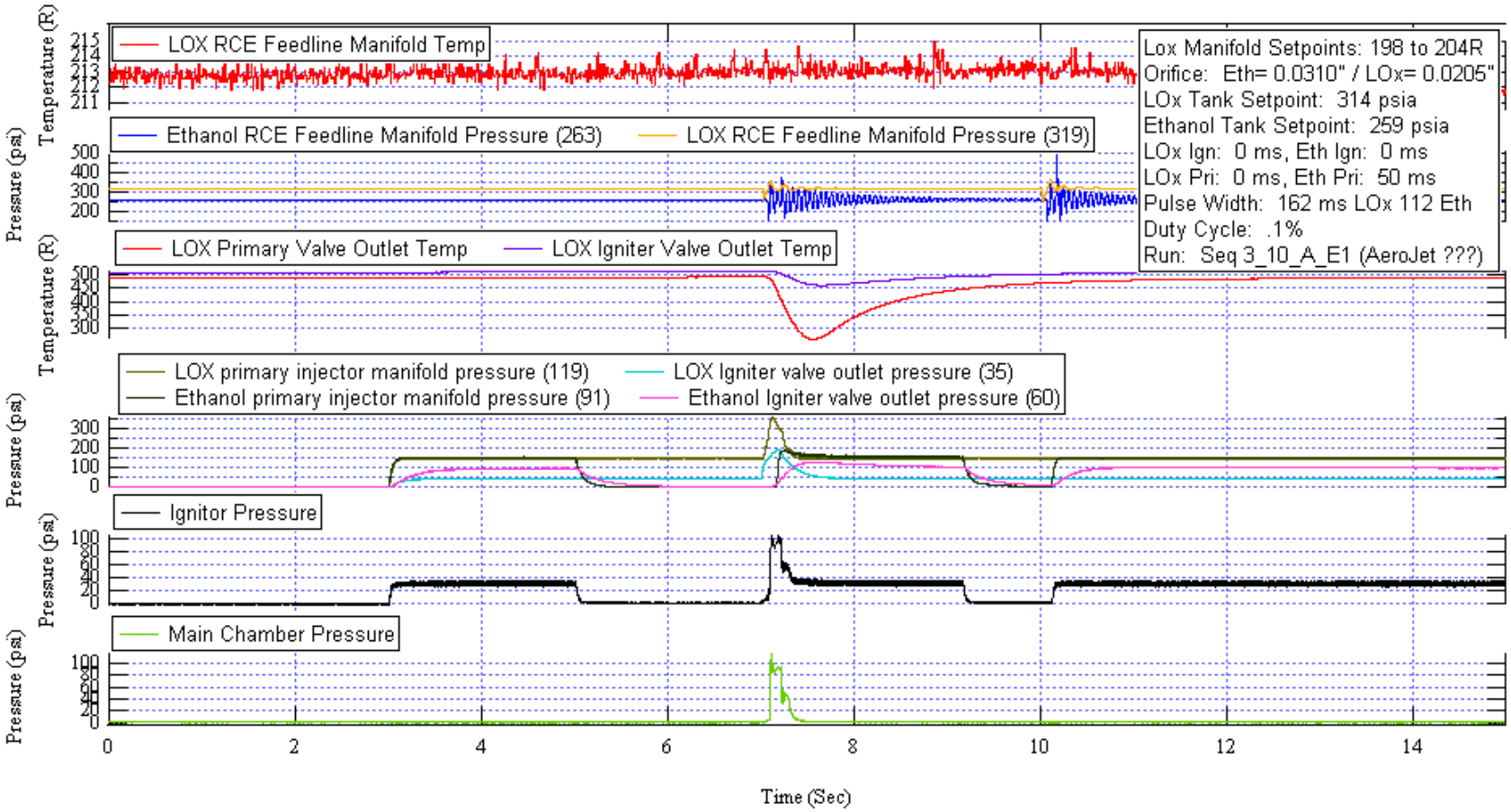

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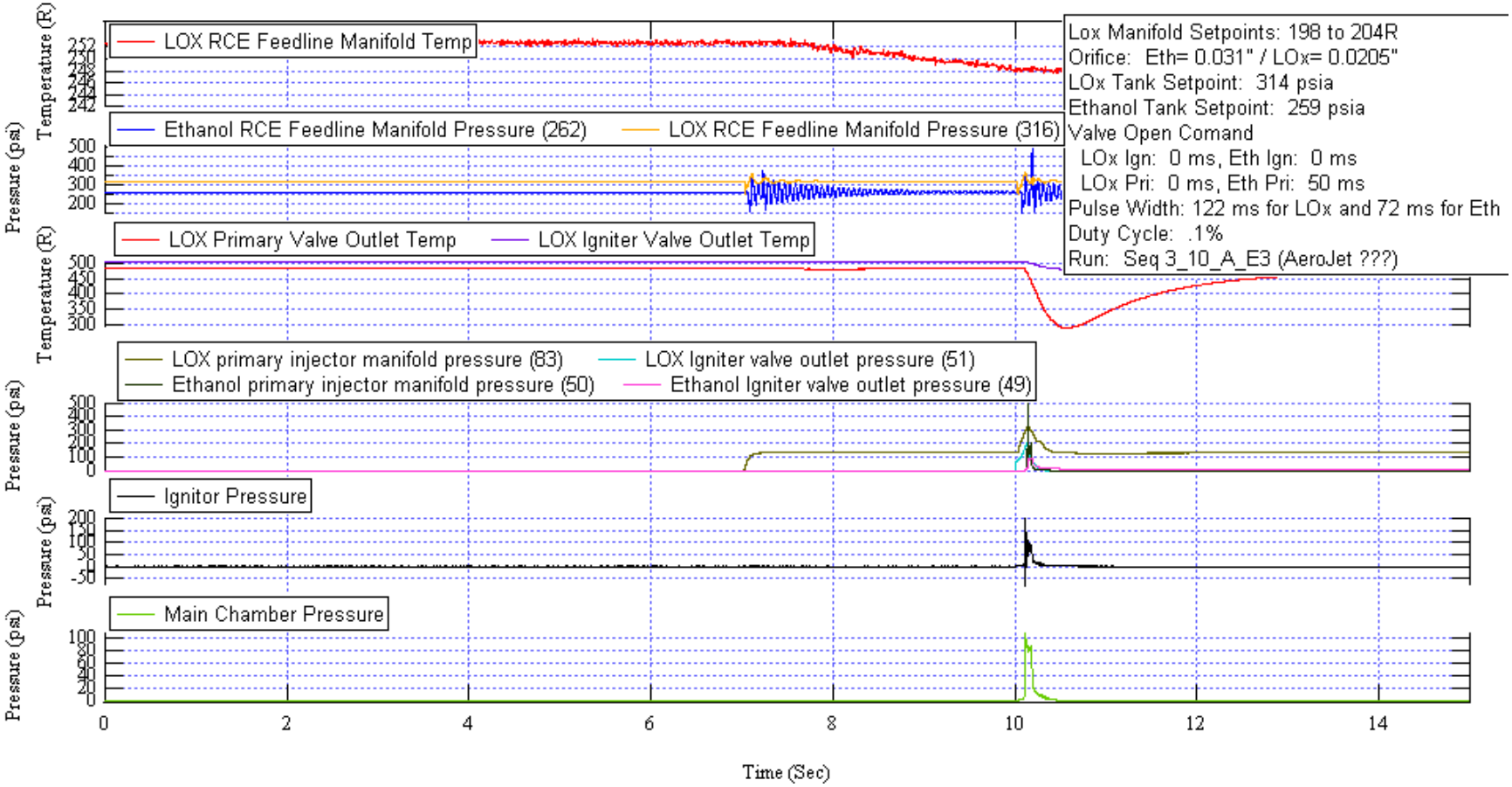

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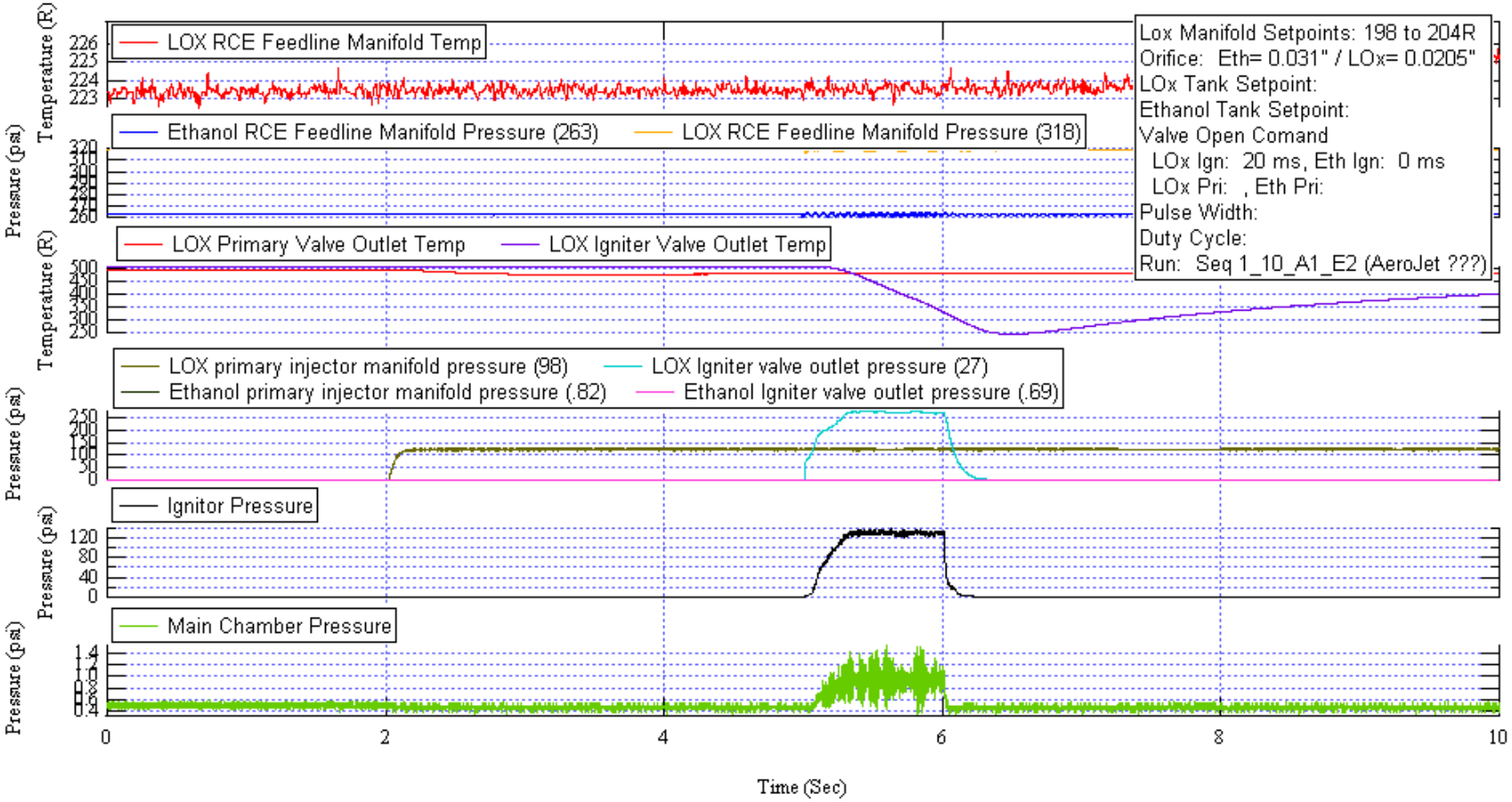

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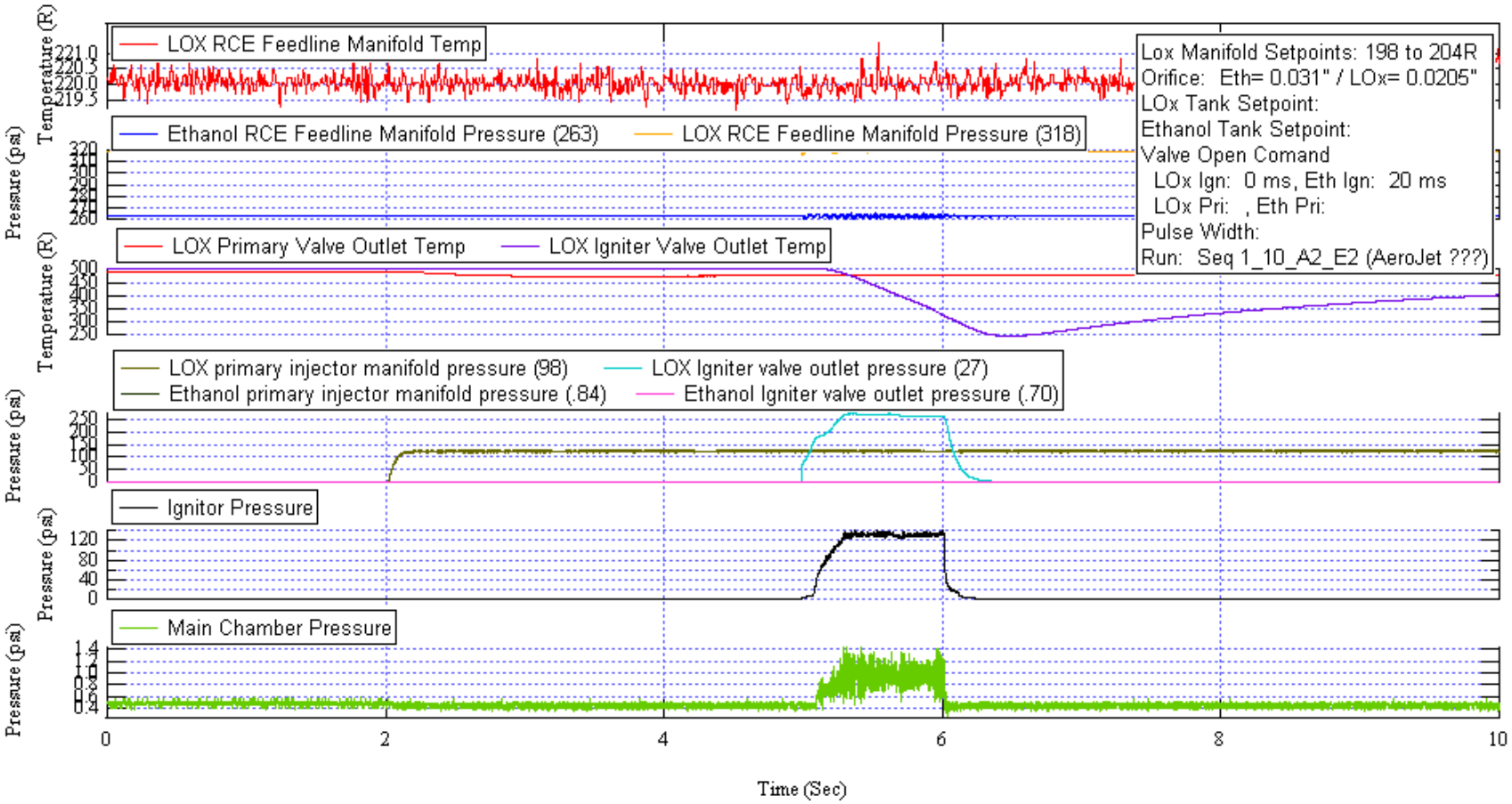

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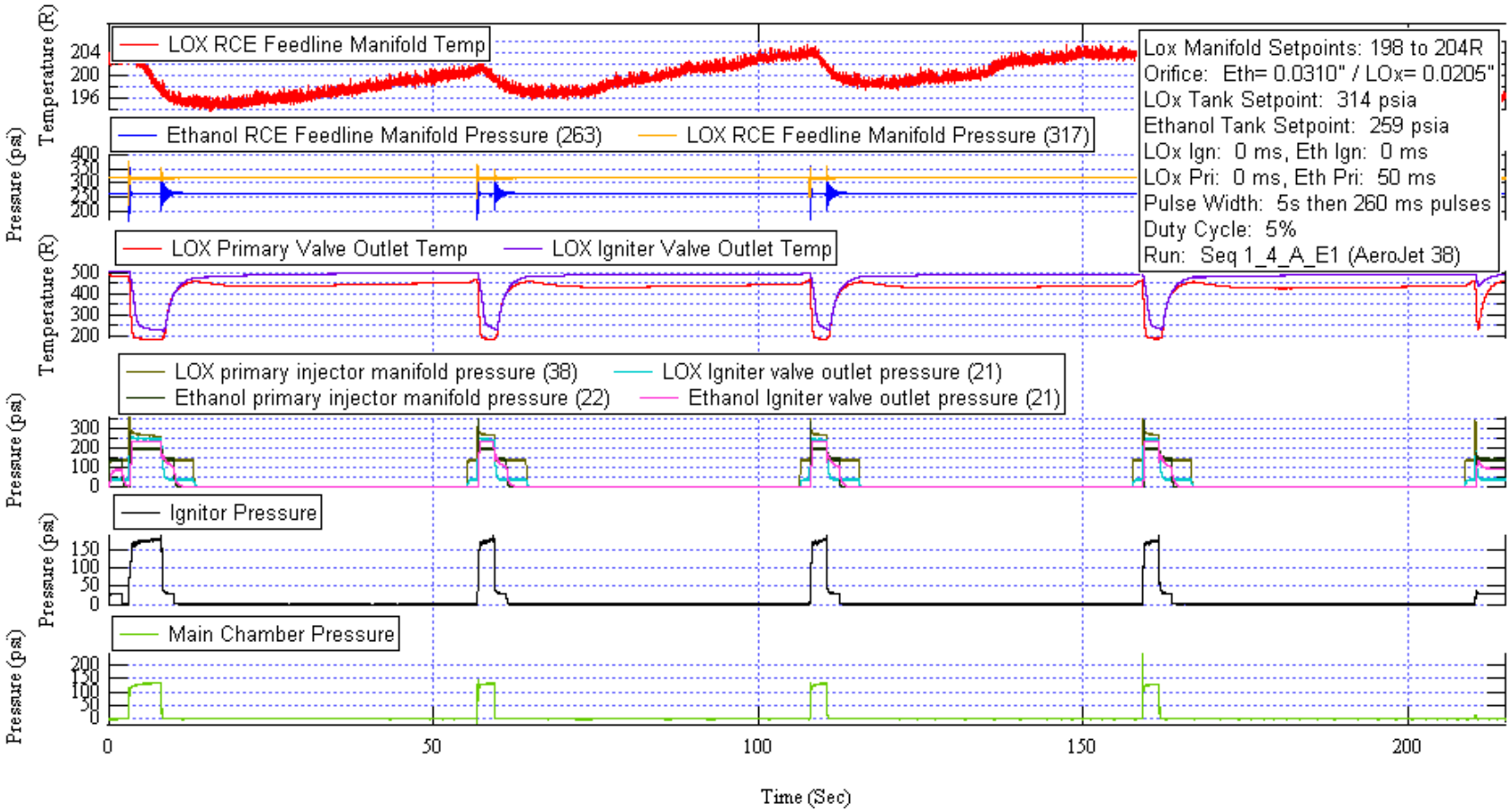

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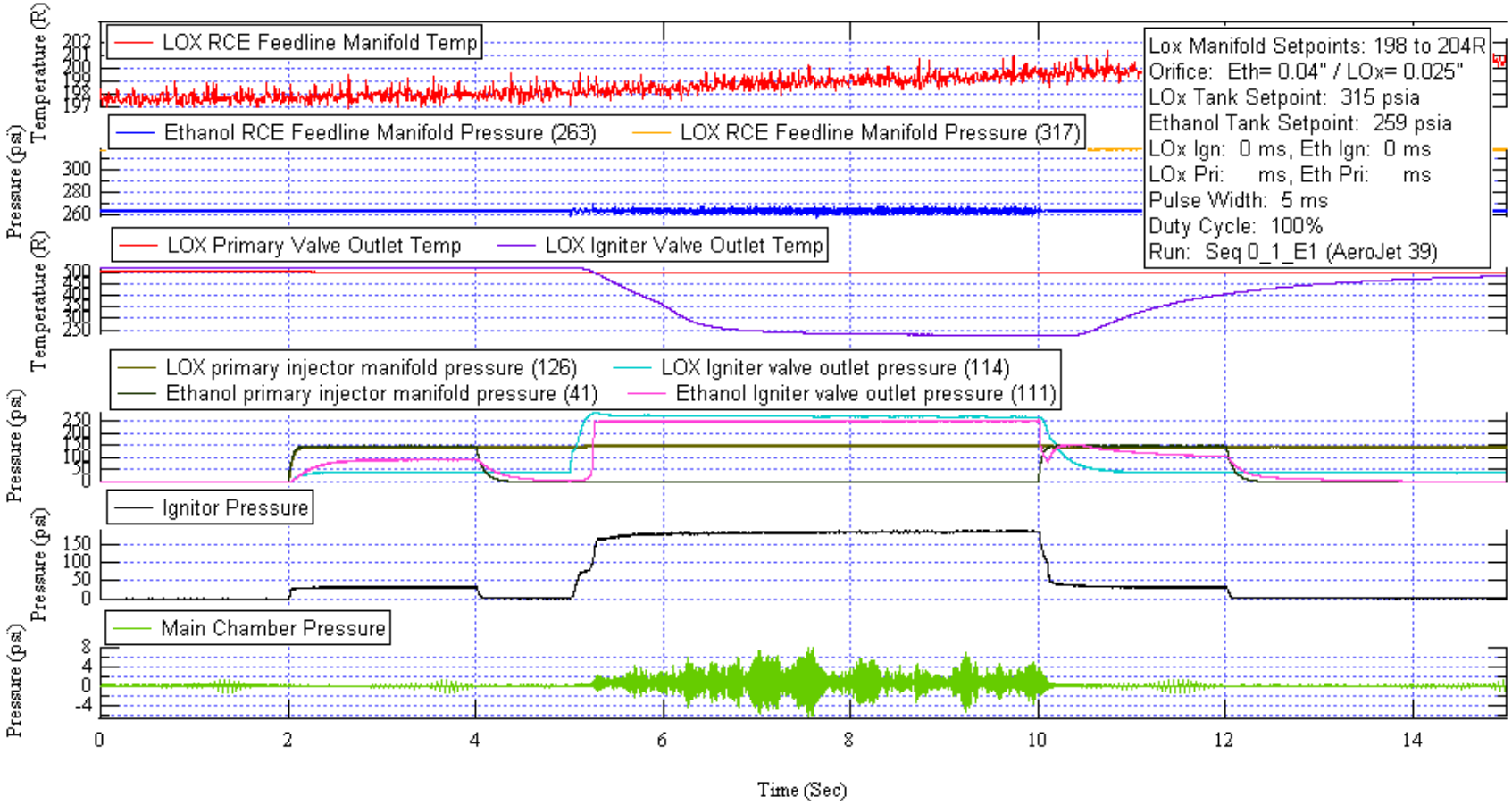

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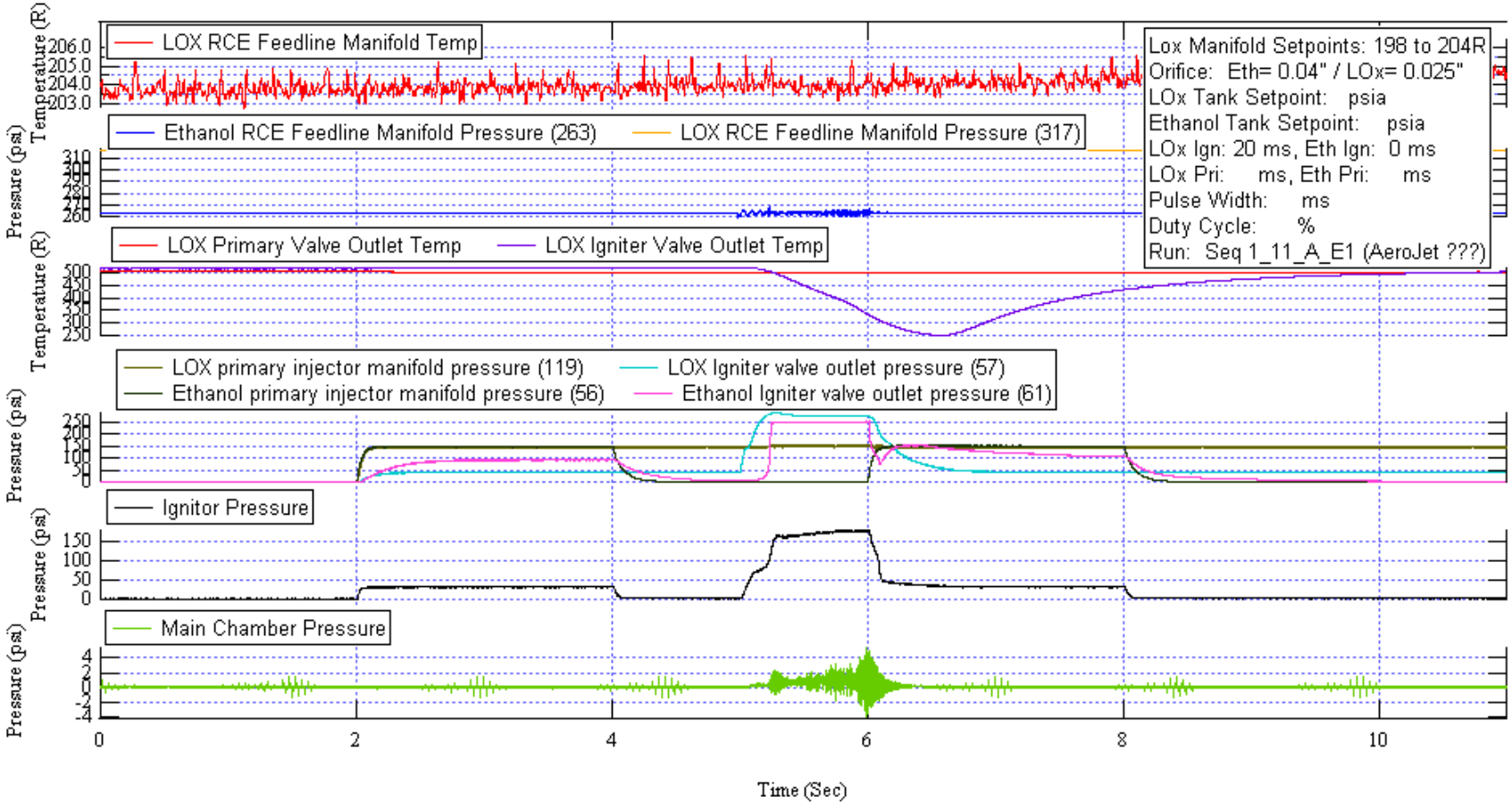

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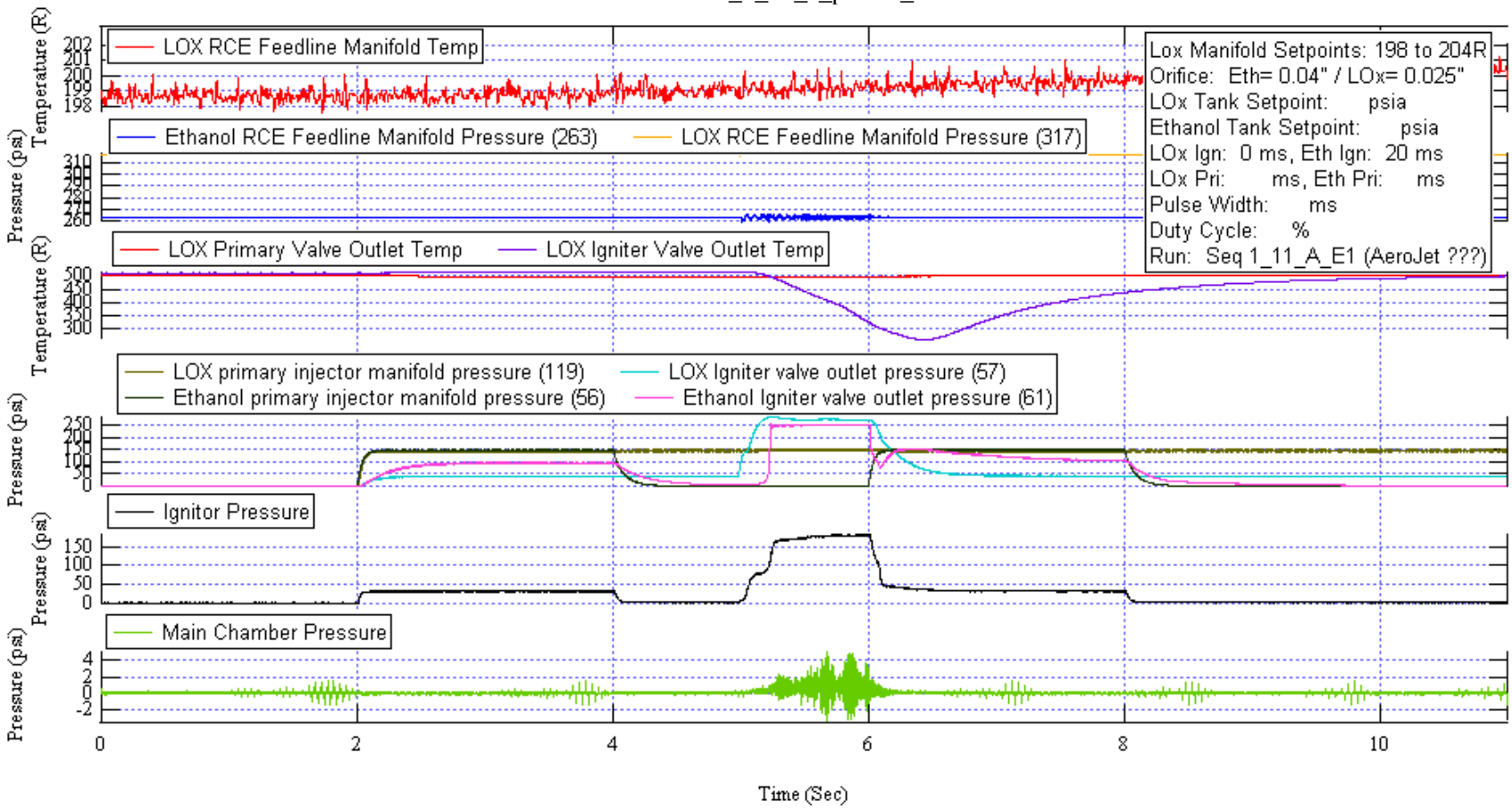

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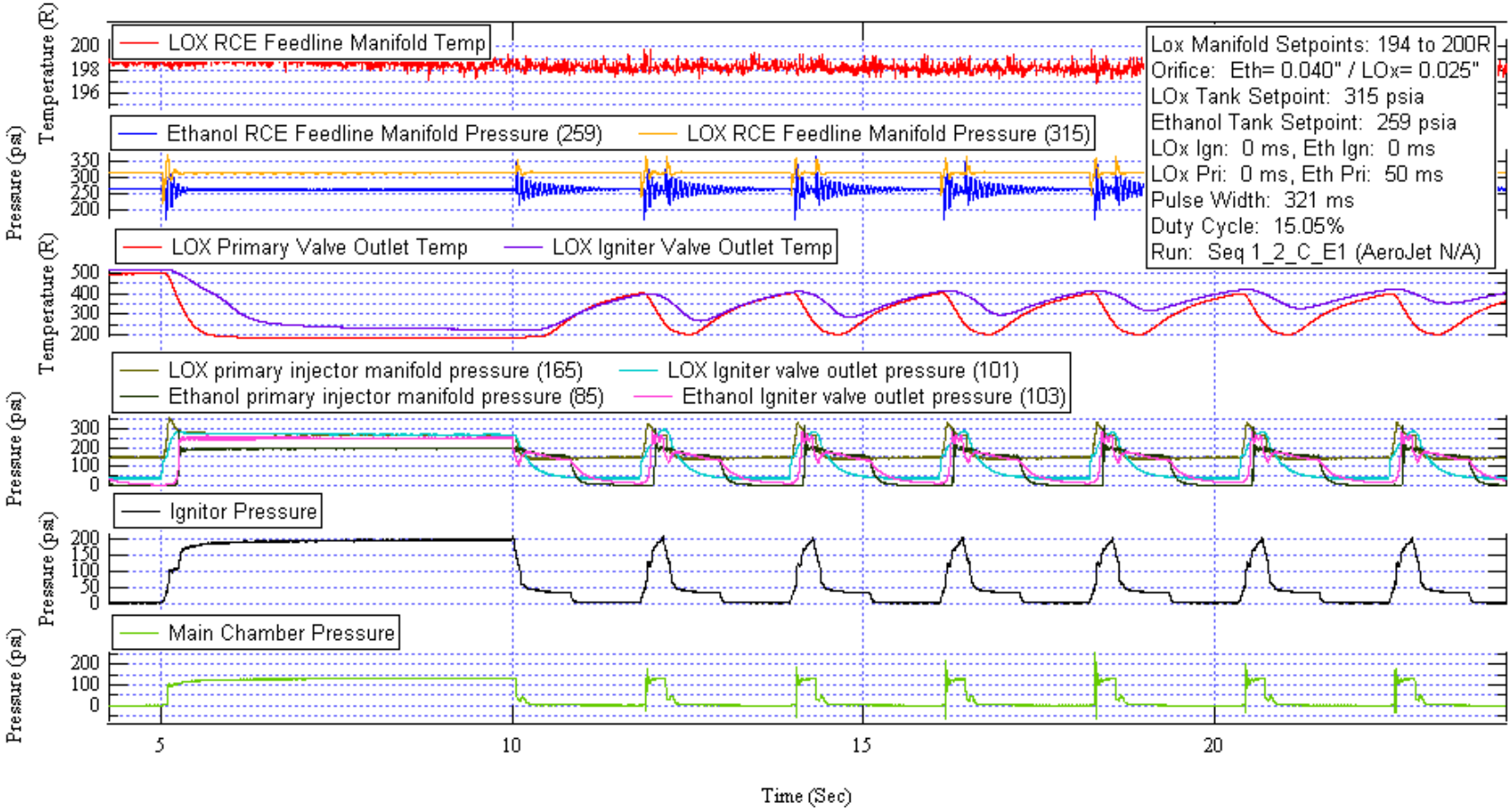

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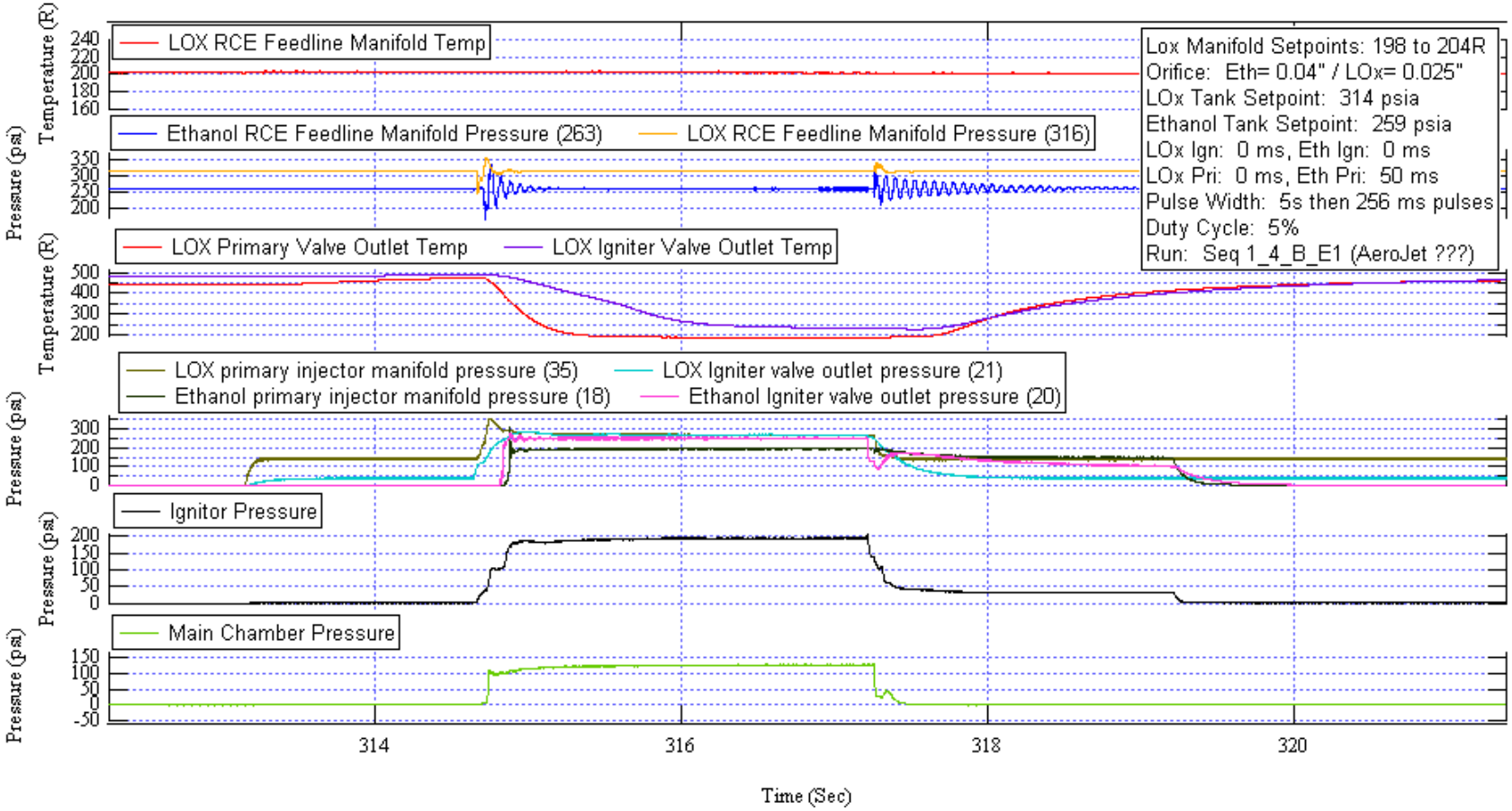

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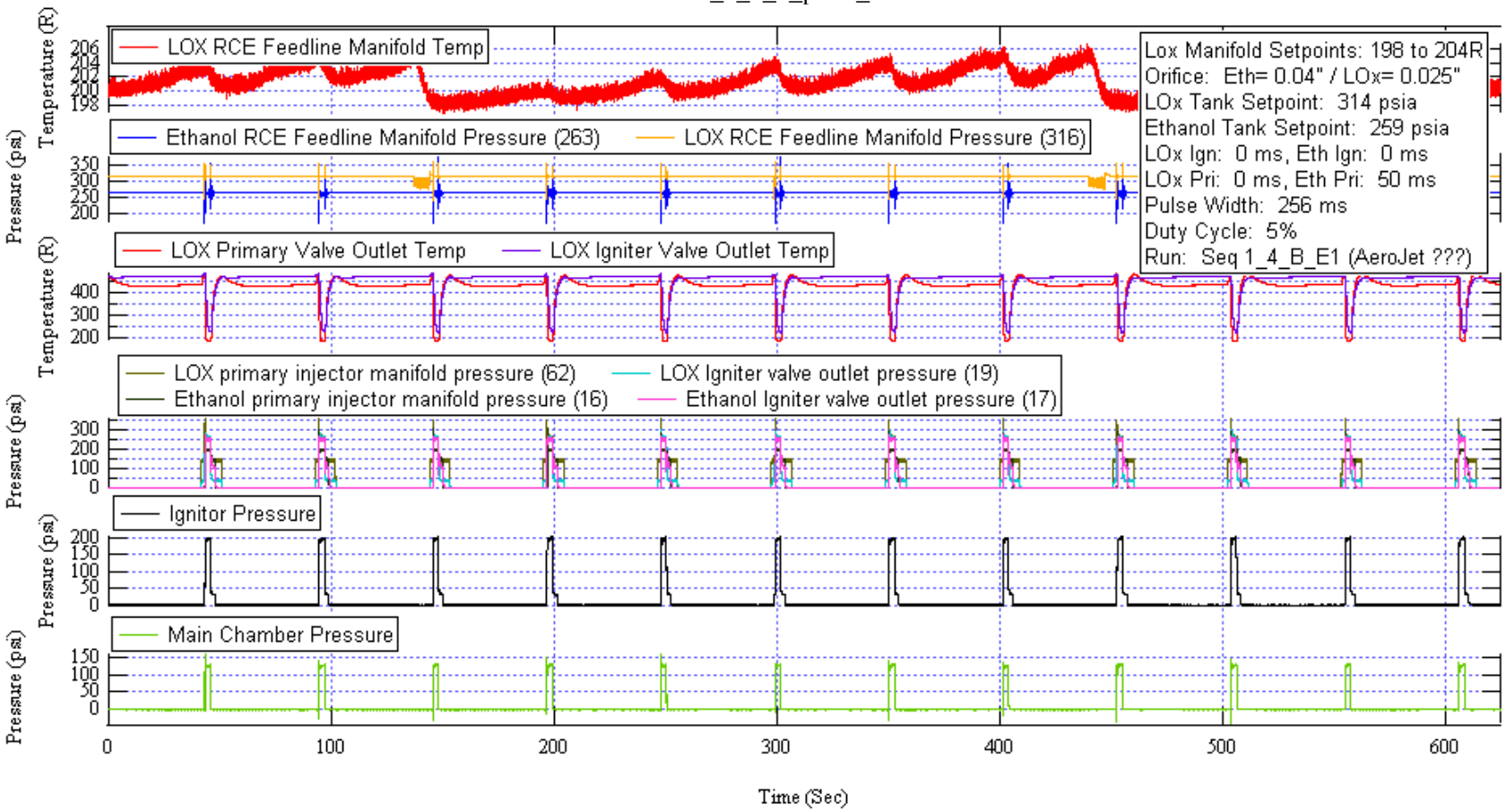

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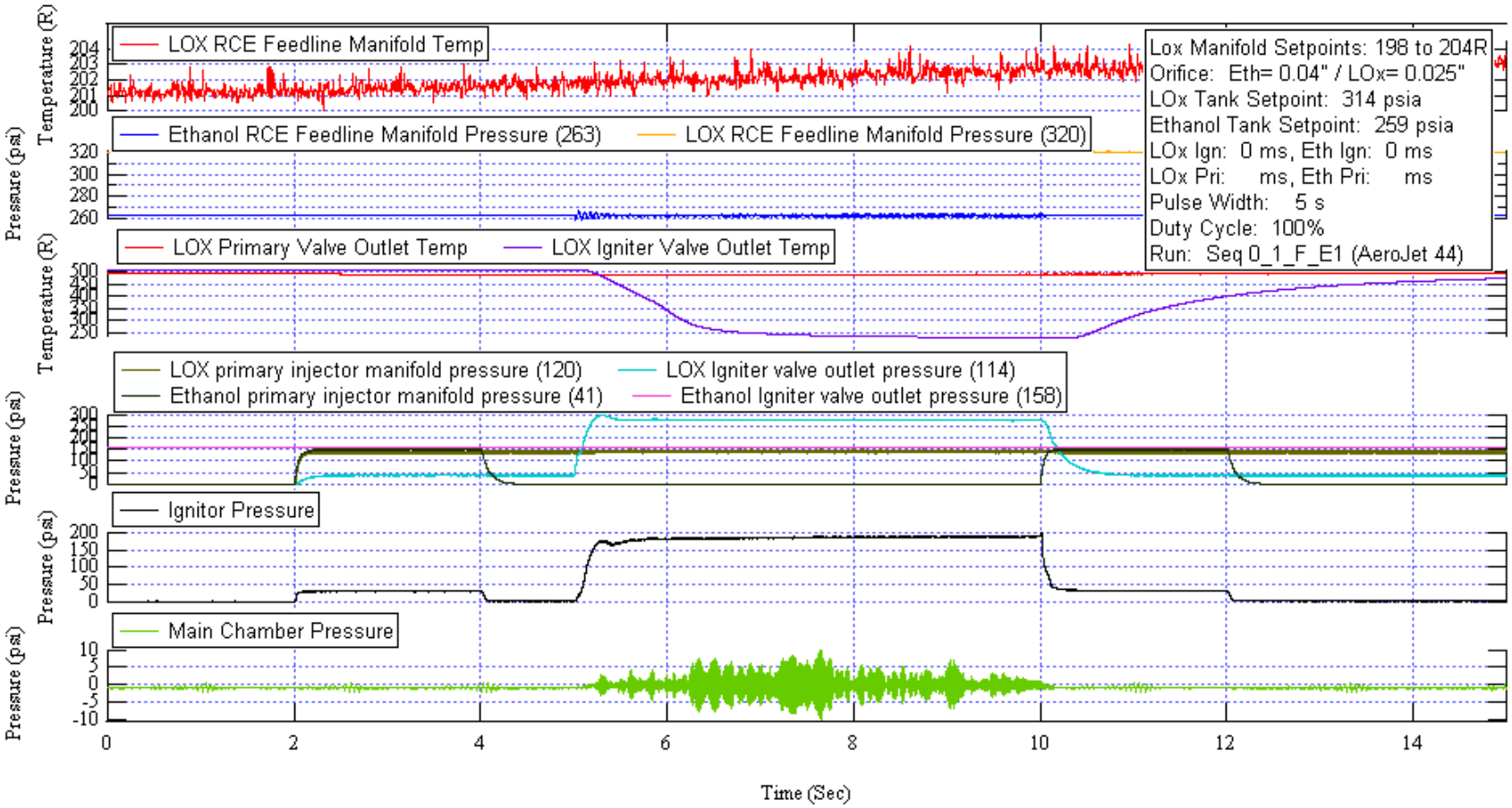

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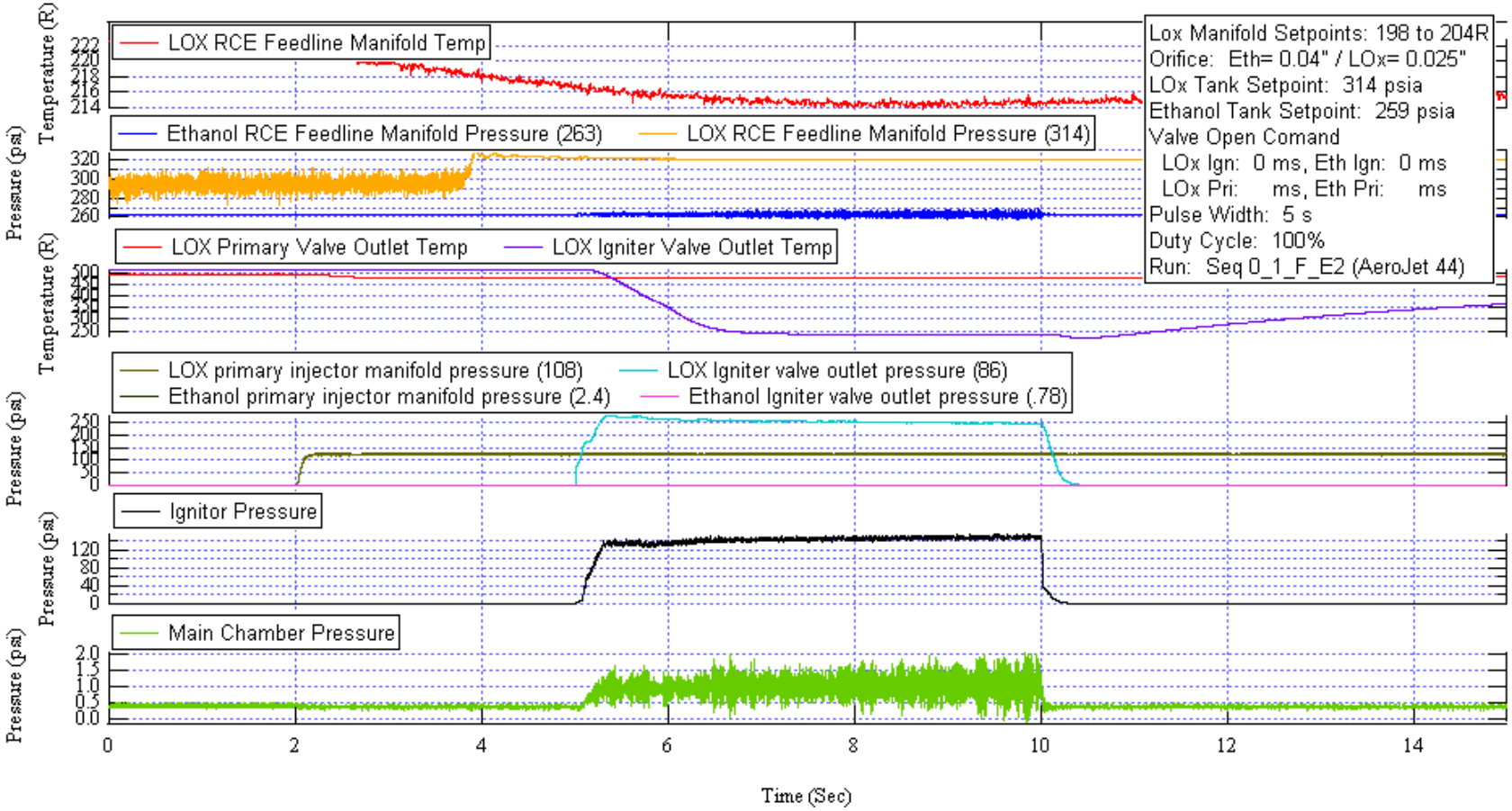

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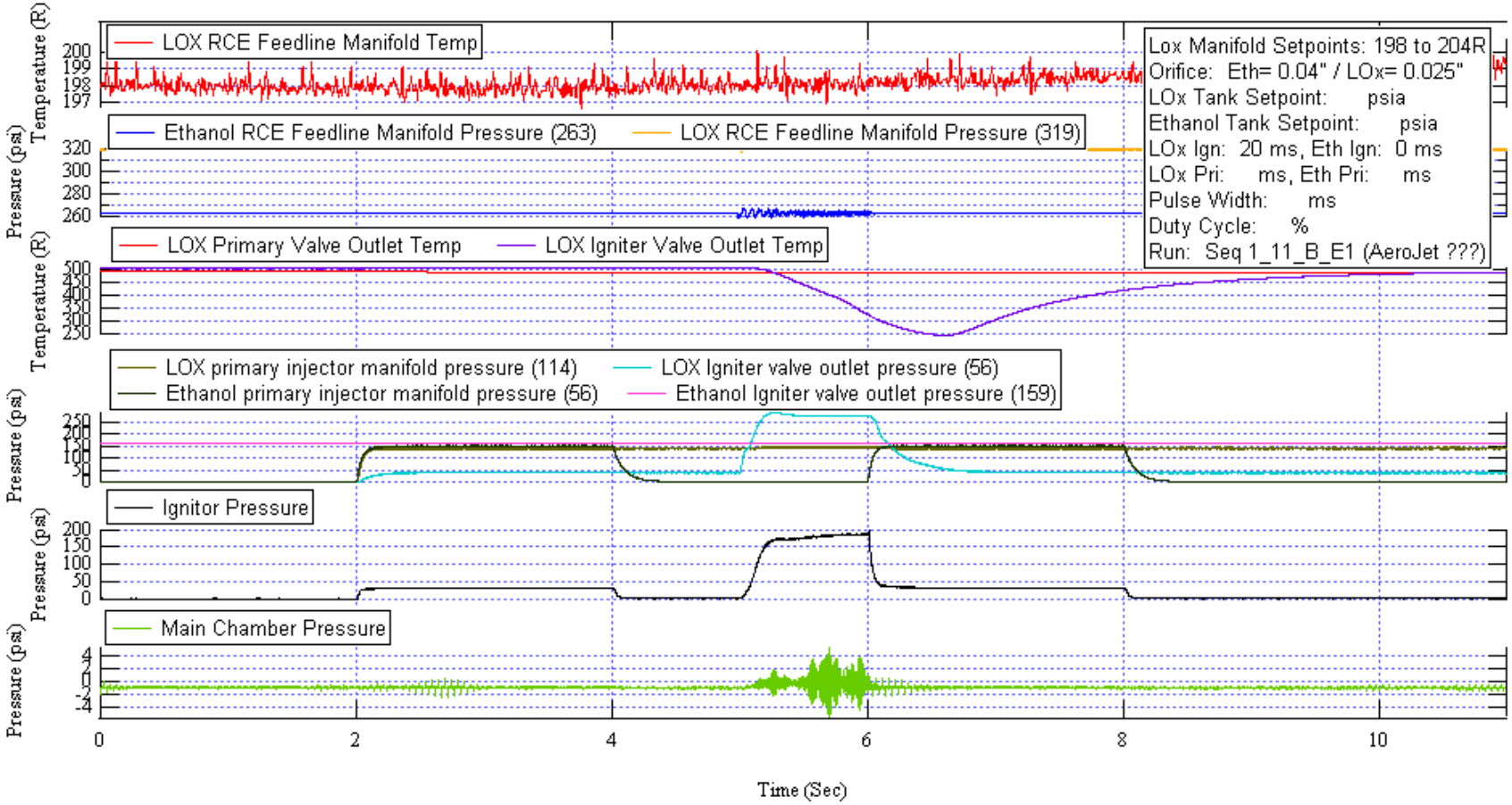

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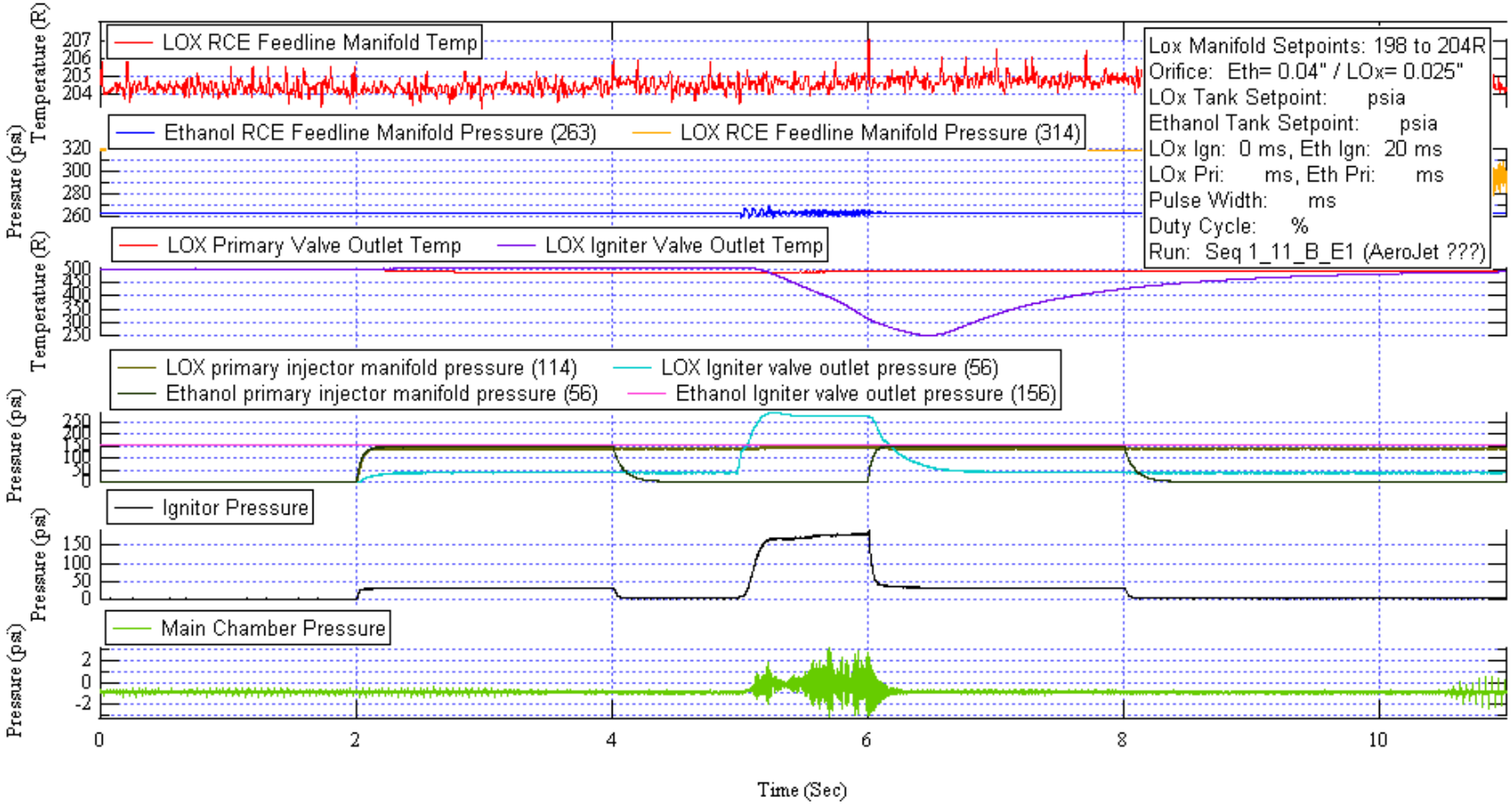

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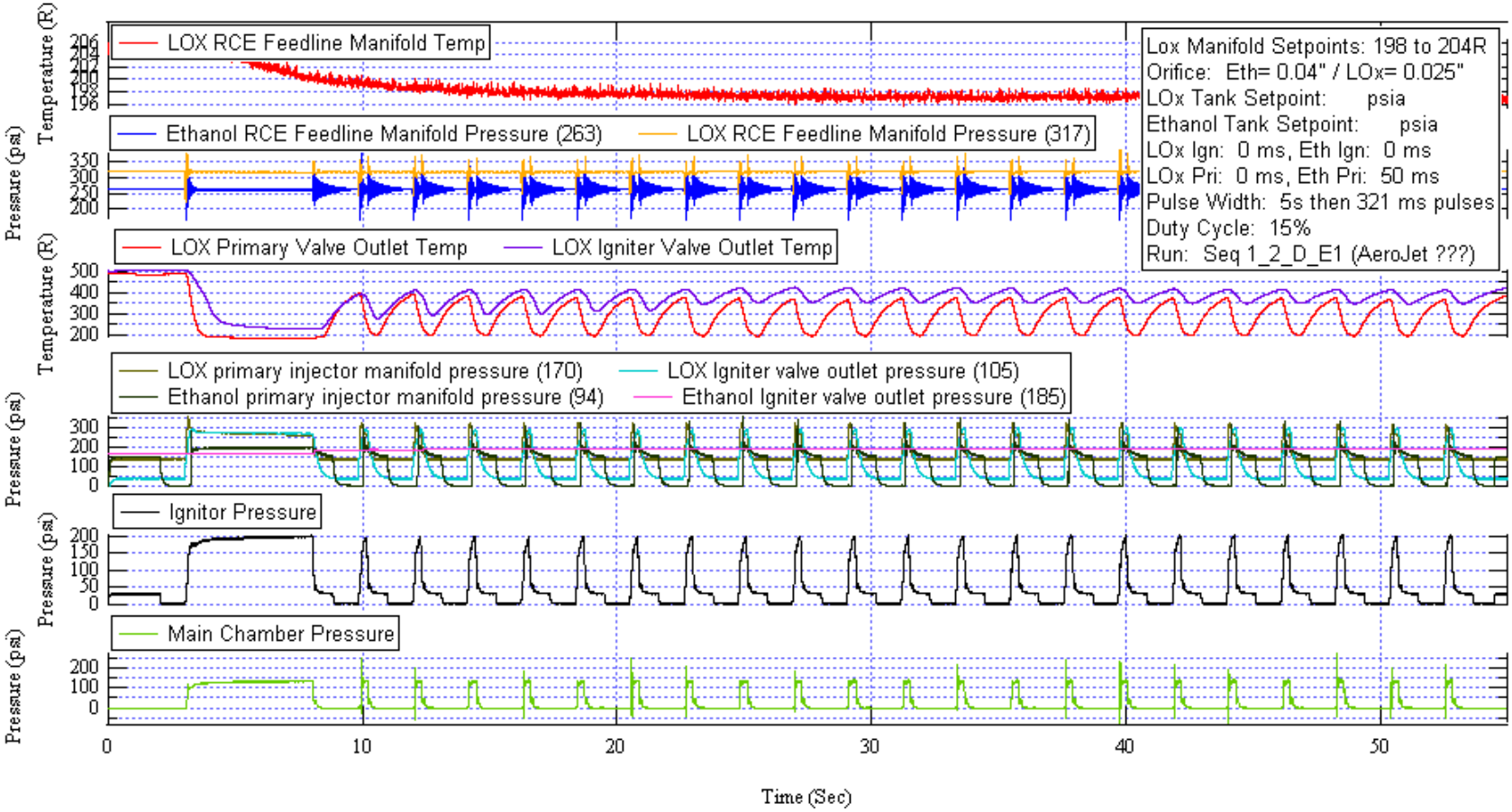

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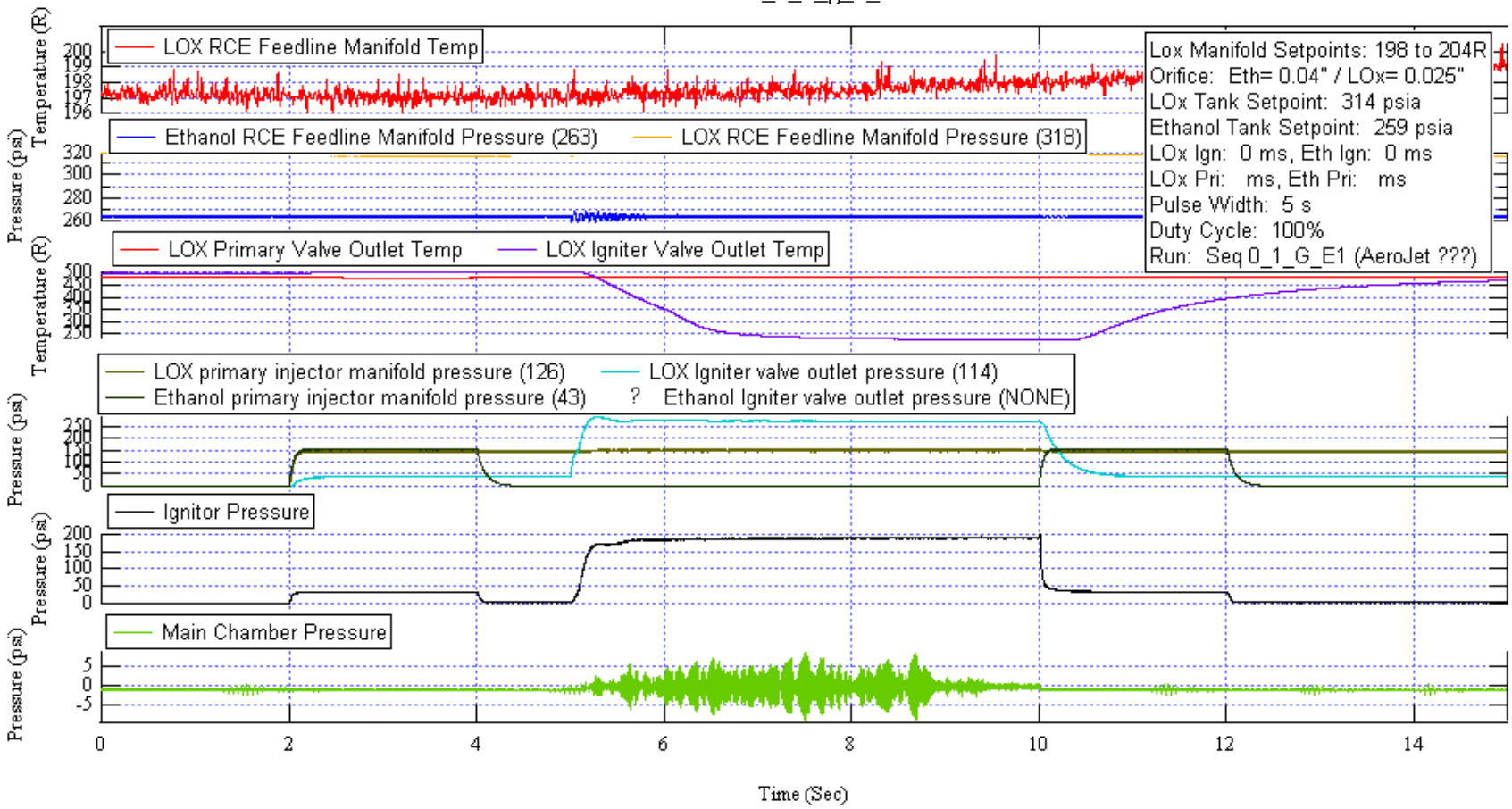

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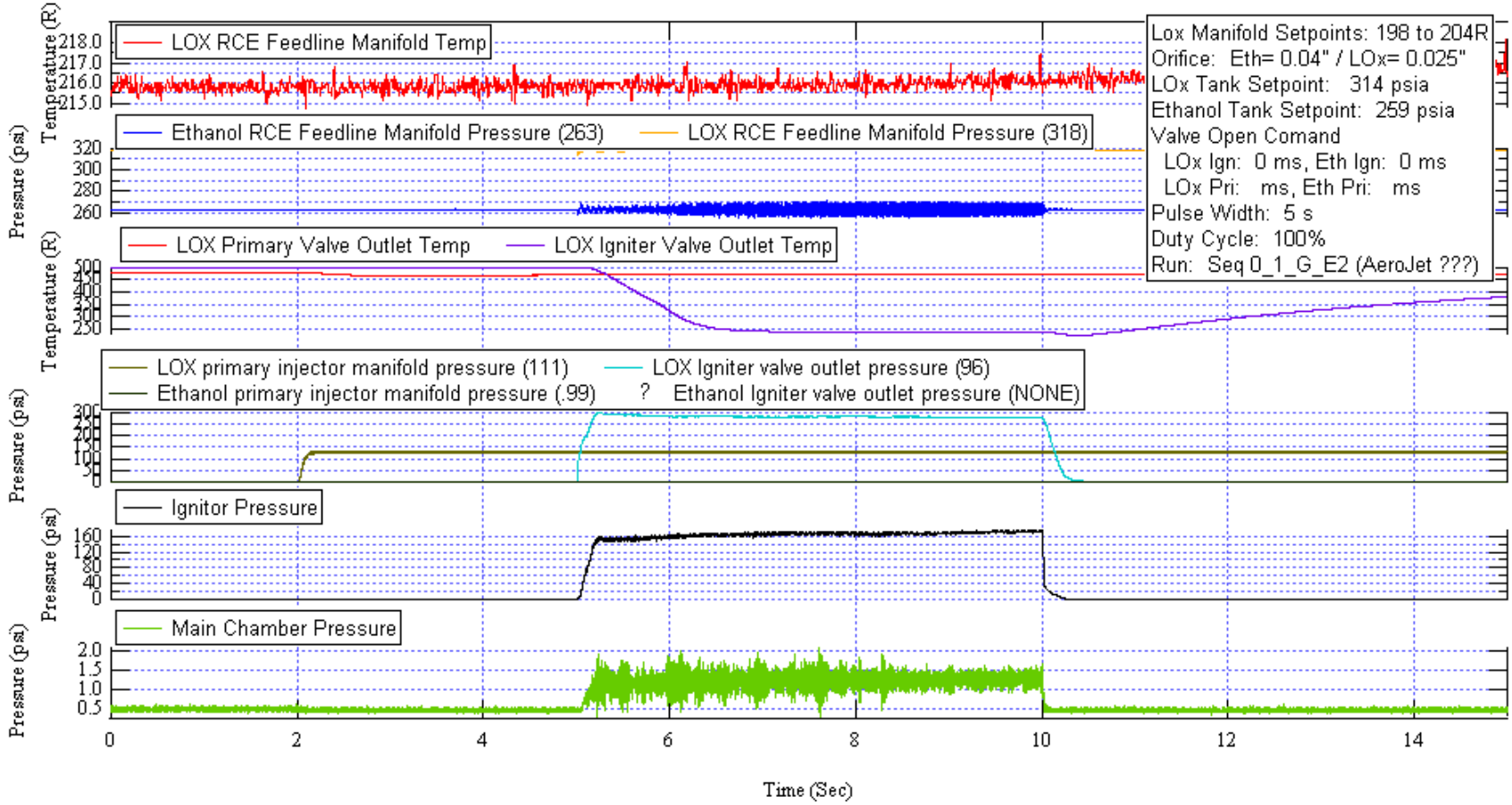

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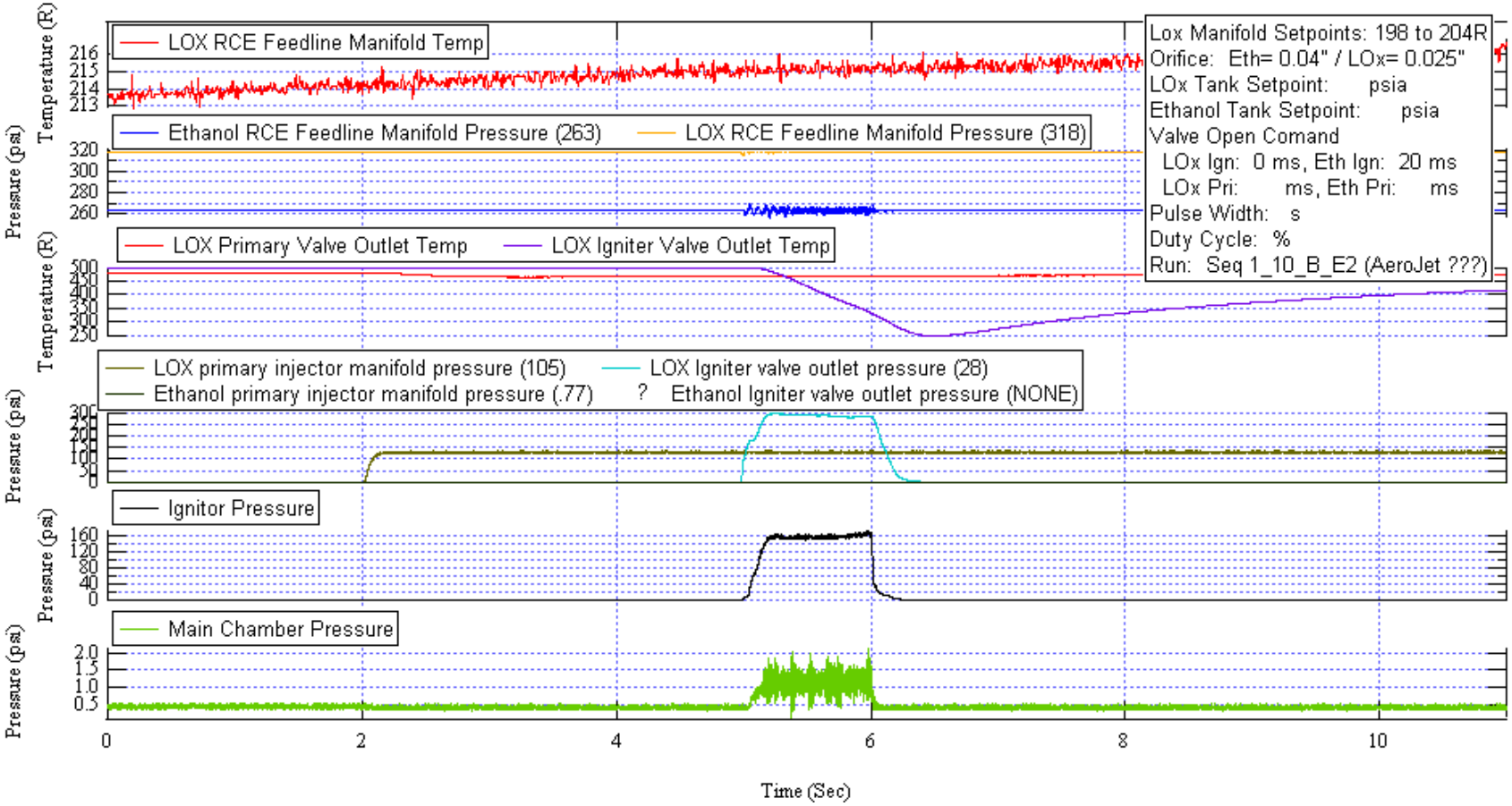

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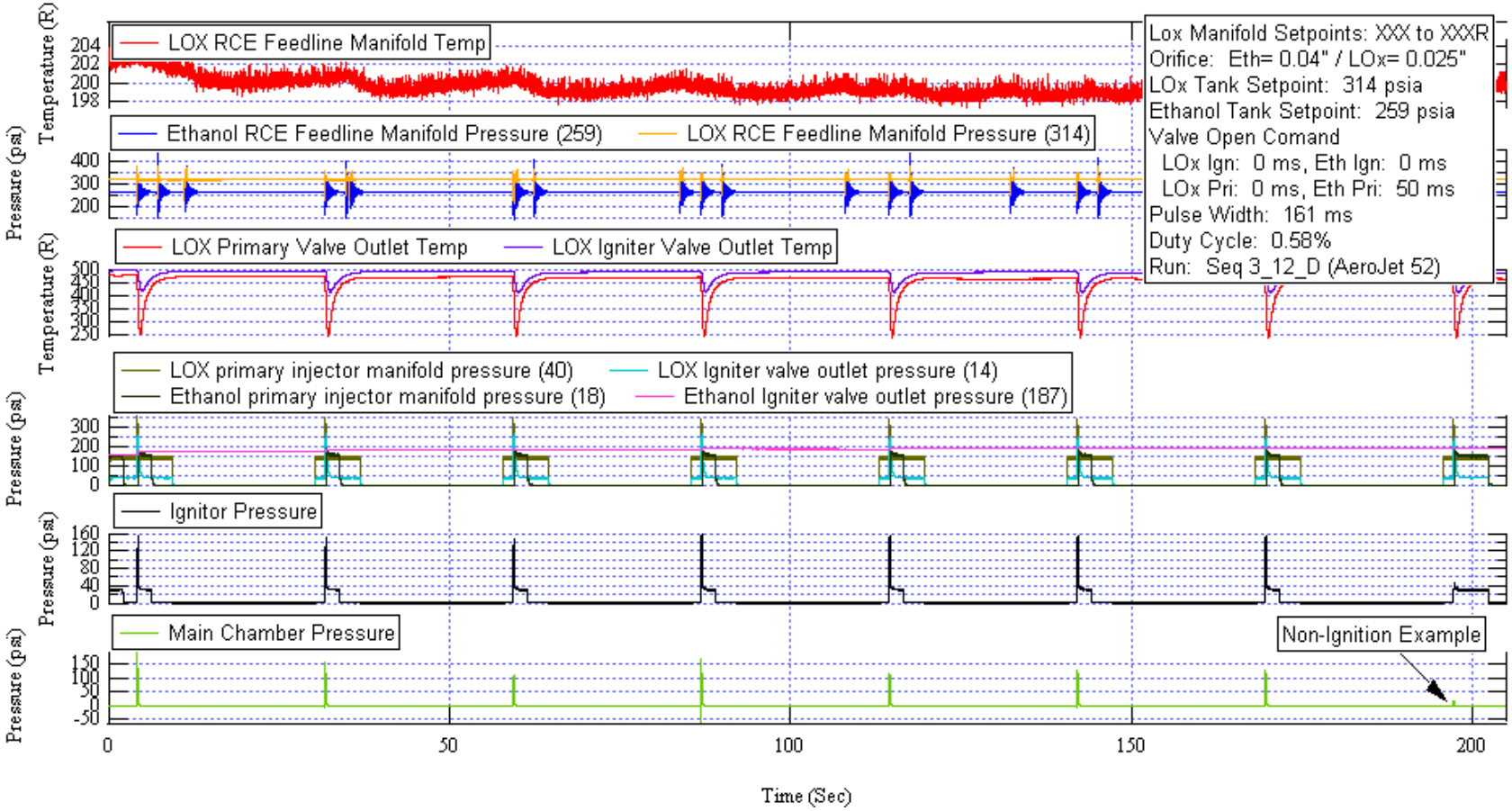

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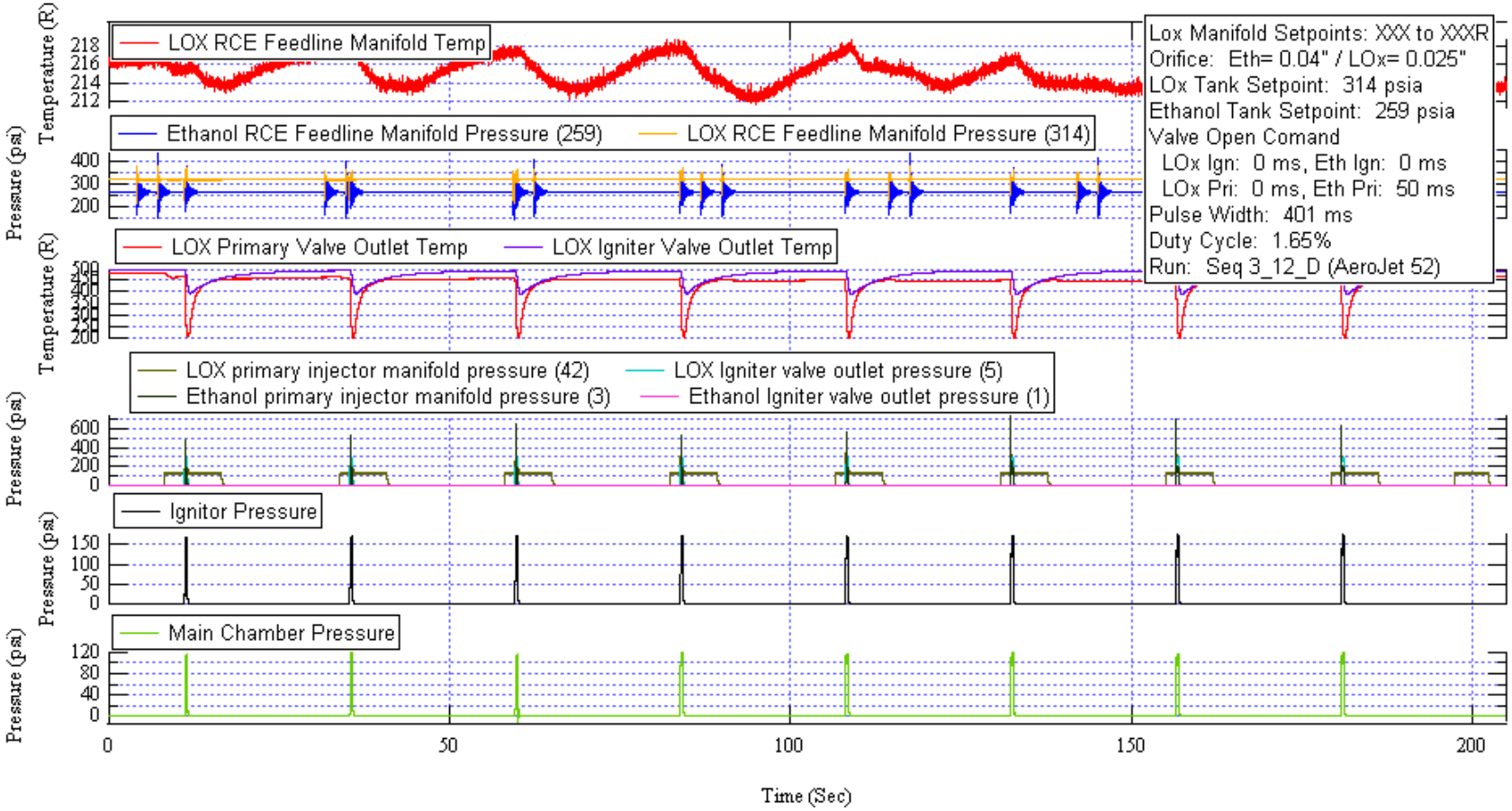

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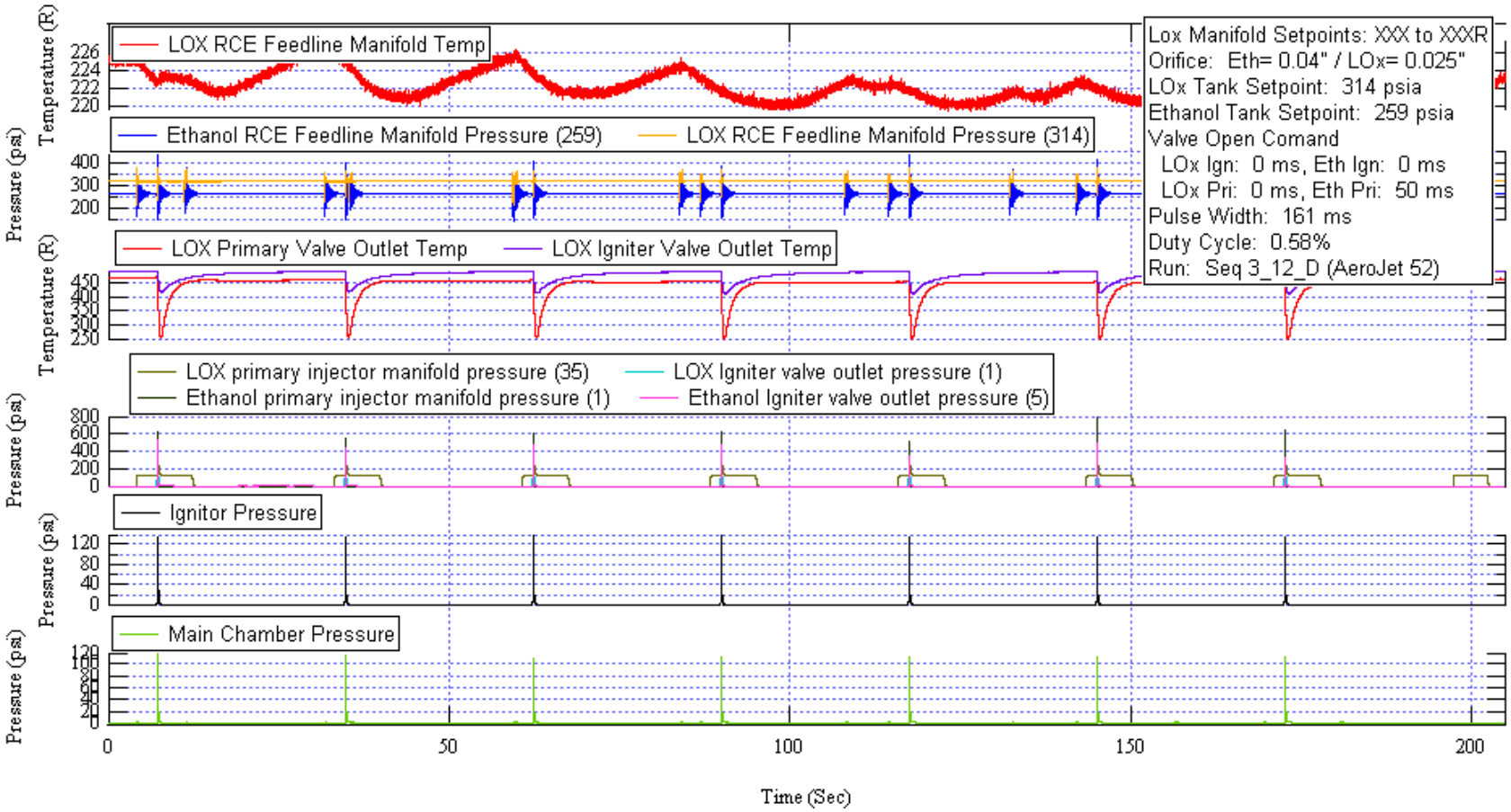

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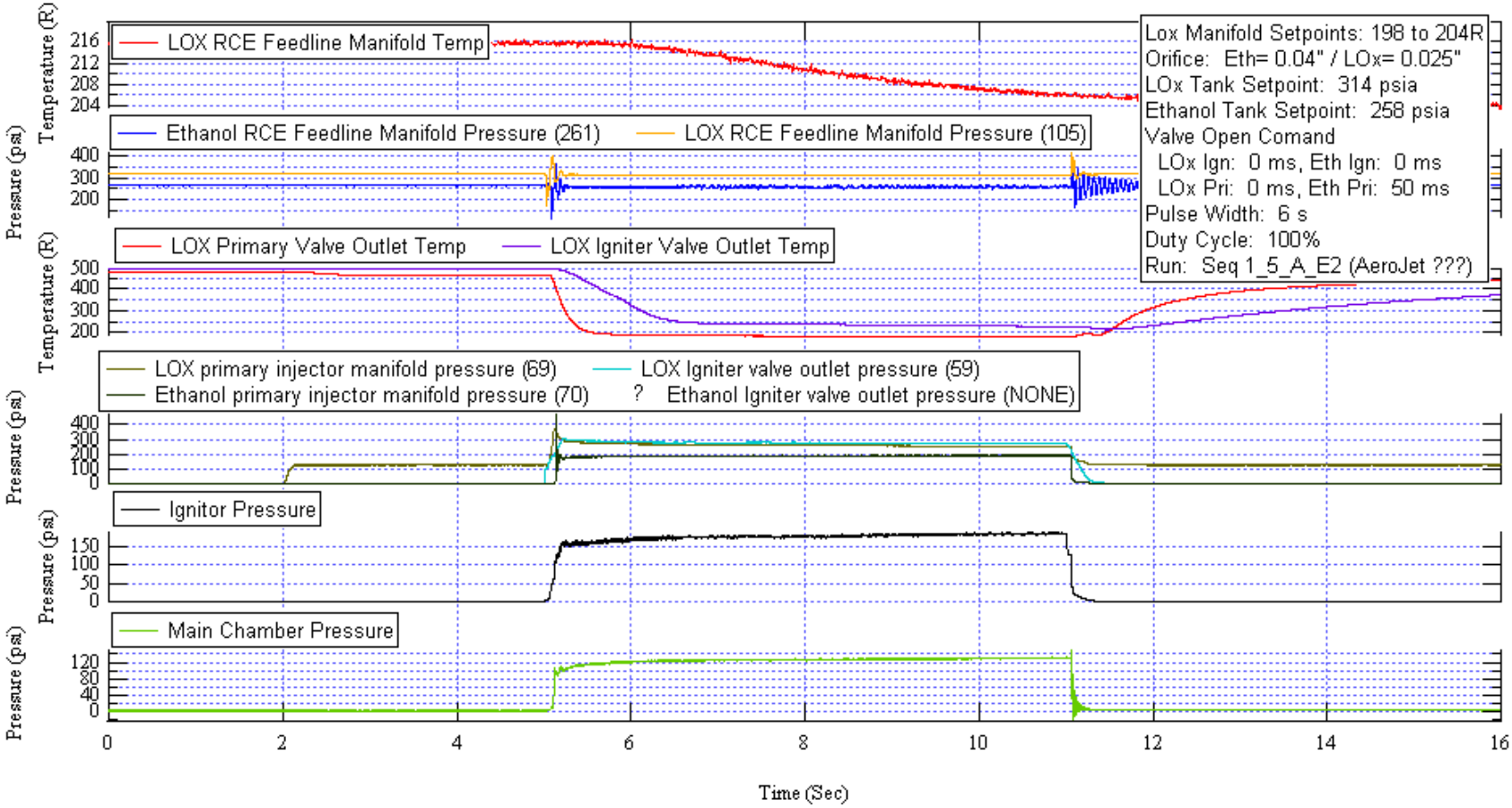

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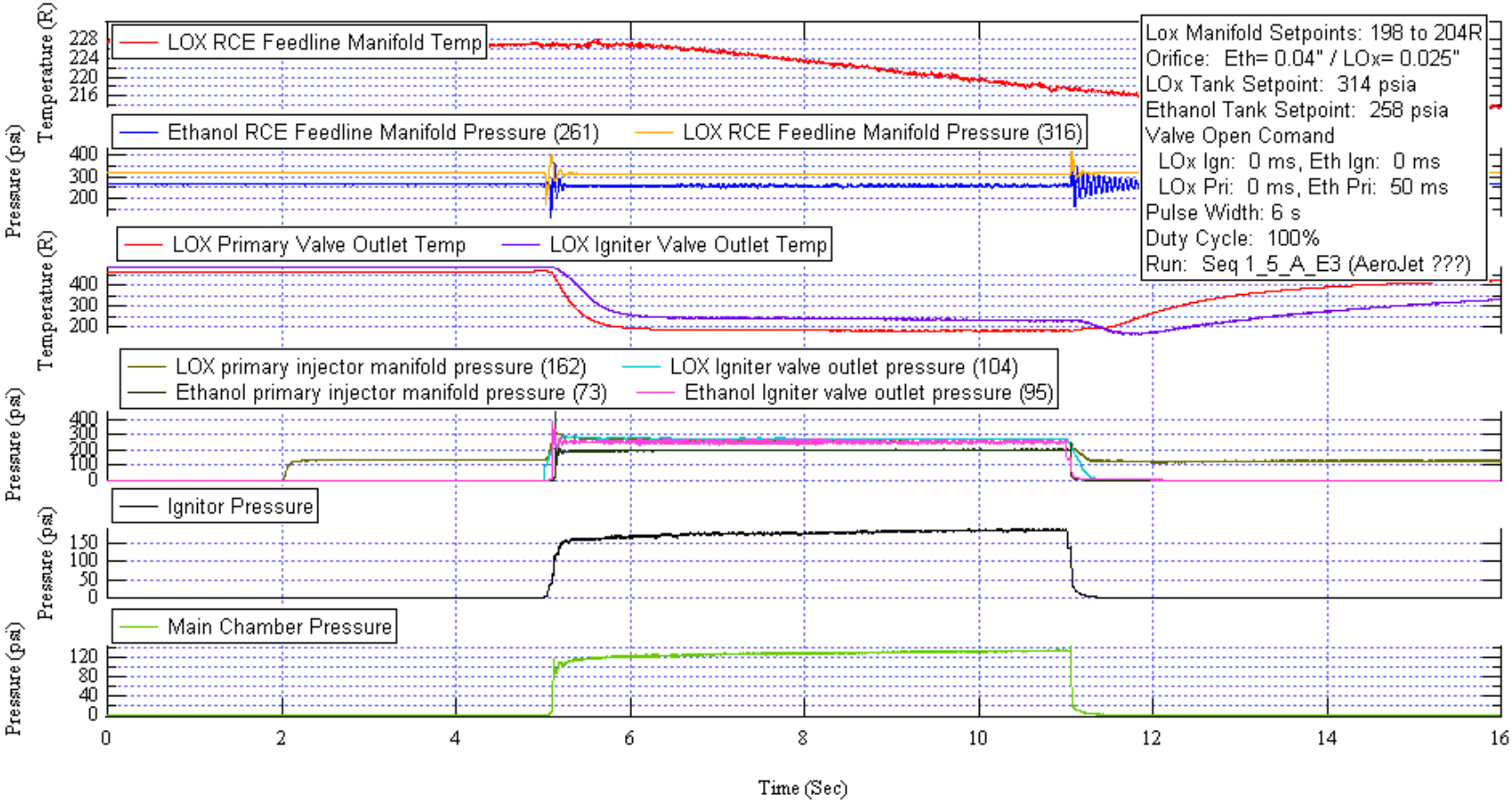

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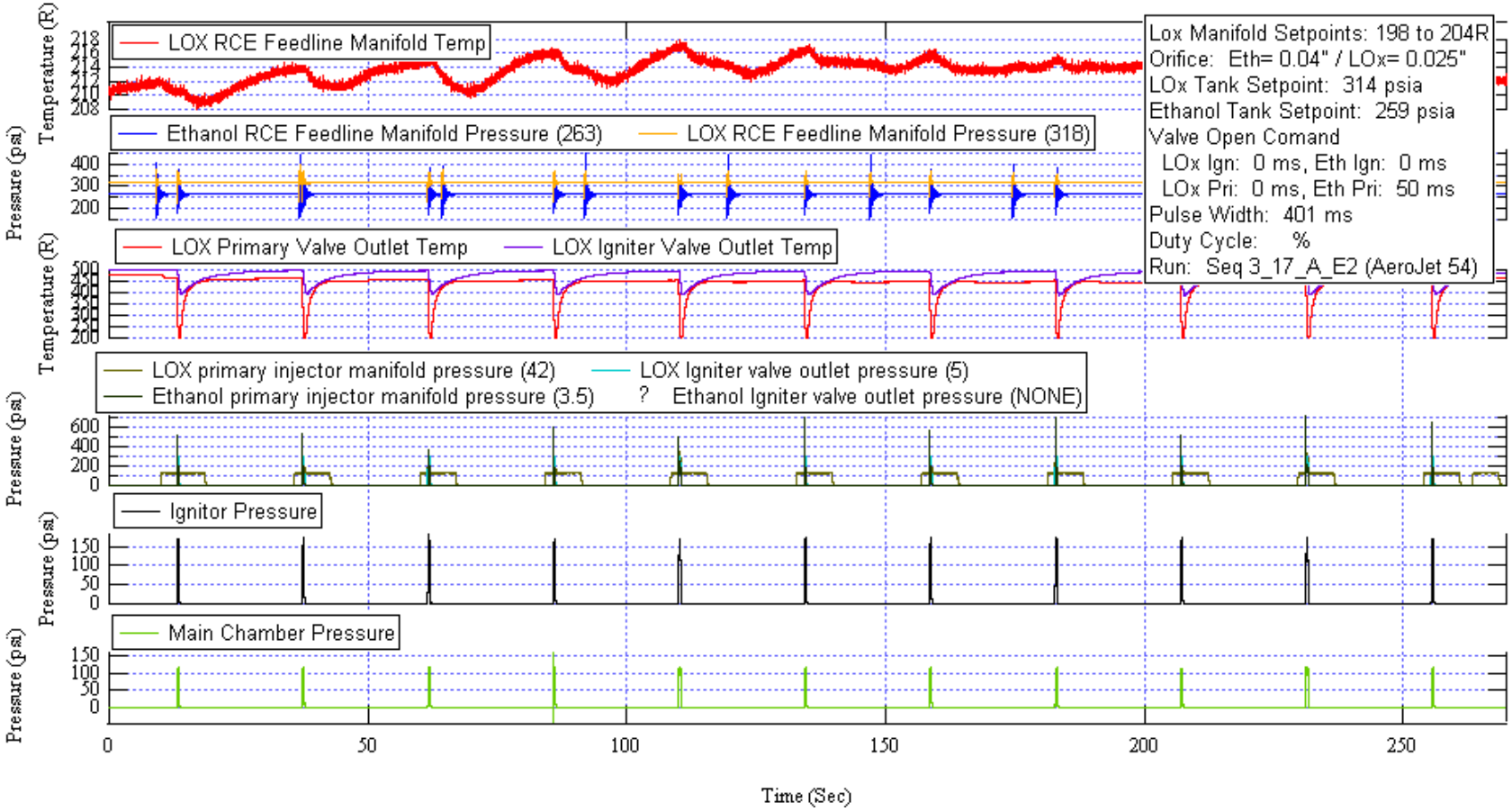

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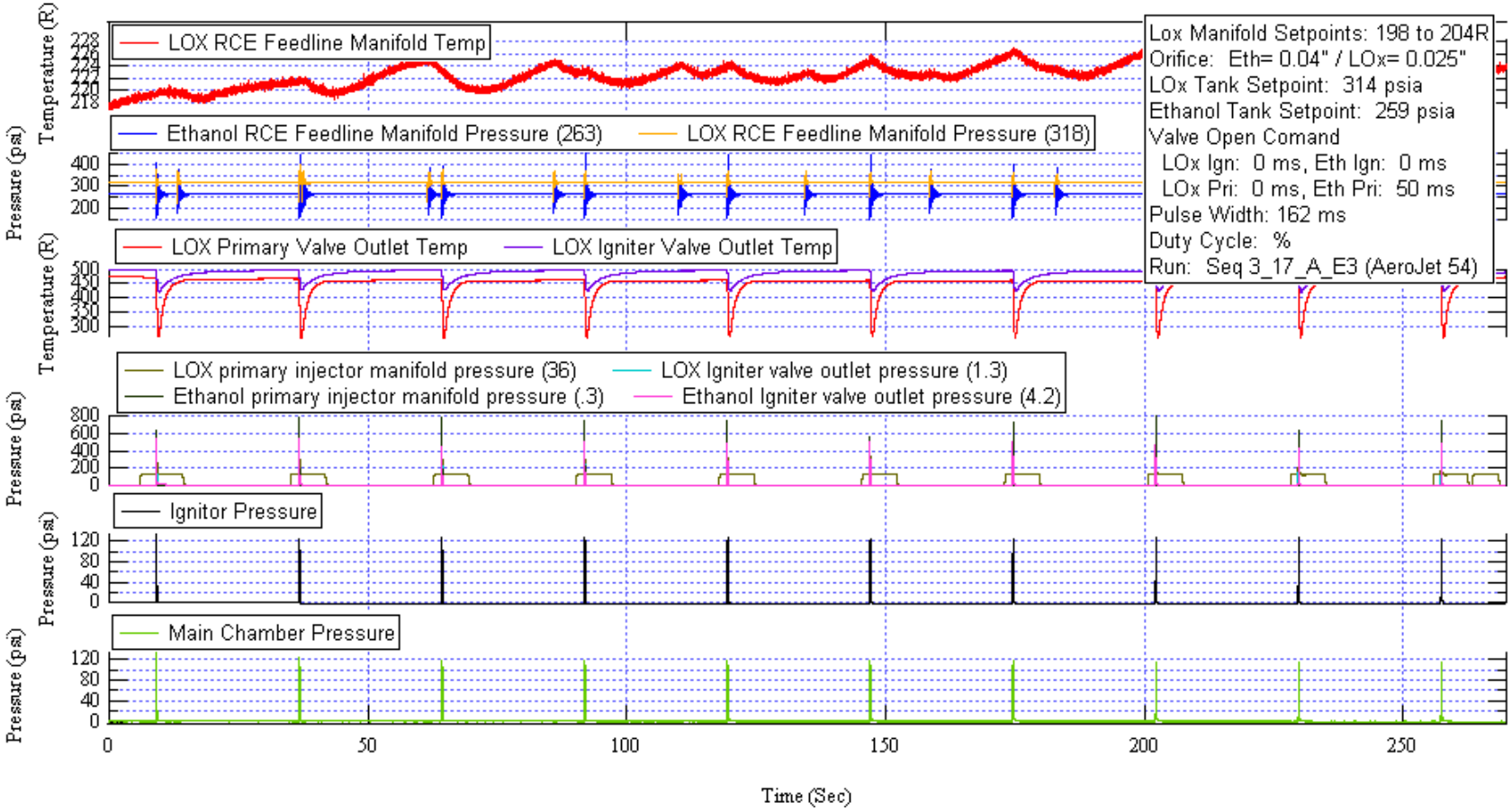

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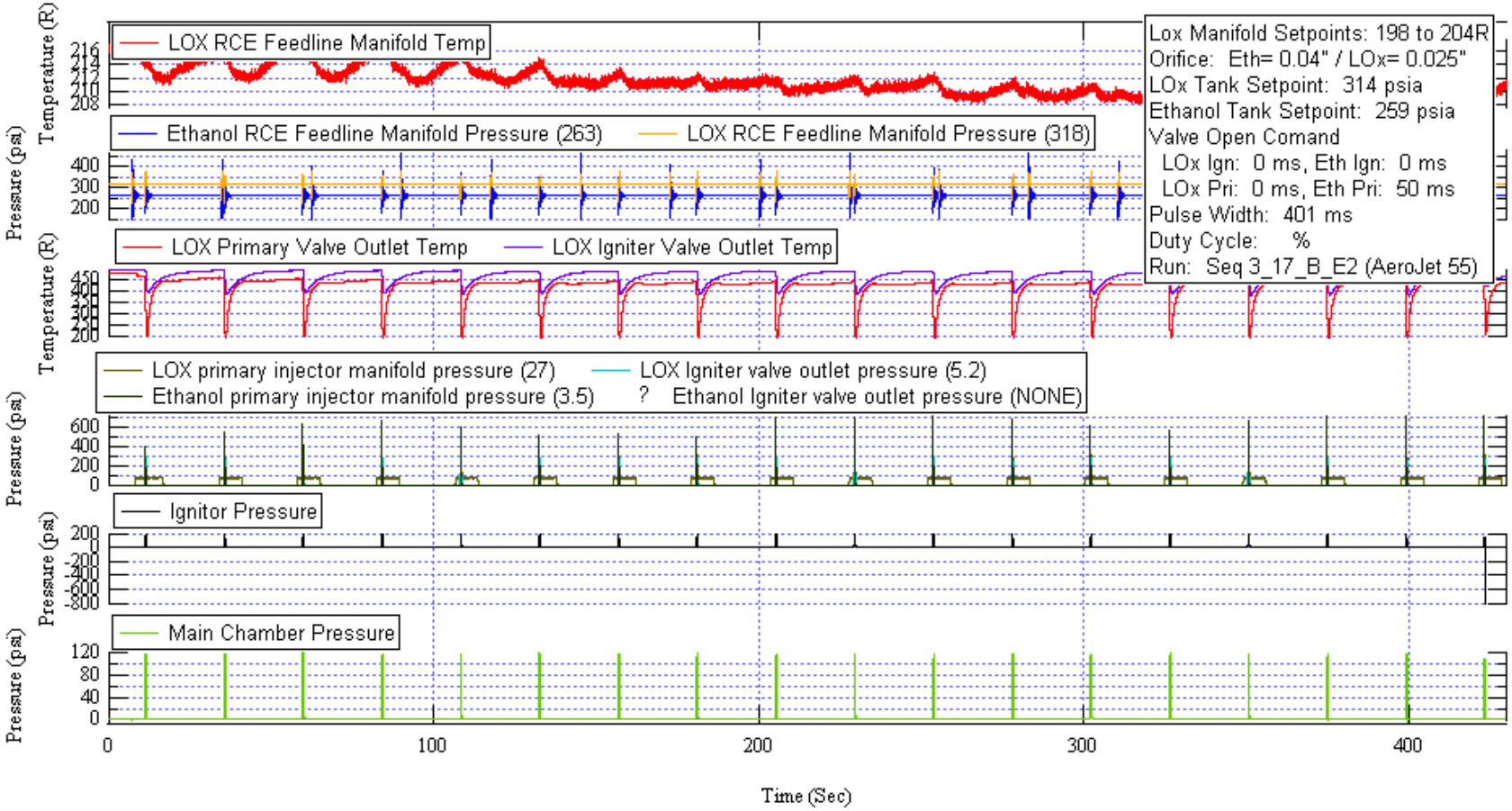

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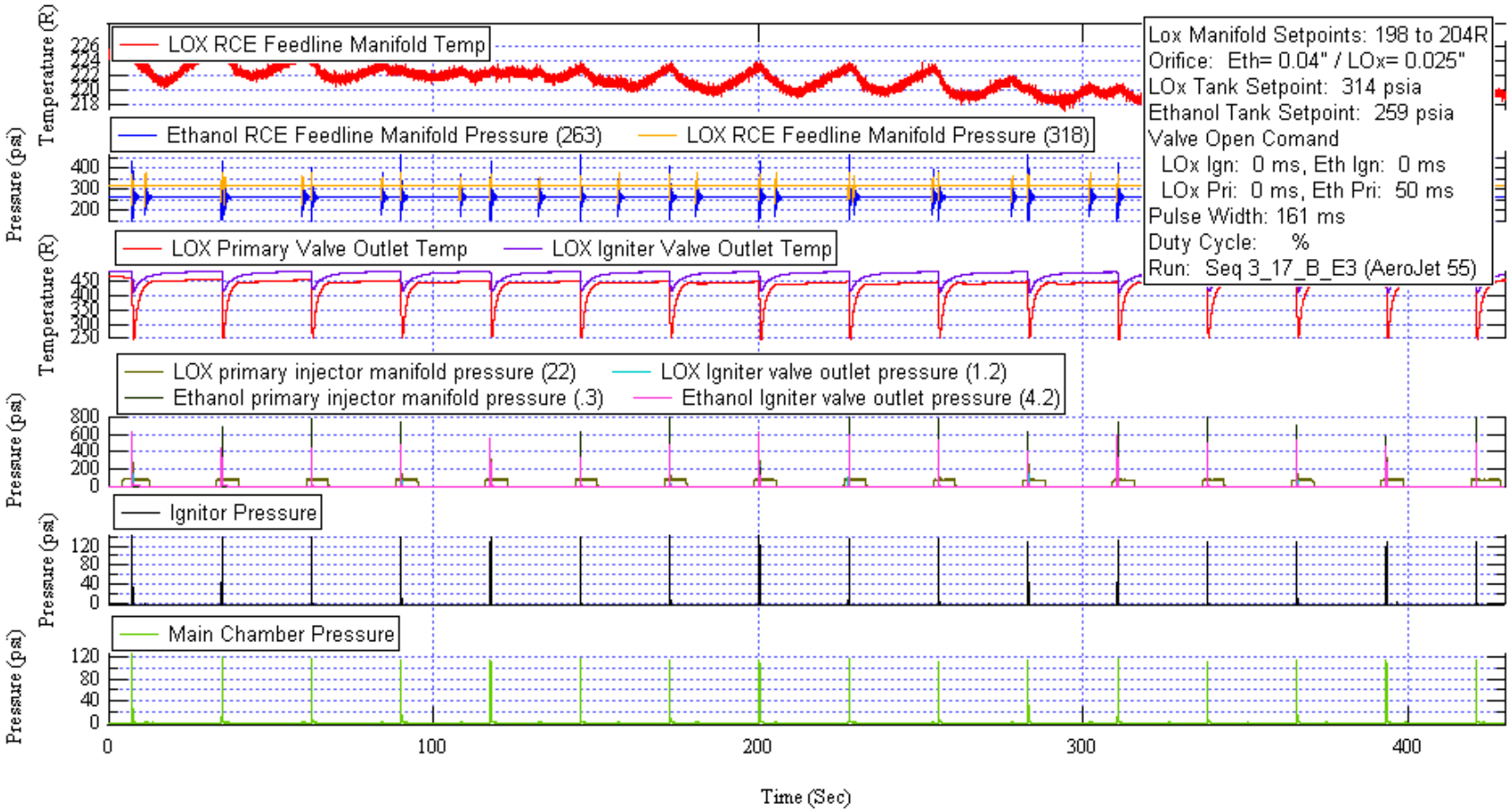

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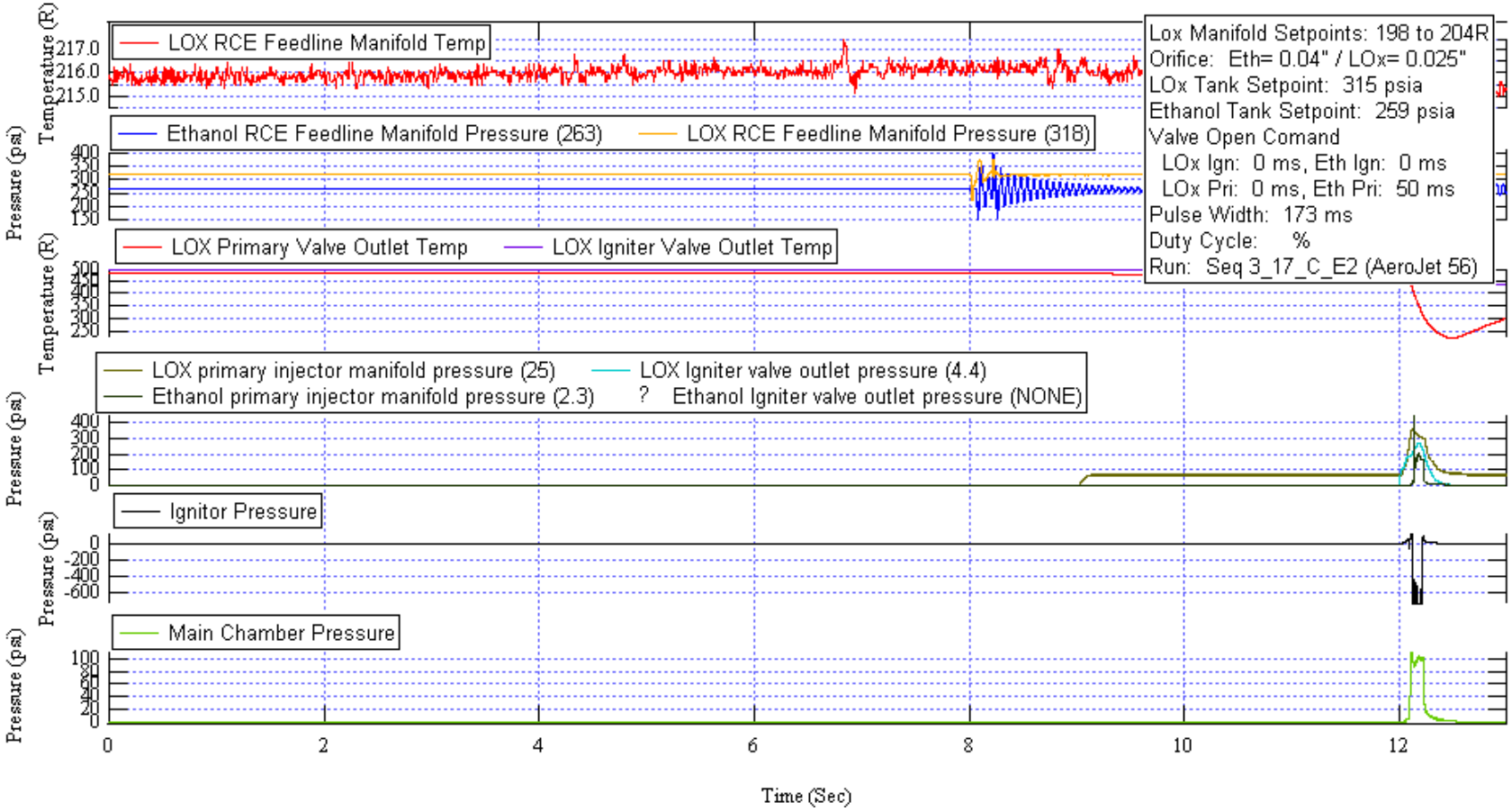
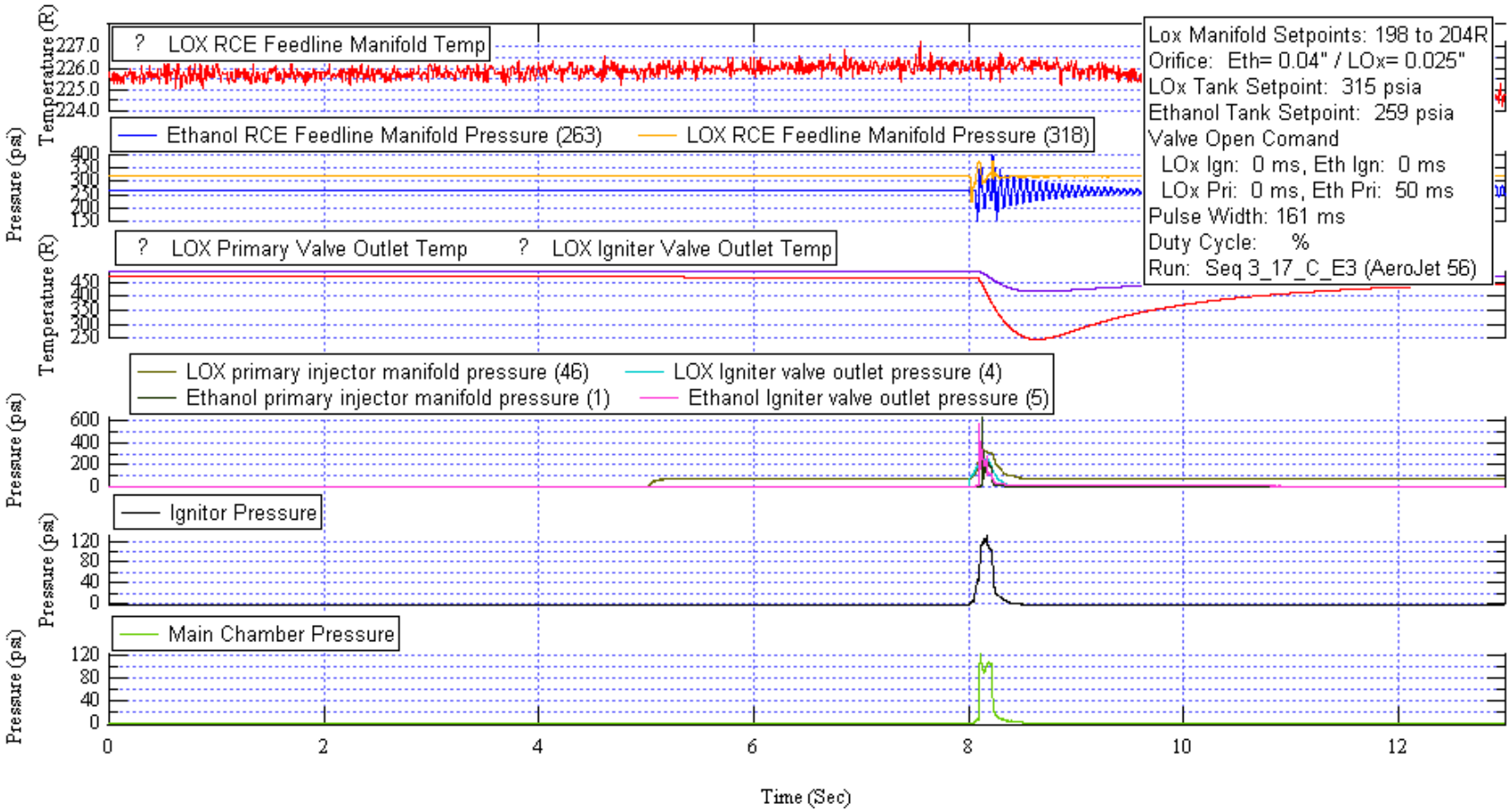
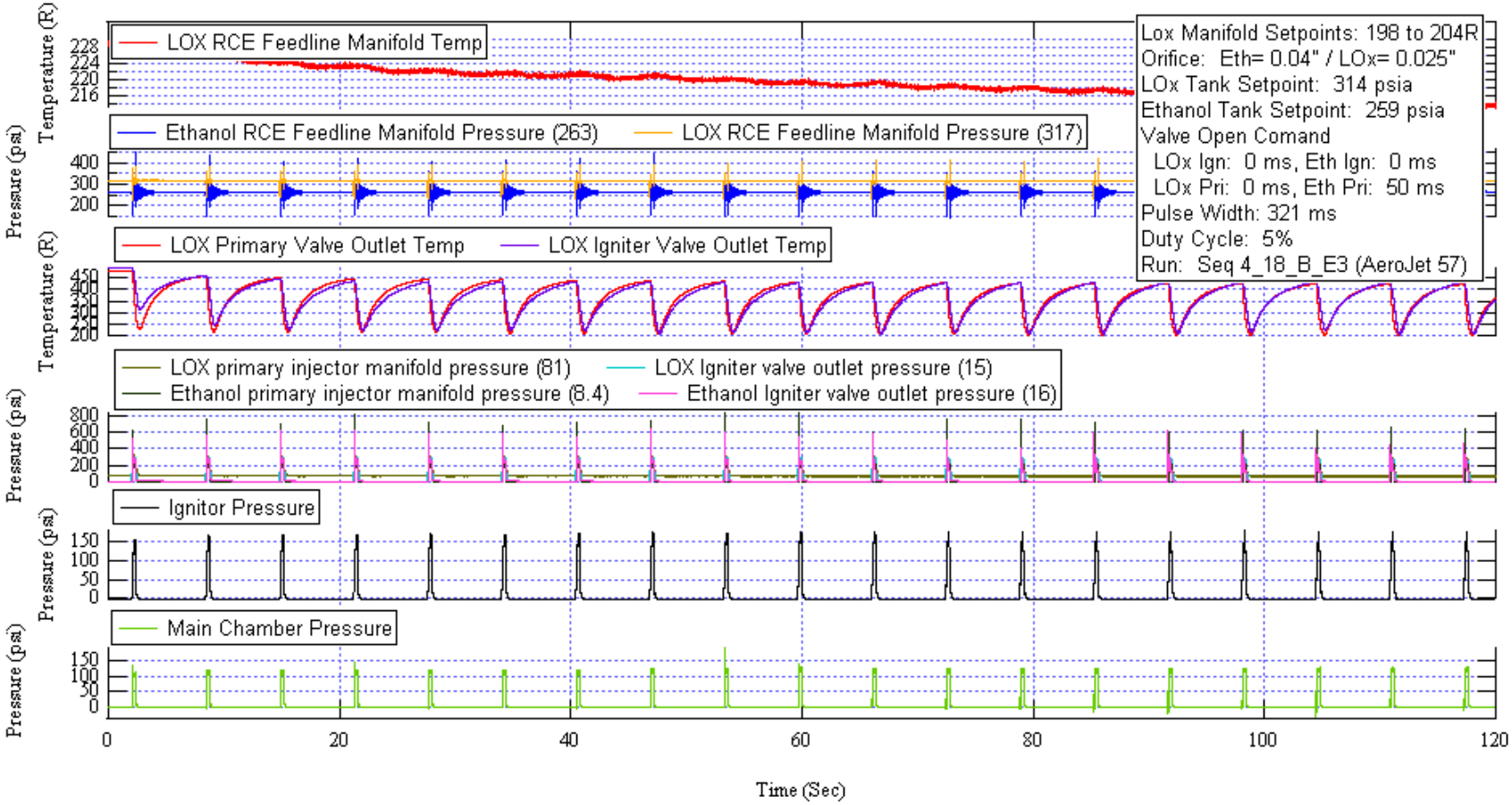


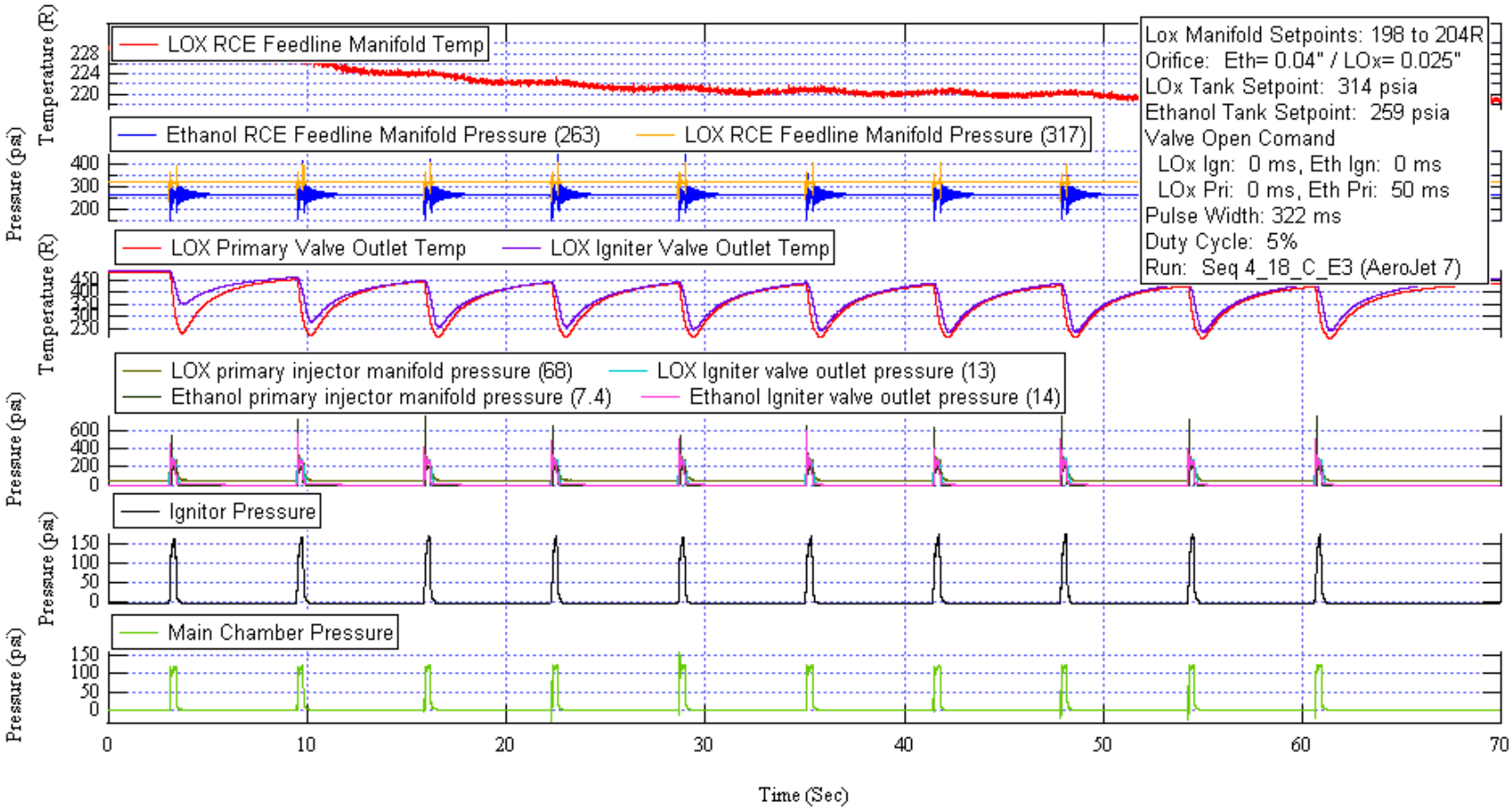
030906_3_17a_c_e3



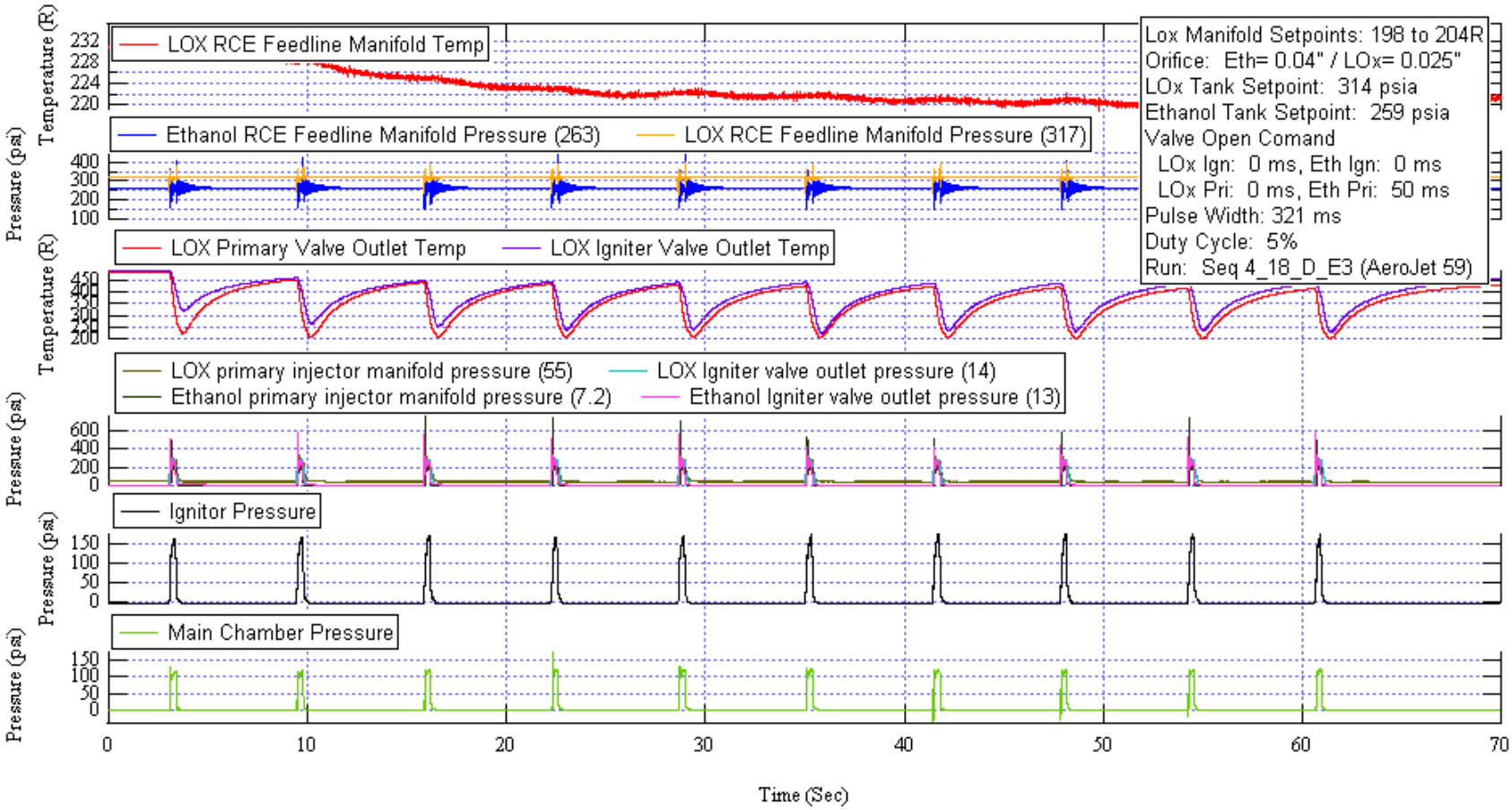
030906_4_18_b_e3



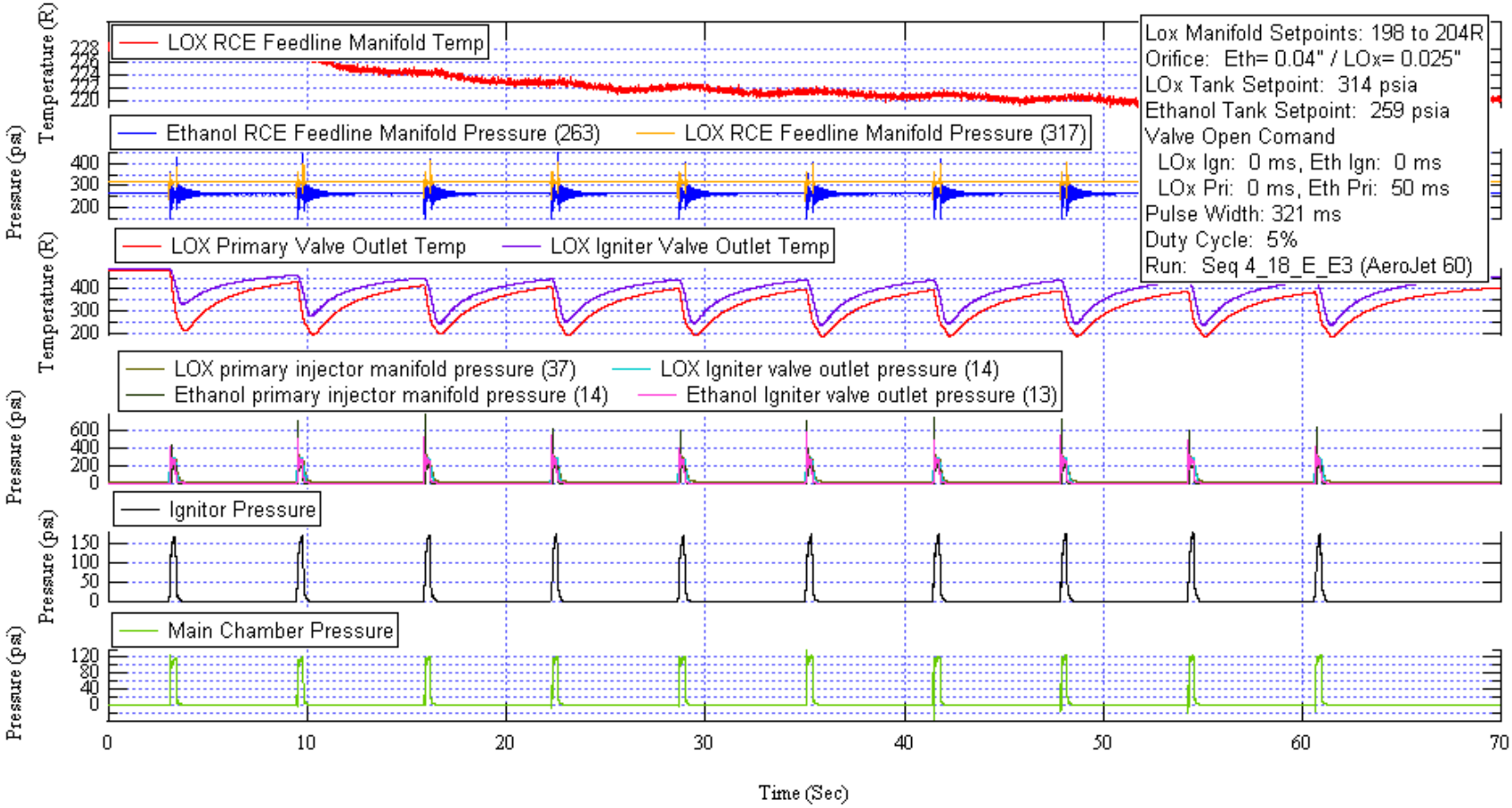
030906_4_18_c_e3



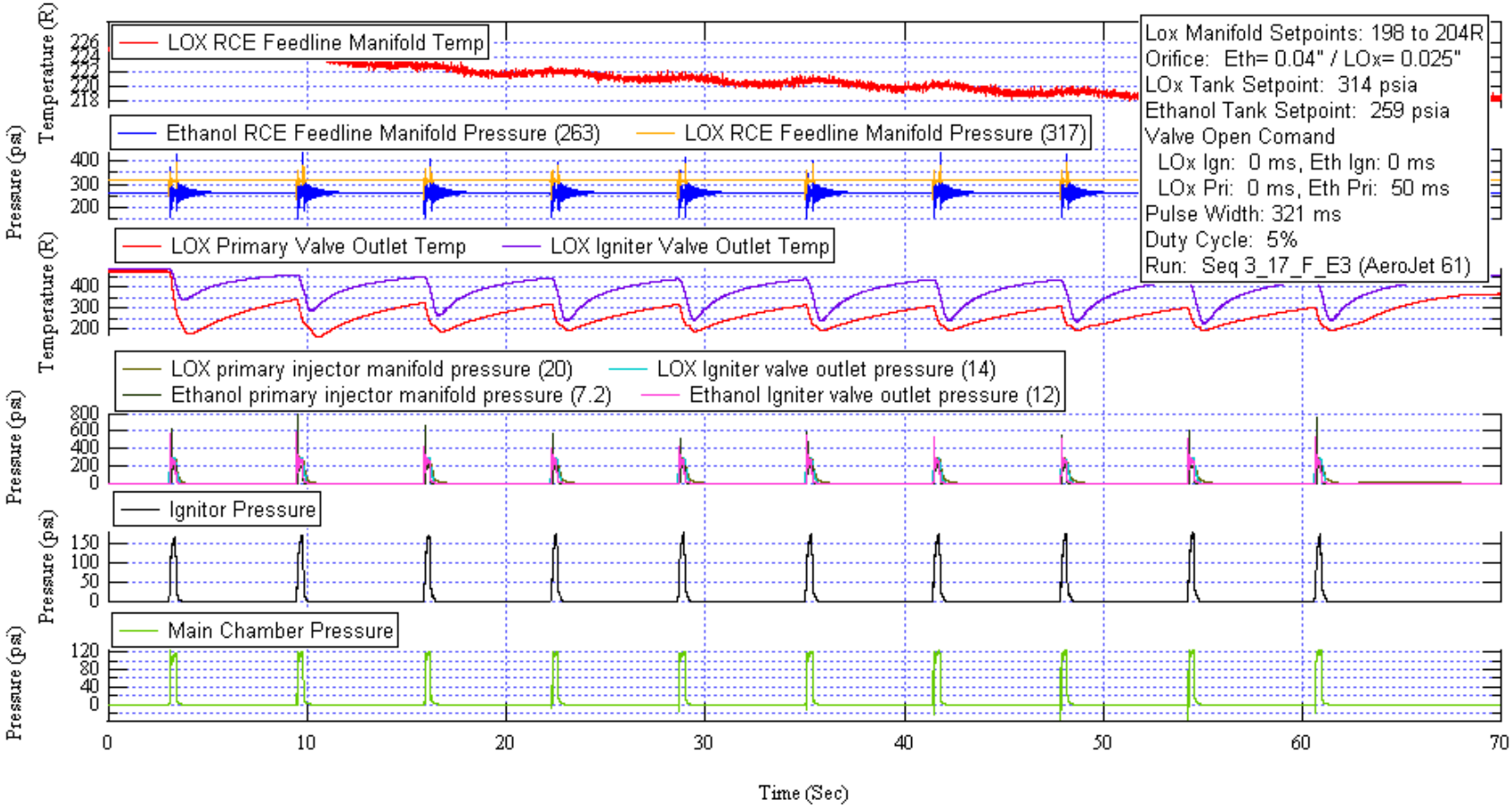
030906_4_18_d_e3



030906_4_18_e_e3

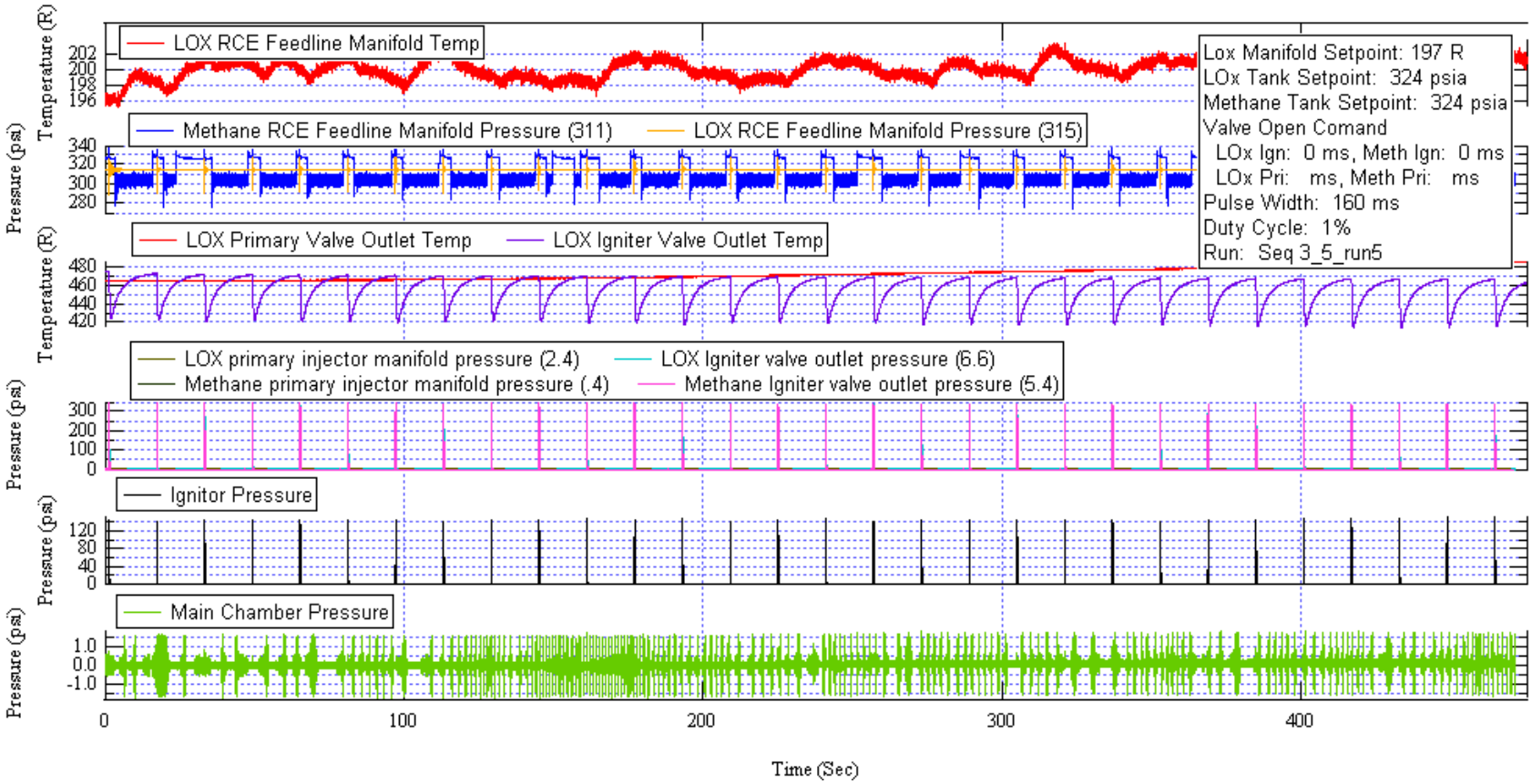


030906_4_18_f_e3

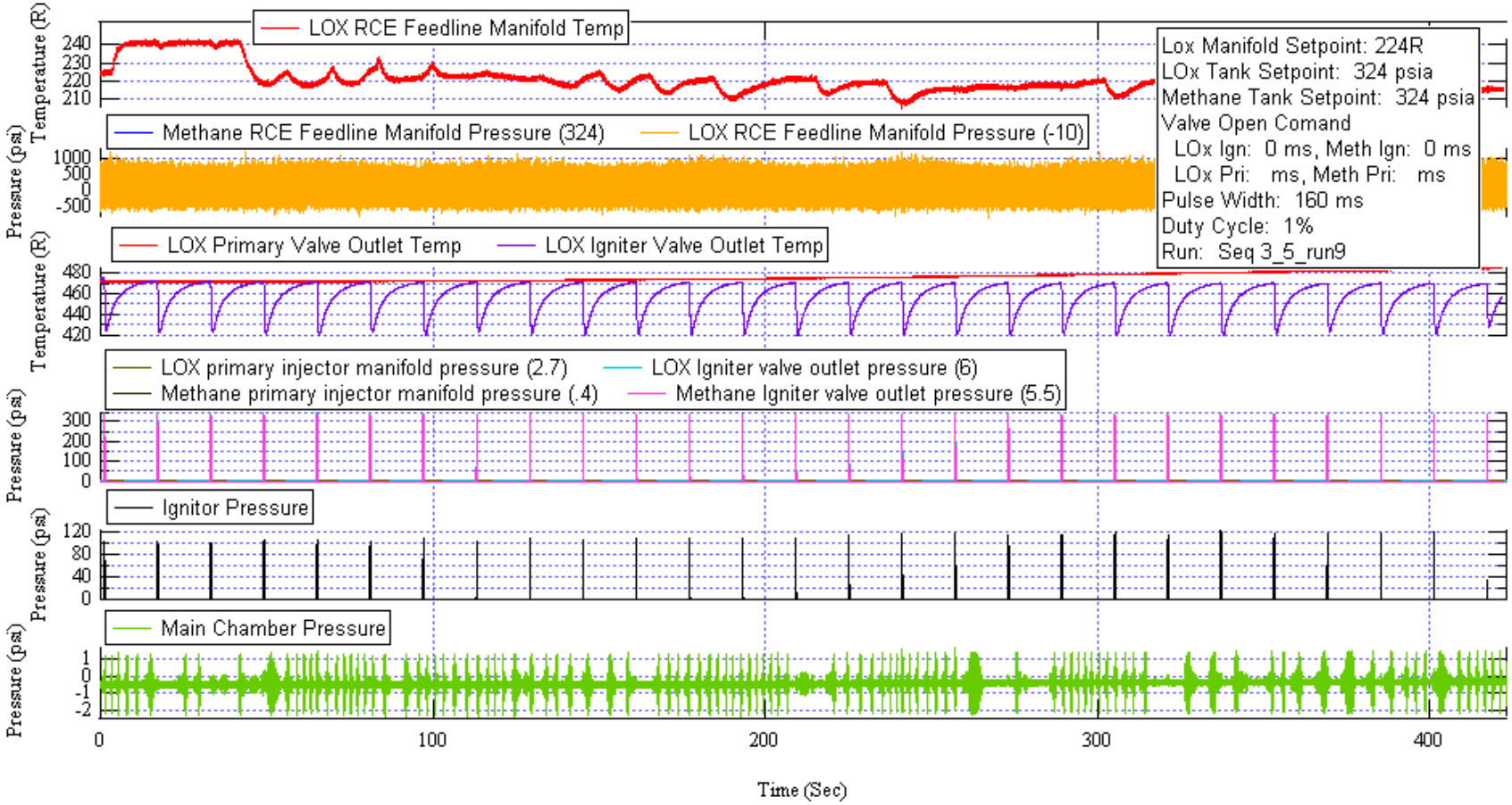


Appendix G: WSTF LO_2/LCH_4 Test Plots

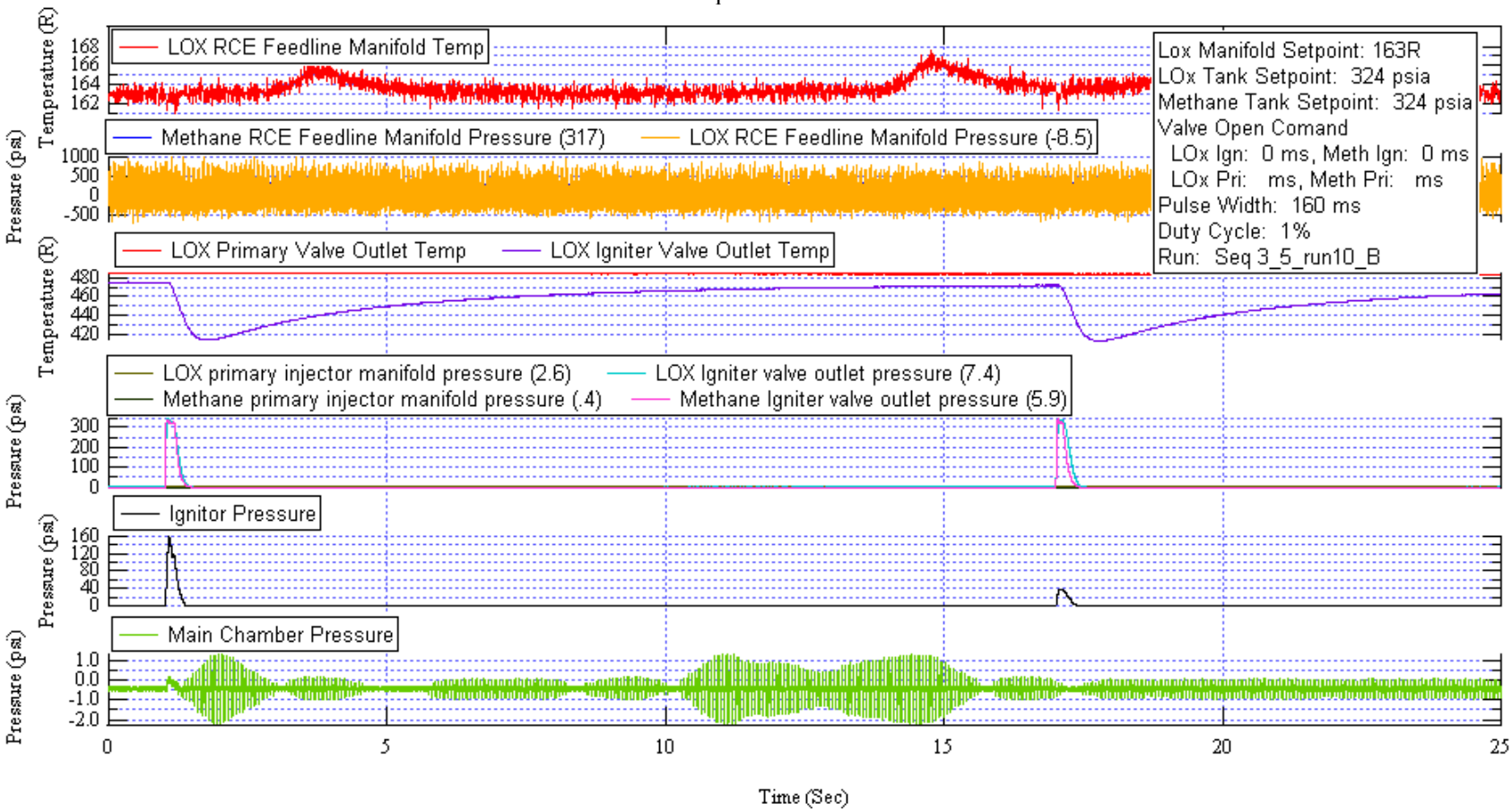
Seq3-5 run 5



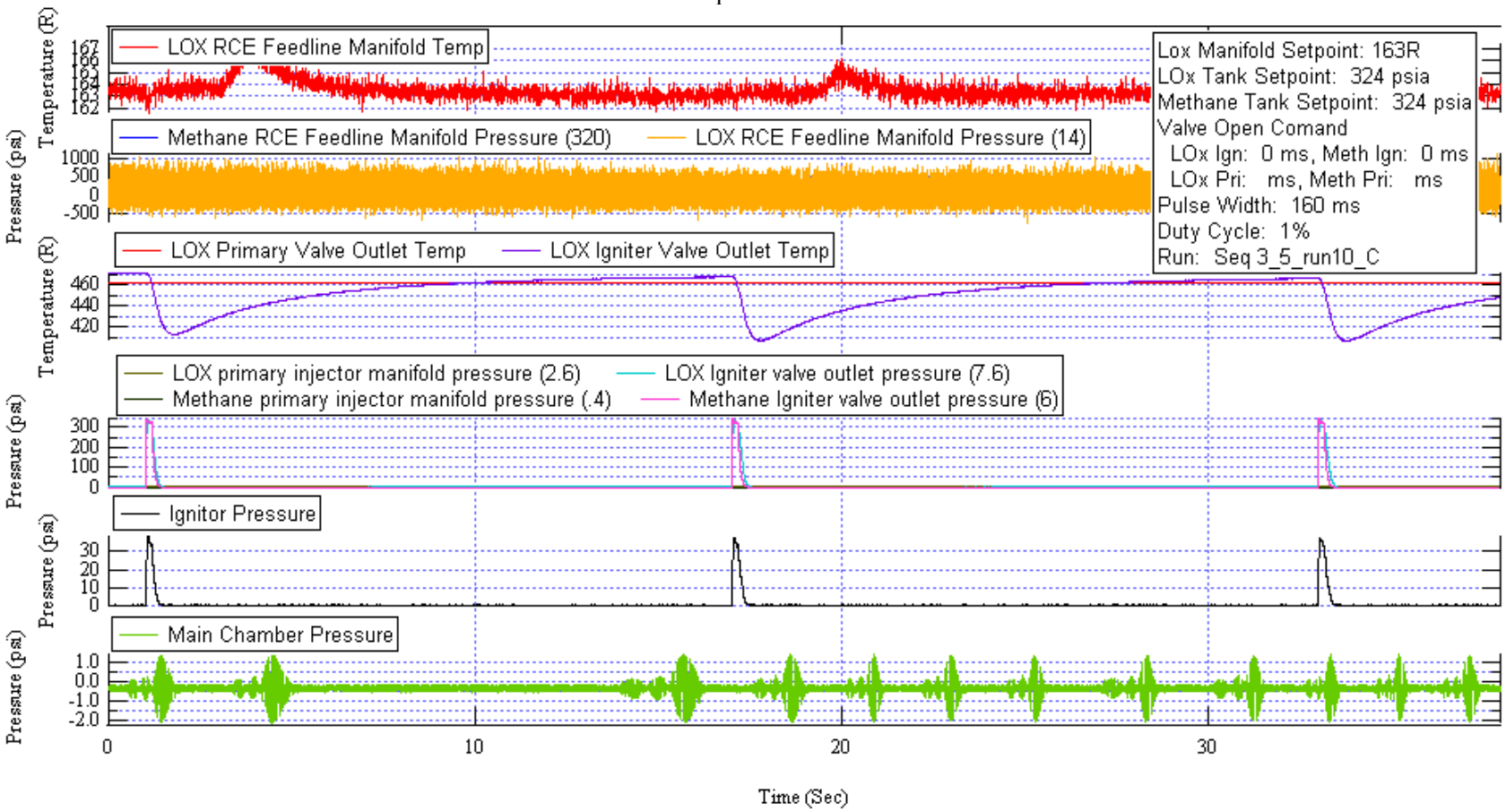
Seq3-5 run 9


LOX RCE Feedline Manifold Temp
Temperature (R)
240
230
220
210
Methane RCE Feedline Manifold Pressure (324)
LOX RCE Feedline Manifold Pressure (-10)
Pressure (psi)
1000
500
0
-500
Lox Manifold Setpoint: 224R
LOx Tank Setpoint: 324 psia
Methane Tank Setpoint: 324 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: ms, Meth Pri: ms
Pulse Width: 160 ms
Duty Cycle: 1%
Run: Seq 3_5_run9
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
480
460
440
420
LOX primary injector manifold pressure (2.7)
LOX Igniter valve outlet pressure (6)
Methane primary injector manifold pressure (.4)
Methane Igniter valve outlet pressure (5.5)
Pressure (psi)
300
200
100
0
Ignitor Pressure
Pressure (psi)
120
80
40
0
Main Chamber Pressure
Pressure (psi)
1
0
-1
-2
0
100
200
300
400
Time (Sec)

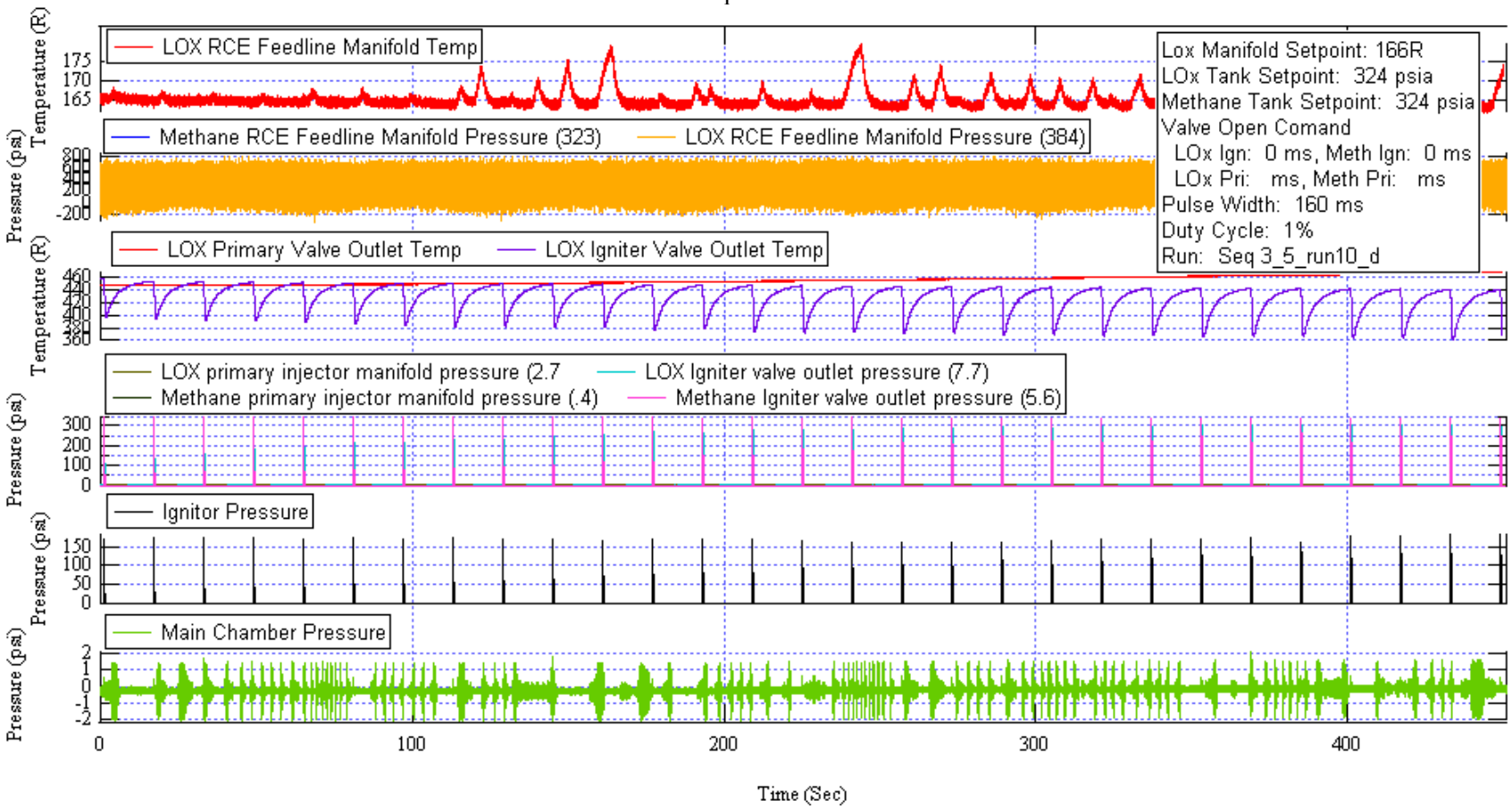
Seq3-5 run 10b



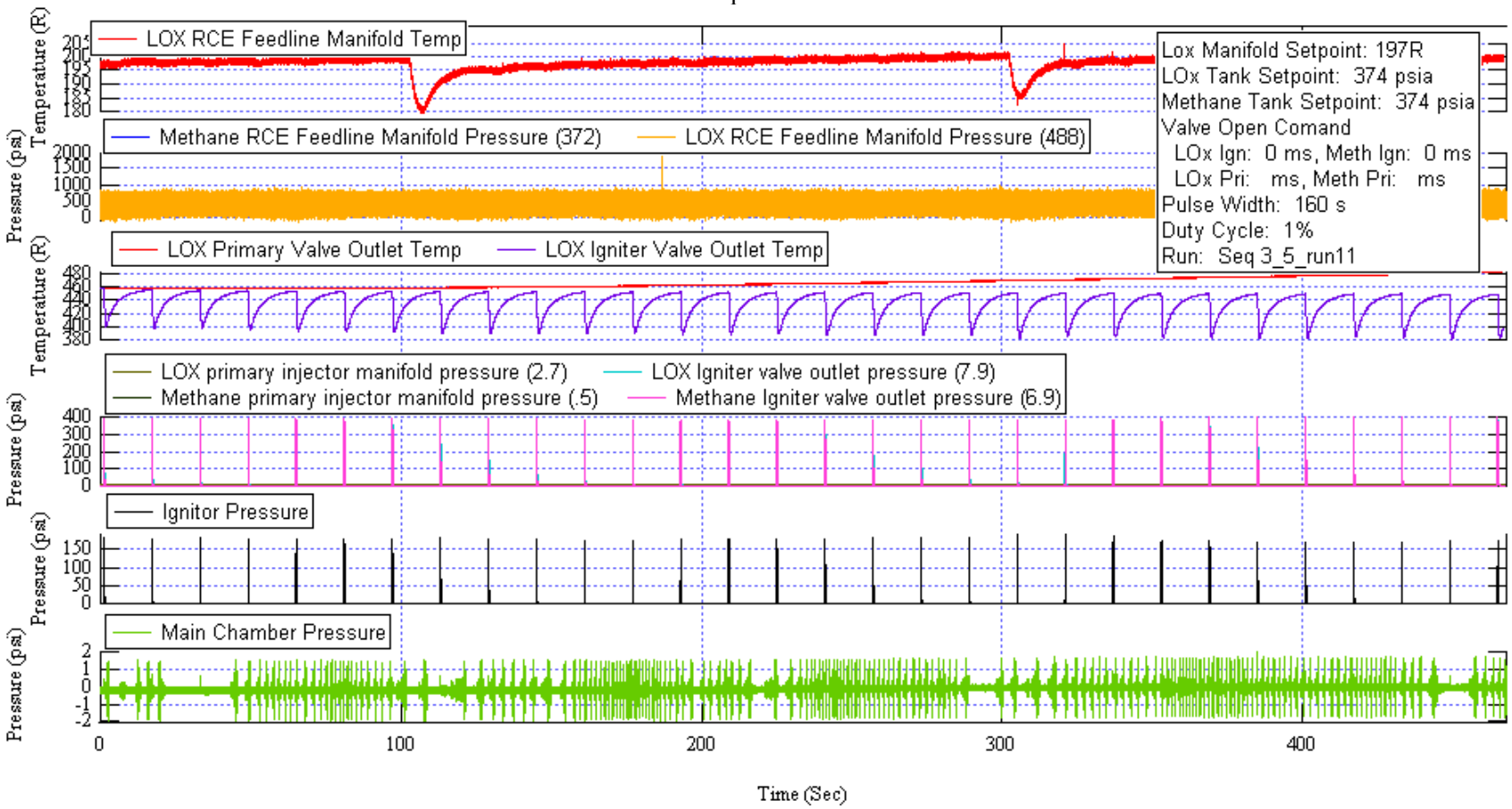
Seq3-5 run 10c



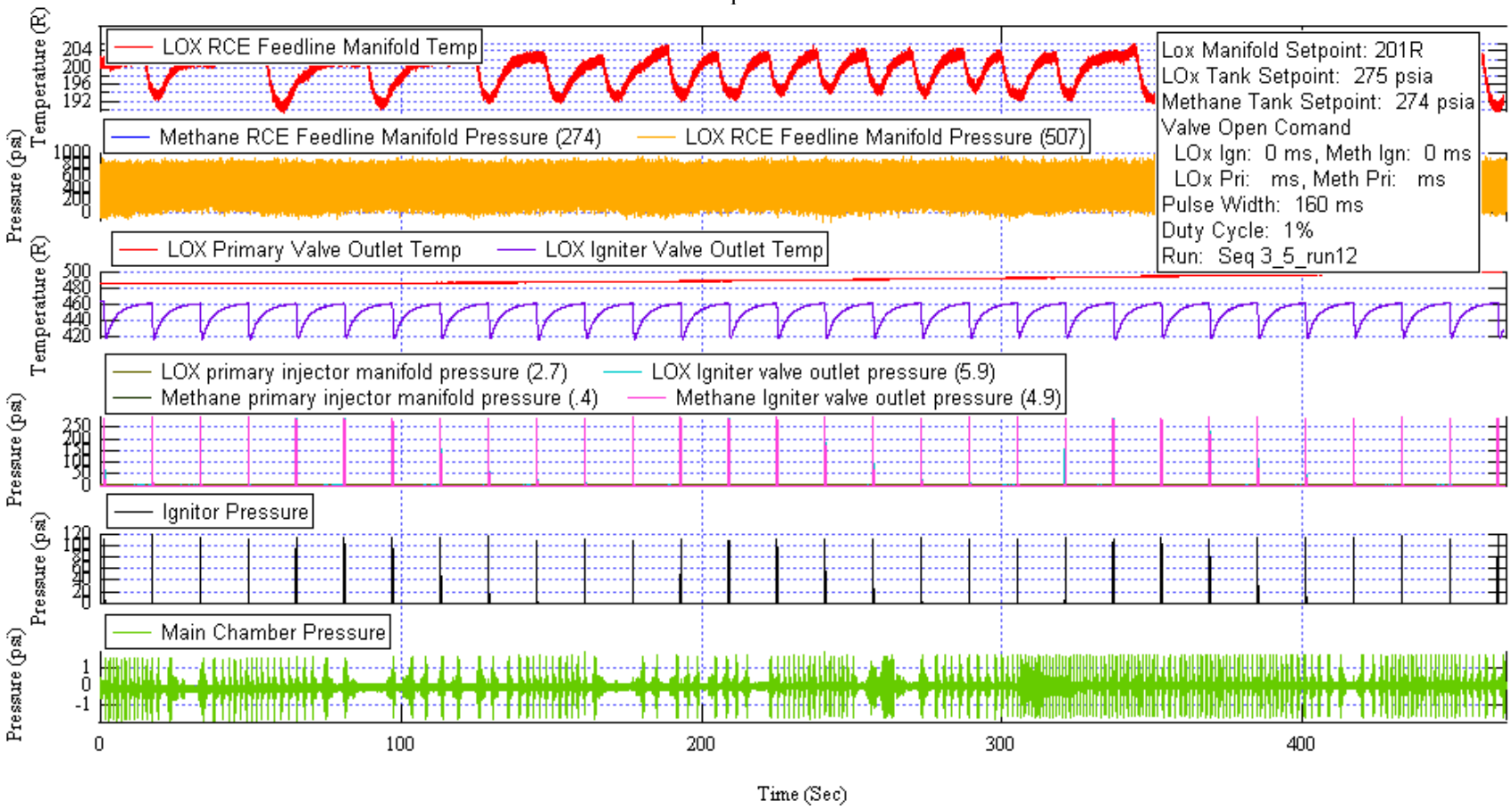
Seq3-5 run 10d



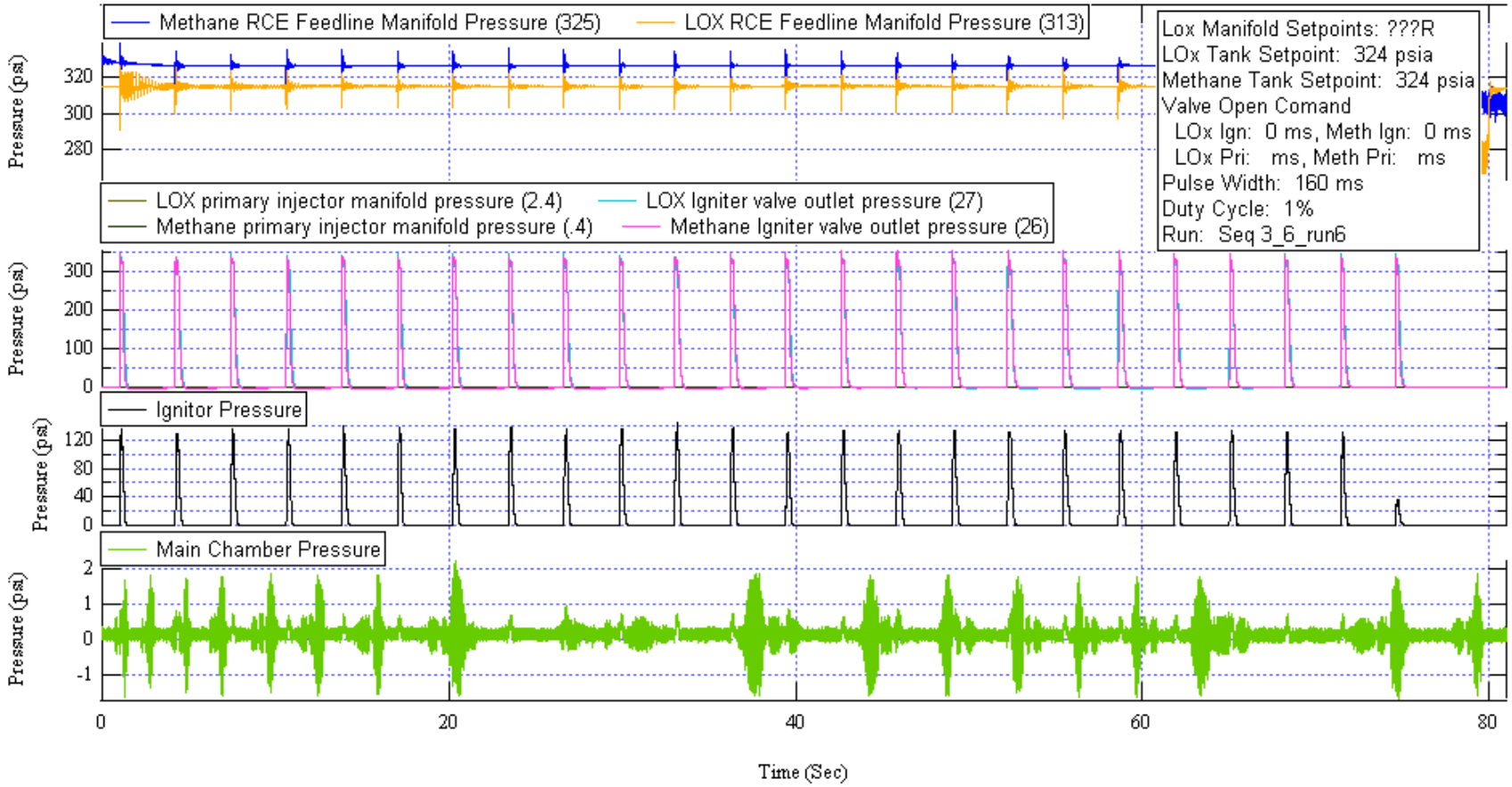
Seq3-5 run 11


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (372)
LOX RCE Feedline Manifold Pressure (488)
Pressure (psi)
Lox Manifold Setpoint: 197R
LOx Tank Setpoint: 374 psia
Methane Tank Setpoint: 374 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: ms, Meth Pri: ms
Pulse Width: 160 s
Duty Cycle: 1%
Run: Seq 3_5_run11
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (2.7)
LOX Igniter valve outlet pressure (7.9)
Methane primary injector manifold pressure (.5)
Methane Igniter valve outlet pressure (6.9)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
0
100
200
300
400
Time (Sec)

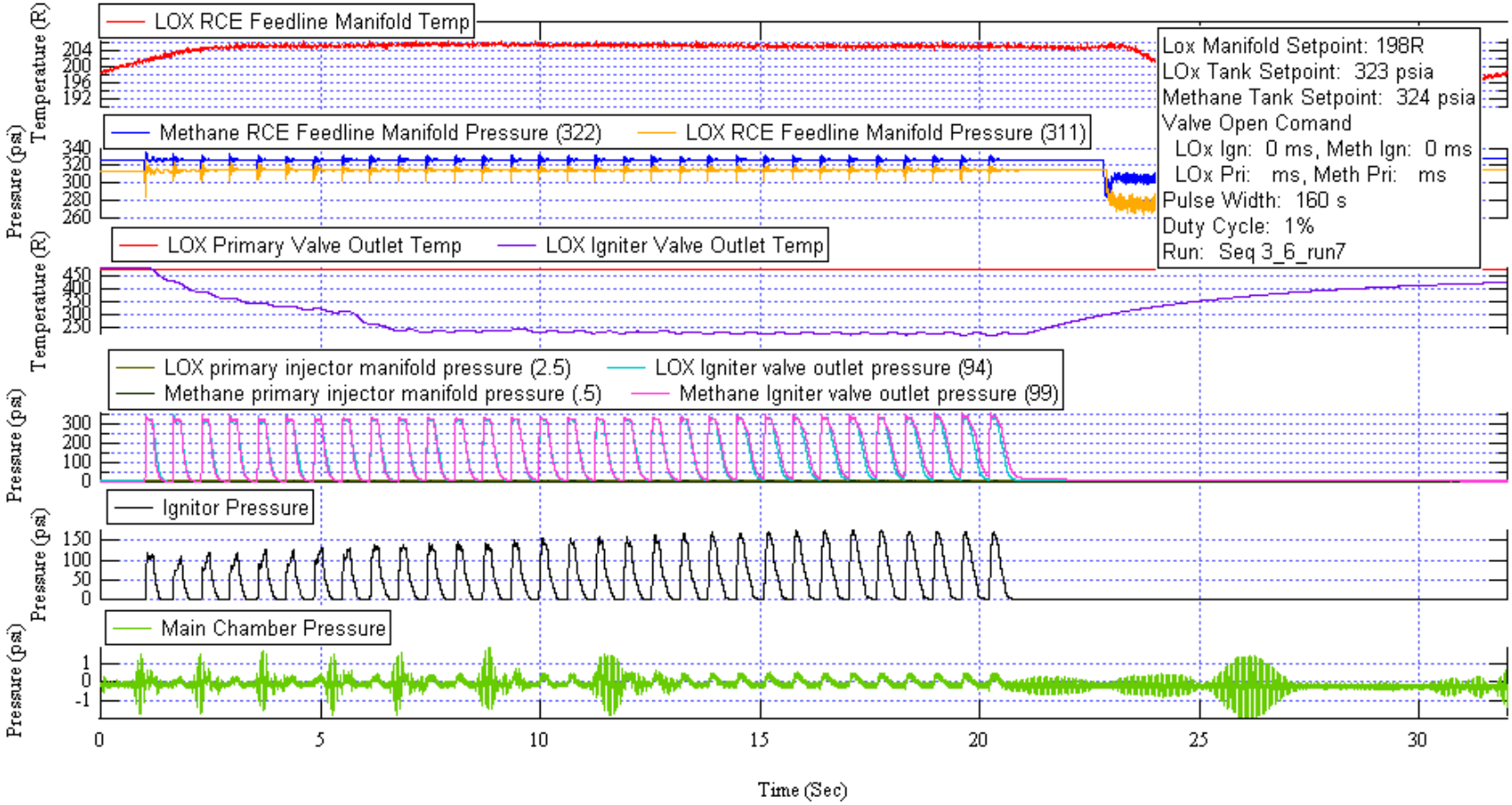
Seq3-5 run 12


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (274)
LOX RCE Feedline Manifold Pressure (507)
Pressure (psi)
Lox Manifold Setpoint: 201R
LOx Tank Setpoint: 275 psia
Methane Tank Setpoint: 274 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: ms, Meth Pri: ms
Pulse Width: 160 ms
Duty Cycle: 1%
Run: Seq 3_5_run12
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (2.7)
LOX Igniter valve outlet pressure (5.9)
Methane primary injector manifold pressure (.4)
Methane Igniter valve outlet pressure (4.9)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
0
100
200
300
400
Time (Sec)

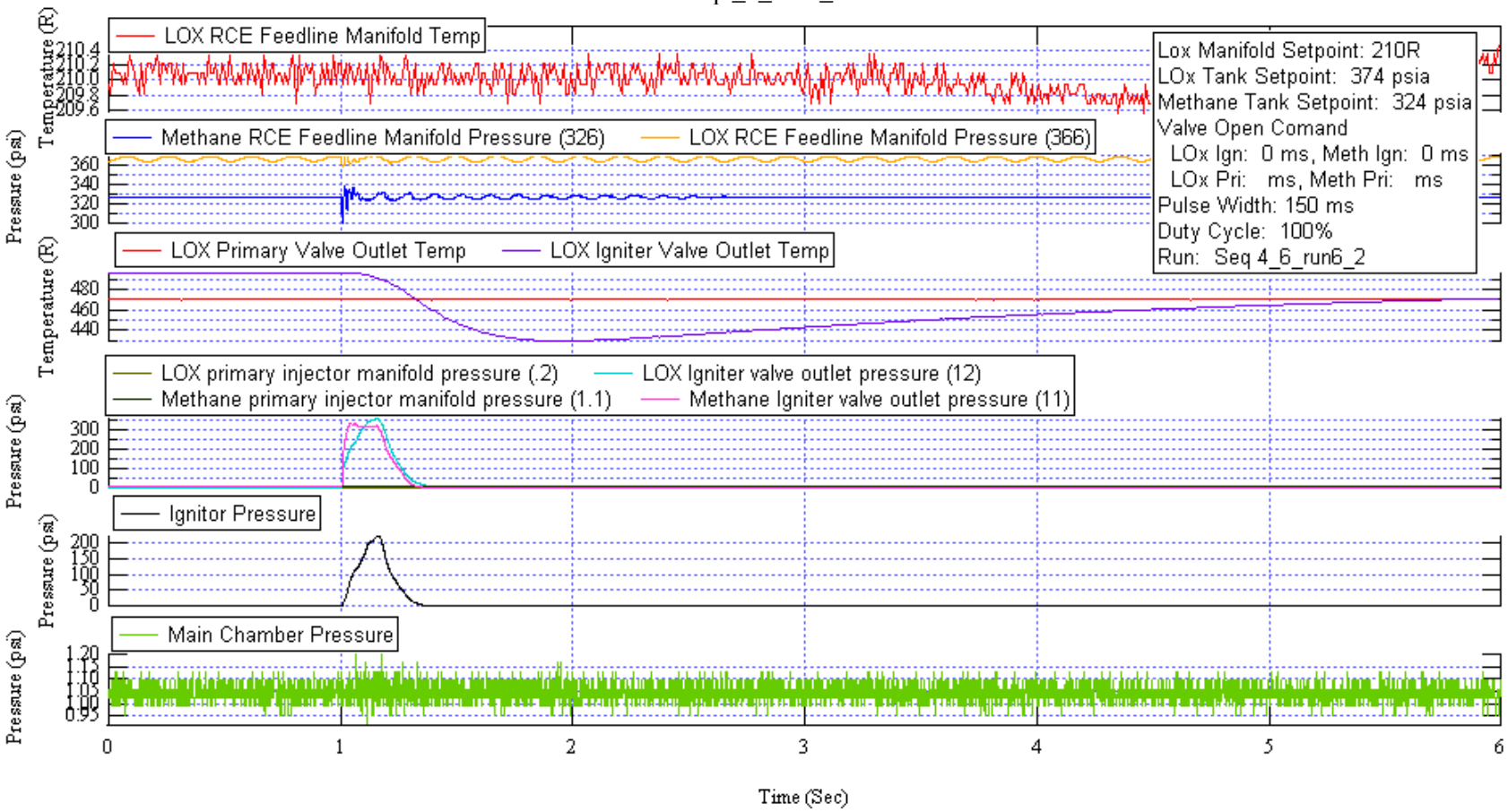
Seq3-6 run 6


Methane RCE Feedline Manifold Pressure (325)
LOX RCE Feedline Manifold Pressure (313)
Lox Manifold Setpoints: ???R
LOx Tank Setpoint: 324 psia
Methane Tank Setpoint: 324 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: ms, Meth Pri: ms
Pulse Width: 160 ms
Duty Cycle: 1%
Run: Seq 3_6_run6
LOX primary injector manifold pressure (2.4)
LOX Igniter valve outlet pressure (27)
Methane primary injector manifold pressure (.4)
Methane Igniter valve outlet pressure (26)
Ignitor Pressure
Main Chamber Pressure
Pressure (psi)
Time (Sec)

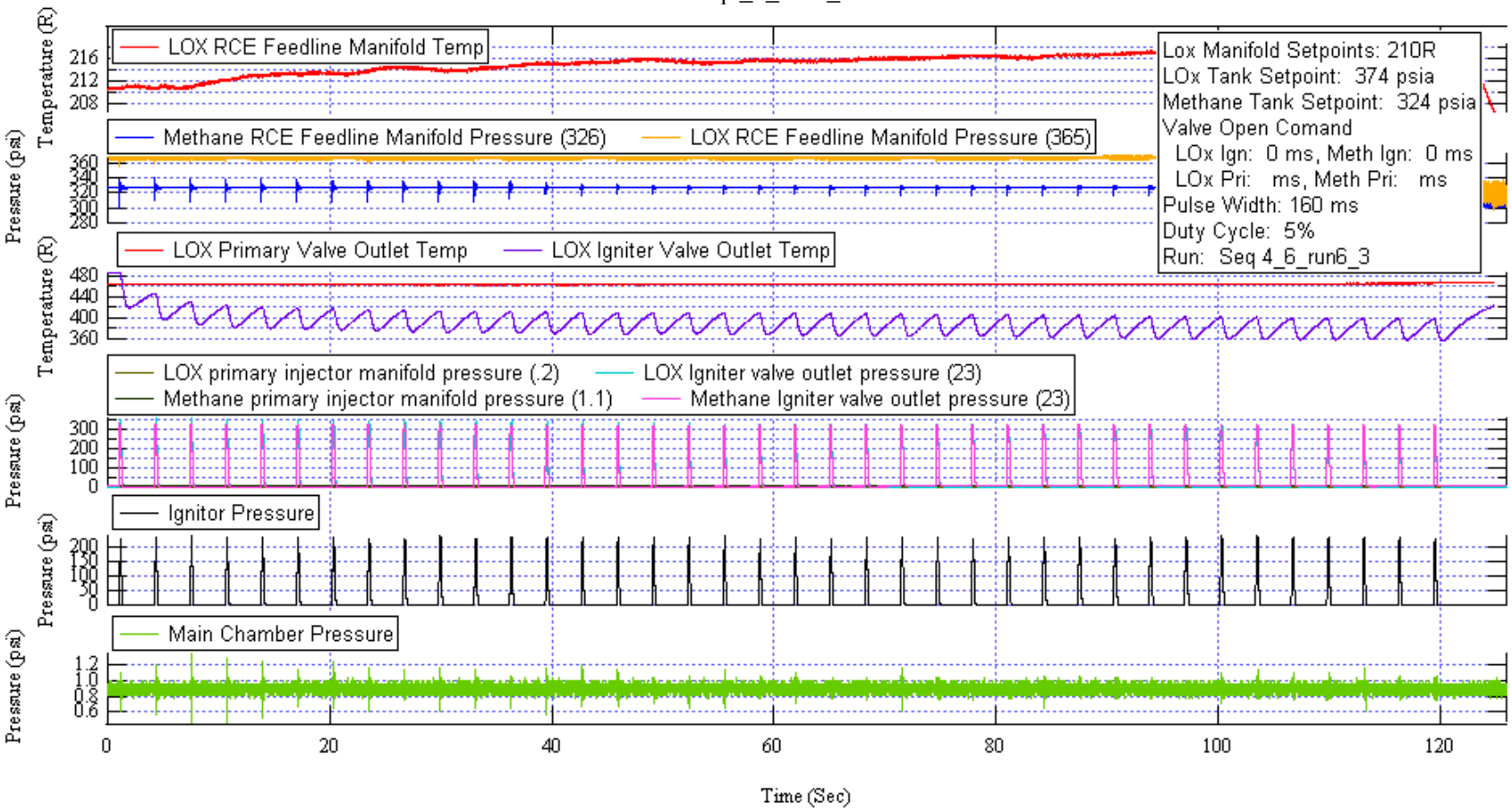
Seq3-7 run 7


LOX RCE Feedline Manifold Temp
Temperature (R)
Lox Manifold Setpoint: 198R
LOx Tank Setpoint: 323 psia
Methane Tank Setpoint: 324 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: ms, Meth Pri: ms
Pulse Width: 160 s
Duty Cycle: 1%
Run: Seq 3_6_run7
Methane RCE Feedline Manifold Pressure (322)
LOX RCE Feedline Manifold Pressure (311)
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (2.5)
LOX Igniter valve outlet pressure (94)
Methane primary injector manifold pressure (.5)
Methane Igniter valve outlet pressure (99)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Time (Sec)

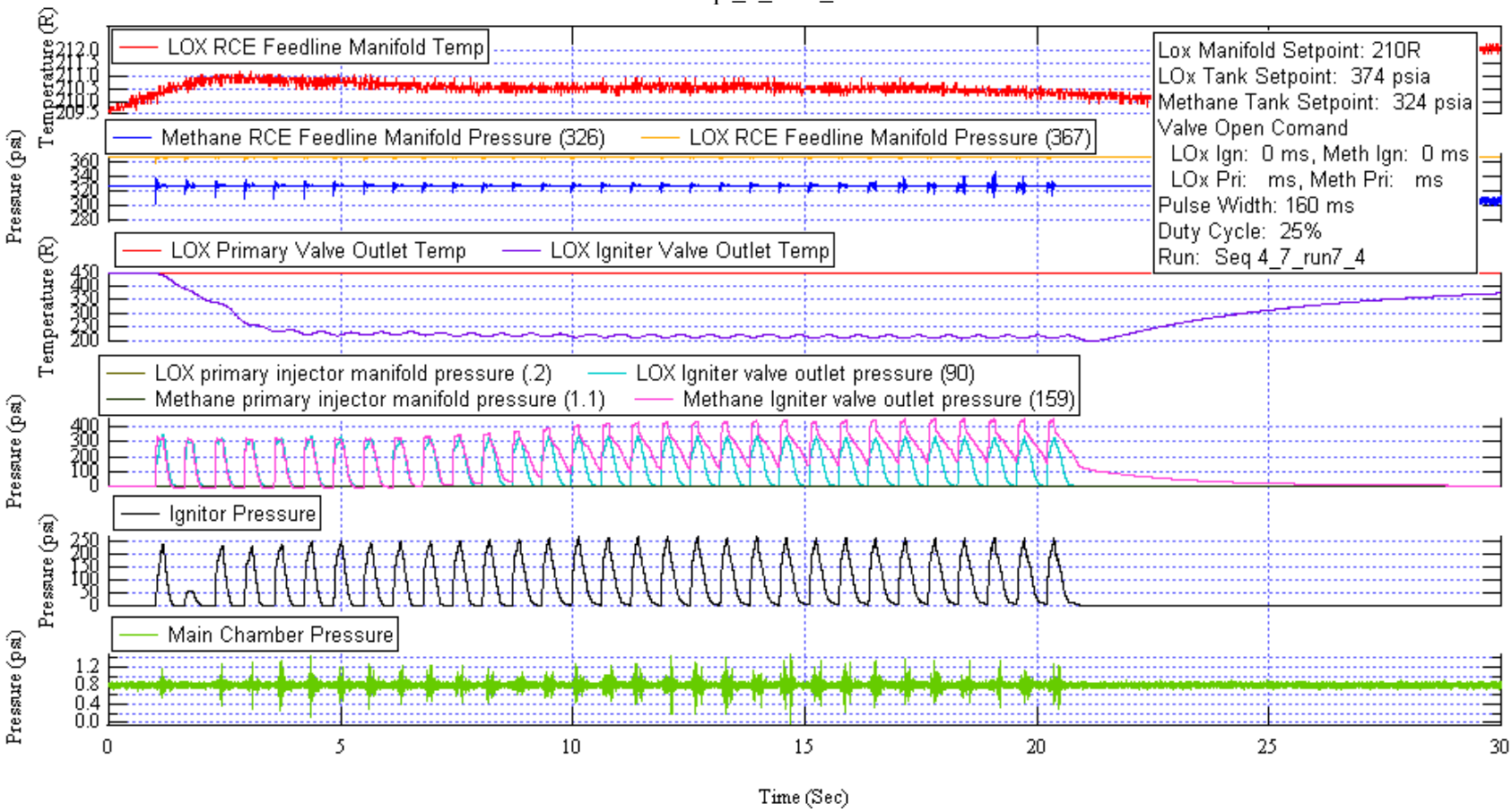
Seq4_6_run6_2


LOX RCE Feedline Manifold Temp
Temperature (R)
Lox Manifold Setpoint: 210R
LOx Tank Setpoint: 374 psia
Methane Tank Setpoint: 324 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: ms, Meth Pri: ms
Pulse Width: 150 ms
Duty Cycle: 100%
Run: Seq 4_6_run6_2
Methane RCE Feedline Manifold Pressure (326)
LOX RCE Feedline Manifold Pressure (366)
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (.2)
LOX Igniter valve outlet pressure (12)
Methane primary injector manifold pressure (1.1)
Methane Igniter valve outlet pressure (11)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Time (Sec)

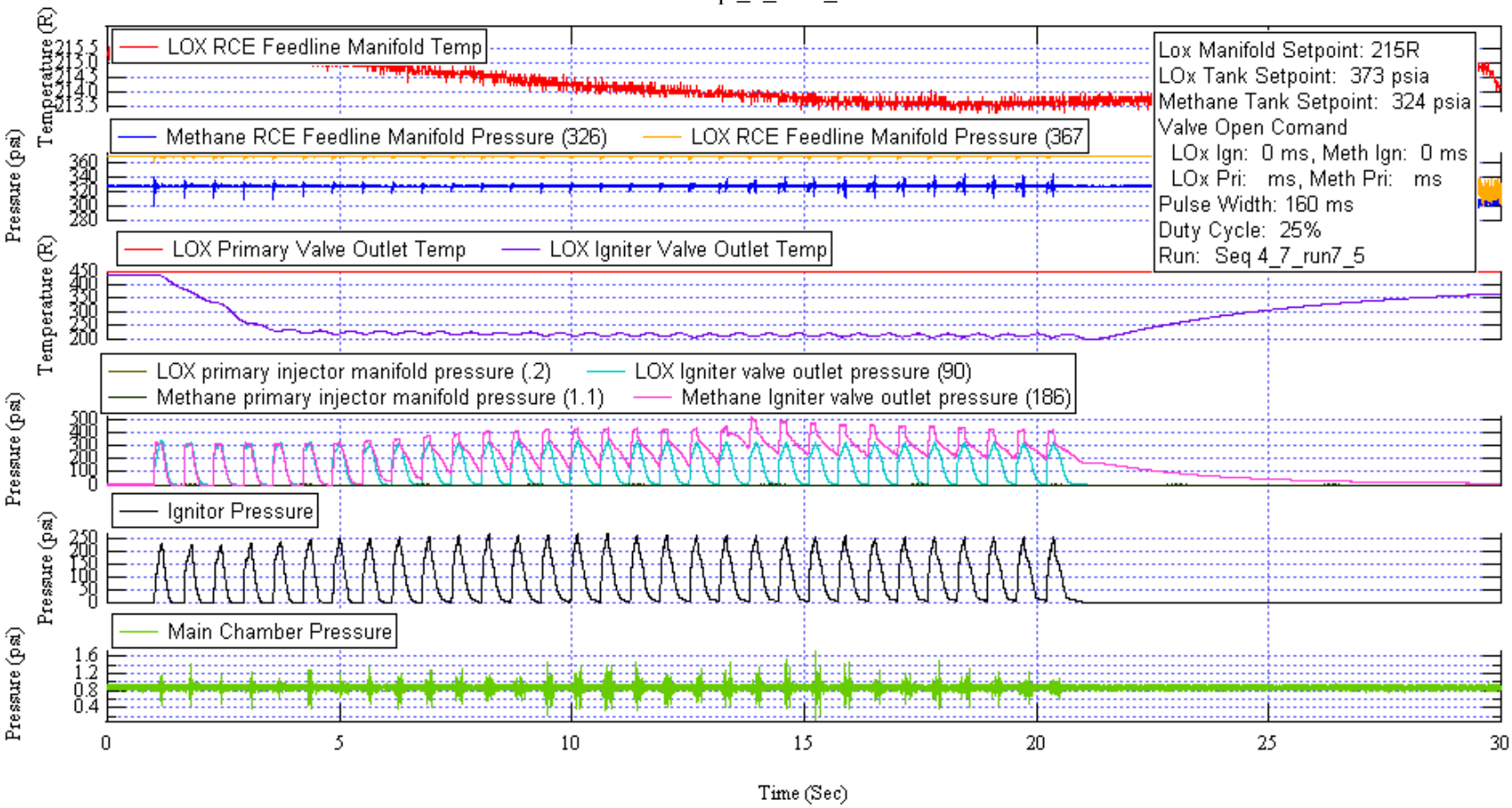
Seq4_6_run6_3


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (326)
LOX RCE Feedline Manifold Pressure (365)
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (.2)
LOX Igniter valve outlet pressure (23)
Methane primary injector manifold pressure (1.1)
Methane Igniter valve outlet pressure (23)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Lox Manifold Setpoints: 210R
LOx Tank Setpoint: 374 psia
Methane Tank Setpoint: 324 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: ms, Meth Pri: ms
Pulse Width: 160 ms
Duty Cycle: 5%
Run: Seq 4_6_run6_3
Time (Sec)

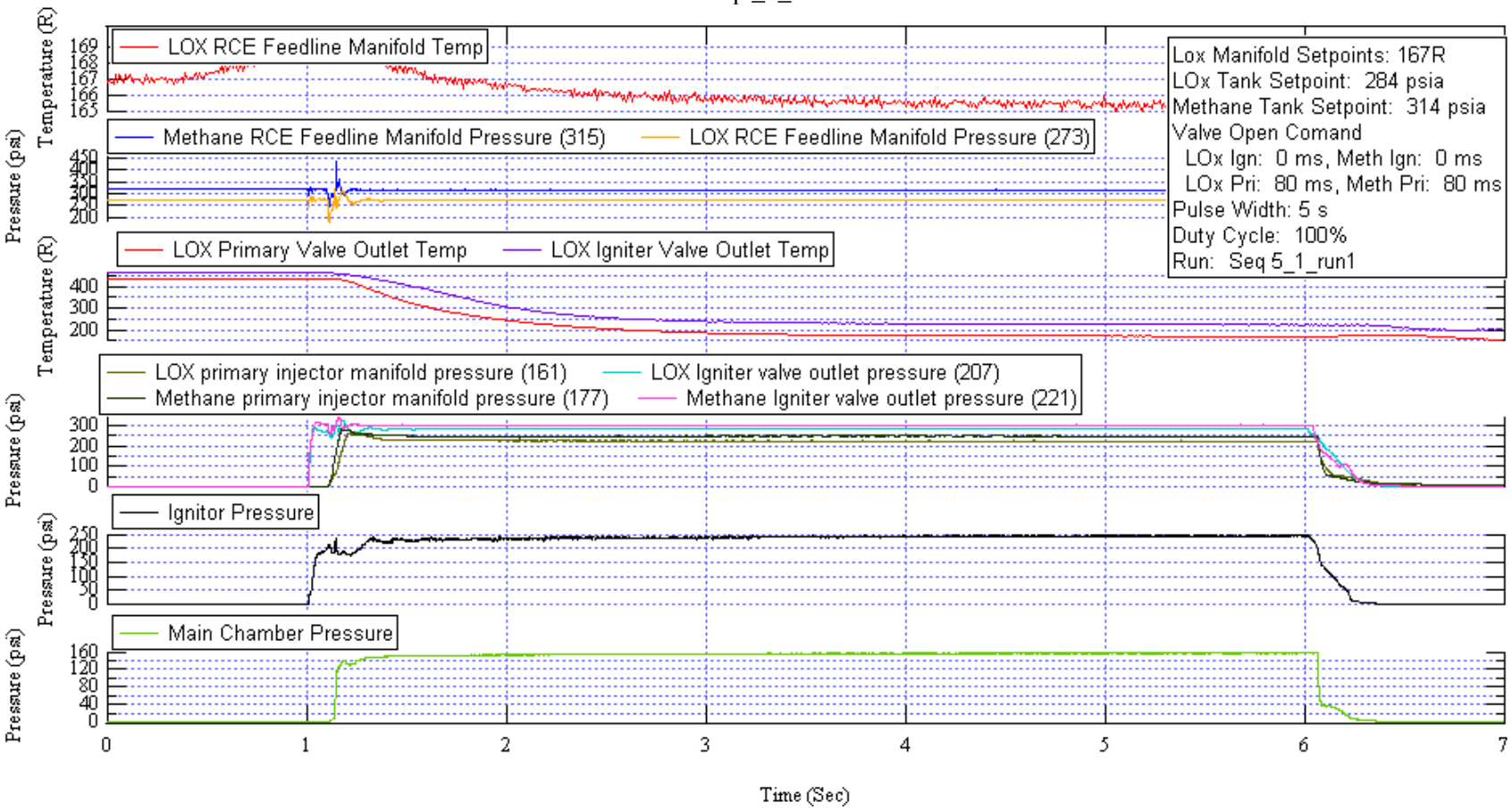
Seq4_7_run7_4


LOX RCE Feedline Manifold Temp
Temperature (R)
Lox Manifold Setpoint: 210R
LOx Tank Setpoint: 374 psia
Methane Tank Setpoint: 324 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: ms, Meth Pri: ms
Pulse Width: 160 ms
Duty Cycle: 25%
Run: Seq 4_7_run7_4
Methane RCE Feedline Manifold Pressure (326)
LOX RCE Feedline Manifold Pressure (367)
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (.2)
LOX Igniter valve outlet pressure (90)
Methane primary injector manifold pressure (1.1)
Methane Igniter valve outlet pressure (159)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Time (Sec)

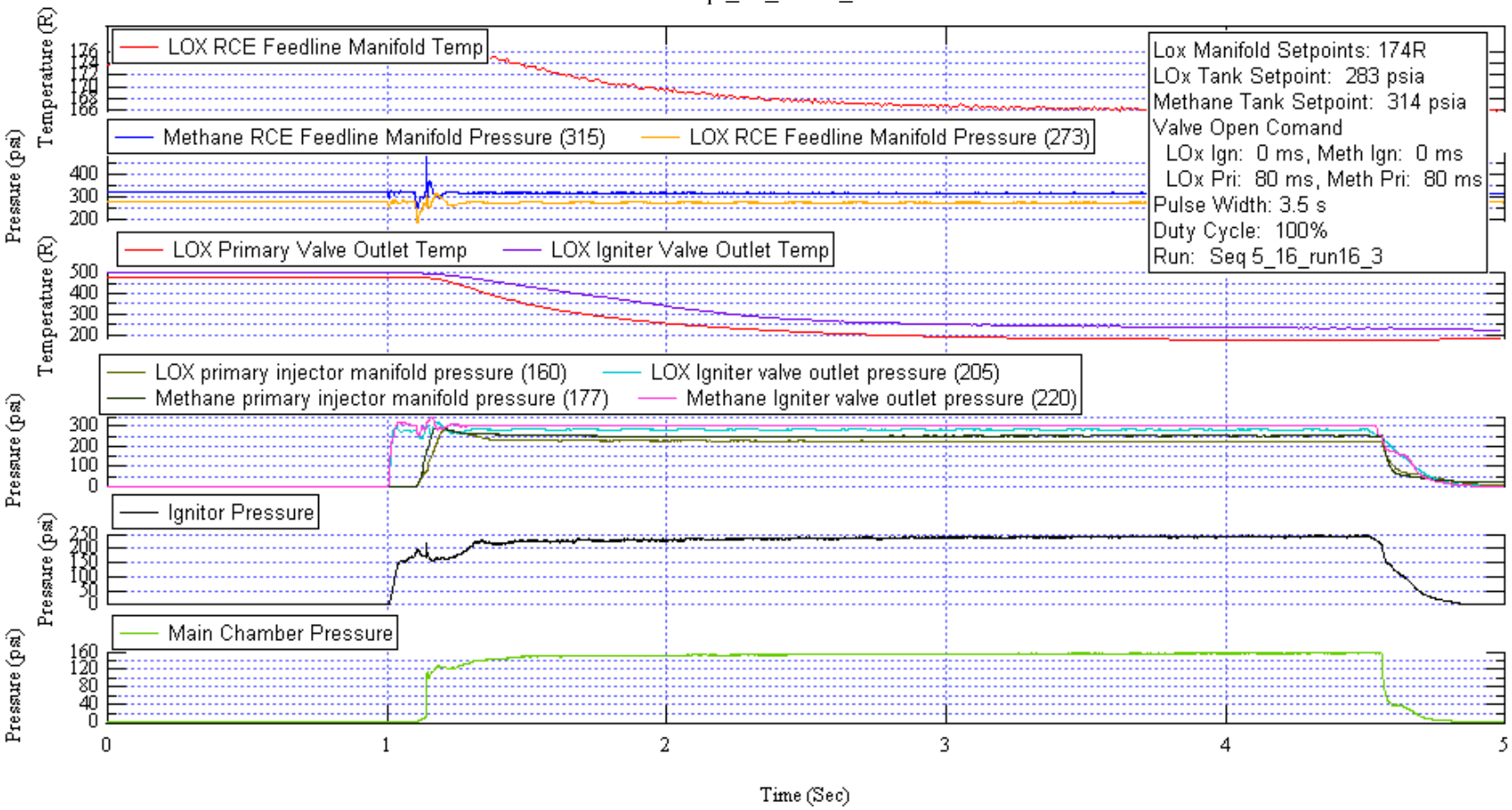
Seq4_7_run7_5


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (326)
LOX RCE Feedline Manifold Pressure (367
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (.2)
LOX Igniter valve outlet pressure (90)
Methane primary injector manifold pressure (1.1)
Methane Igniter valve outlet pressure (186)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Lox Manifold Setpoint: 215R
LOx Tank Setpoint: 373 psia
Methane Tank Setpoint: 324 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: ms, Meth Pri: ms
Pulse Width: 160 ms
Duty Cycle: 25%
Run: Seq 4_7_run7_5
0
5
10
15
20
25
30
Time (Sec)

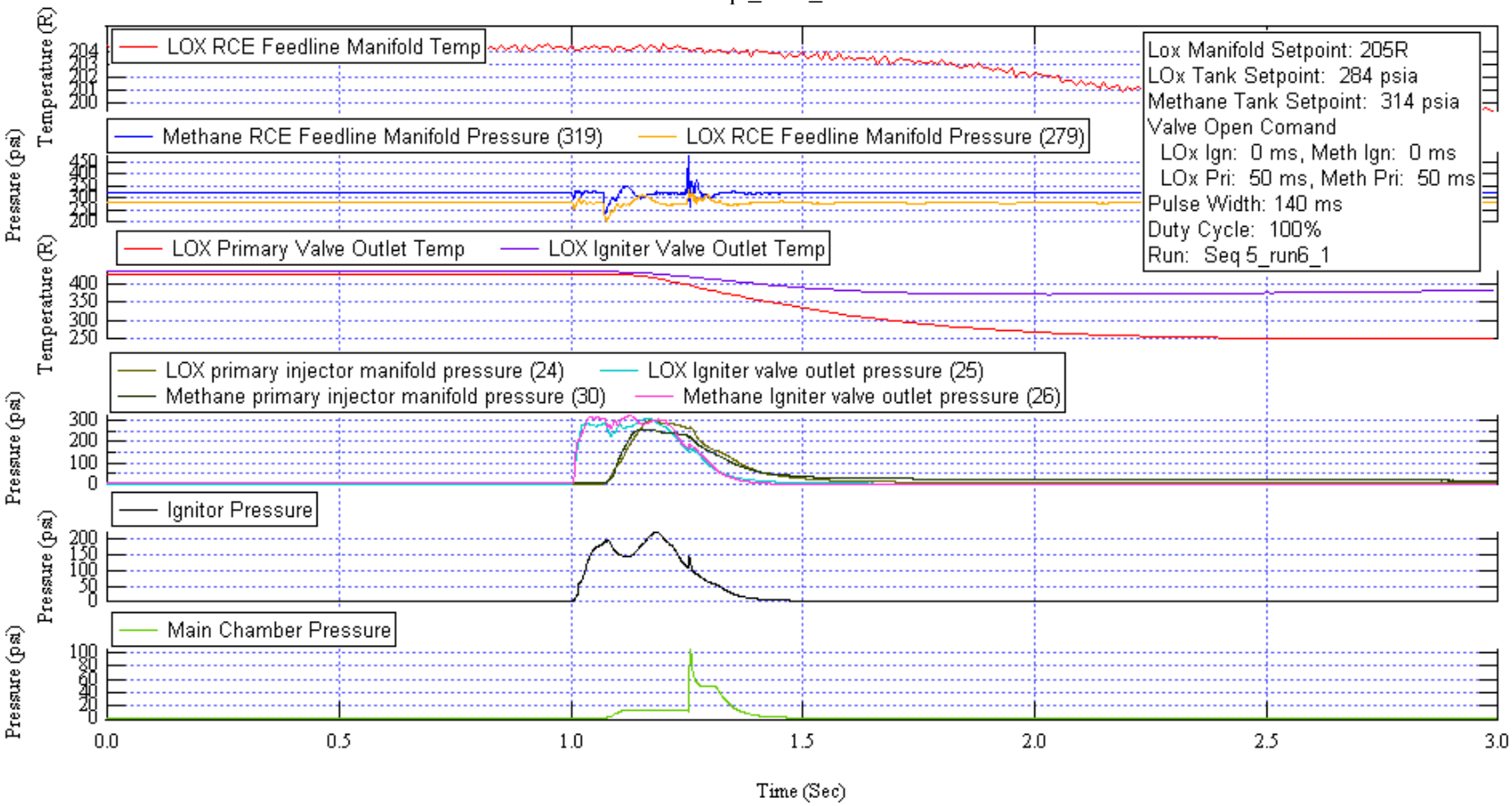
Seq5_1_run1


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (315)
LOX RCE Feedline Manifold Pressure (273)
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (161)
LOX Igniter valve outlet pressure (207)
Methane primary injector manifold pressure (177)
Methane Igniter valve outlet pressure (221)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Time (Sec)
Lox Manifold Setpoints: 167R
LOx Tank Setpoint: 284 psia
Methane Tank Setpoint: 314 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 80 ms, Meth Pri: 80 ms
Pulse Width: 5 s
Duty Cycle: 100%
Run: Seq 5_1_run1

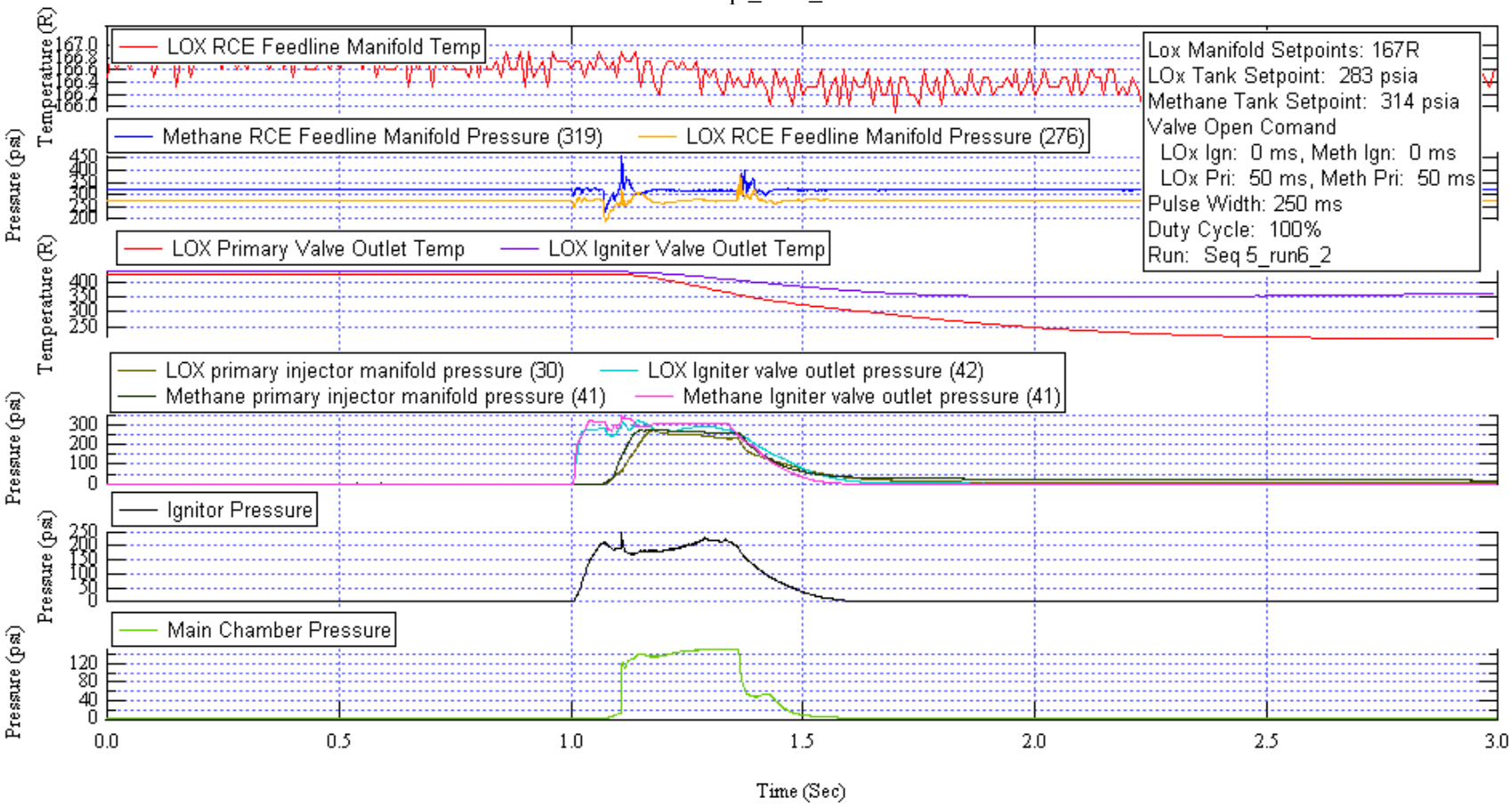
Seq5_16_run16_3



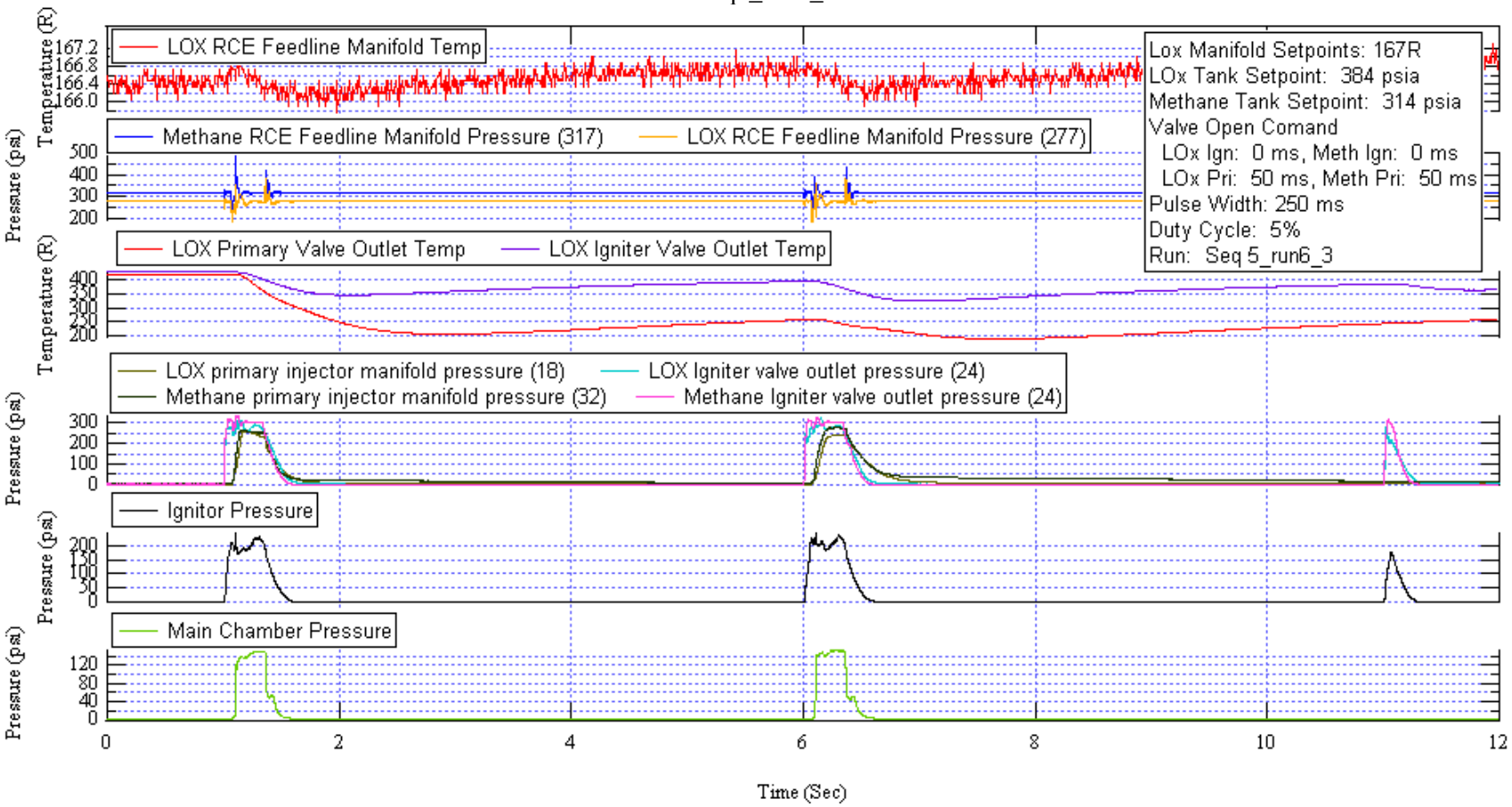
Seq5_run6_1


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (319)
LOX RCE Feedline Manifold Pressure (279)
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (24)
LOX Igniter valve outlet pressure (25)
Methane primary injector manifold pressure (30)
Methane Igniter valve outlet pressure (26)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Lox Manifold Setpoint: 205R
LOx Tank Setpoint: 284 psia
Methane Tank Setpoint: 314 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 50 ms, Meth Pri: 50 ms
Pulse Width: 140 ms
Duty Cycle: 100%
Run: Seq 5_run6_1
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (Sec)

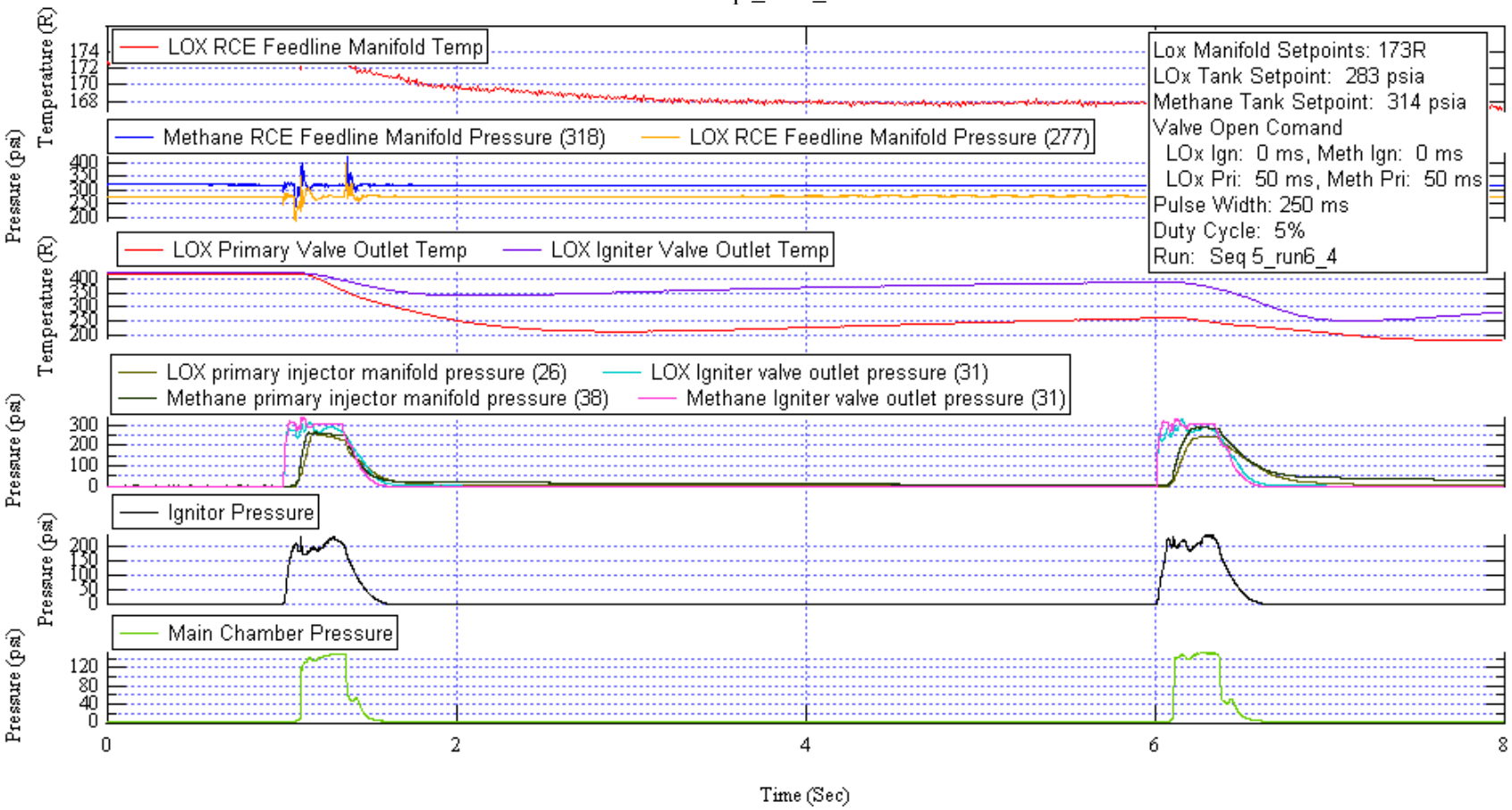
Seq5_run6_2


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (319)
LOX RCE Feedline Manifold Pressure (276)
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (30)
LOX Igniter valve outlet pressure (42)
Methane primary injector manifold pressure (41)
Methane Igniter valve outlet pressure (41)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Lox Manifold Setpoints: 167R
LOx Tank Setpoint: 283 psia
Methane Tank Setpoint: 314 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 50 ms, Meth Pri: 50 ms
Pulse Width: 250 ms
Duty Cycle: 100%
Run: Seq 5_run6_2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (Sec)

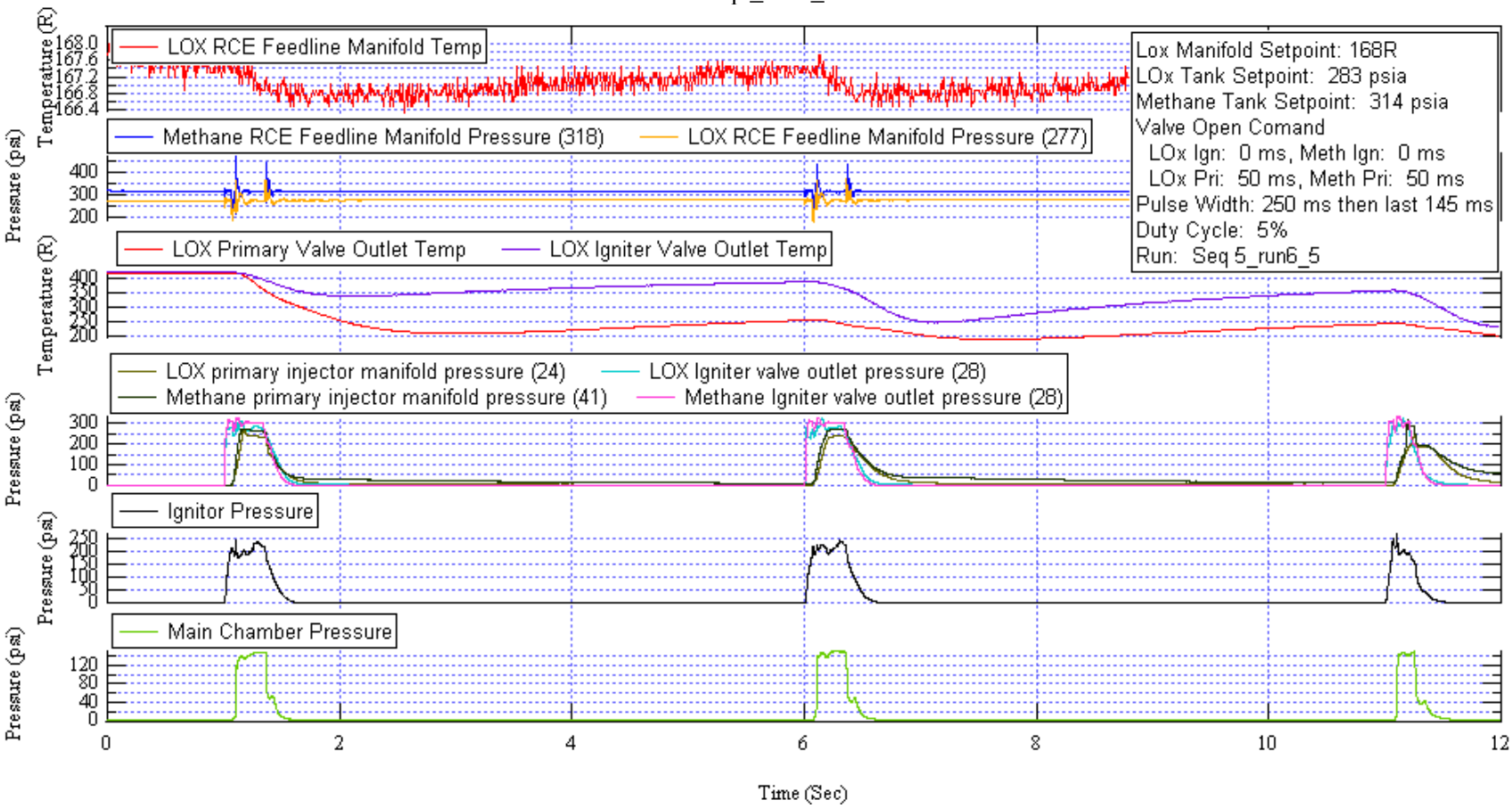
Seq5_run6_3


LOX RCE Feedline Manifold Temp
Temperature (R)
167.2
166.8
166.4
166.0
Methane RCE Feedline Manifold Pressure (317)
LOX RCE Feedline Manifold Pressure (277)
Pressure (psi)
500
400
300
200
Lox Manifold Setpoints: 167R
LOx Tank Setpoint: 384 psia
Methane Tank Setpoint: 314 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 50 ms, Meth Pri: 50 ms
Pulse Width: 250 ms
Duty Cycle: 5%
Run: Seq 5_run6_3
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
400
350
300
250
200
LOX primary injector manifold pressure (18)
LOX Igniter valve outlet pressure (24)
Methane primary injector manifold pressure (32)
Methane Igniter valve outlet pressure (24)
Pressure (psi)
300
200
100
0
Ignitor Pressure
Pressure (psi)
200
150
100
50
0
Main Chamber Pressure
Pressure (psi)
120
80
40
0
0
2
4
6
8
10
12
Time (Sec)

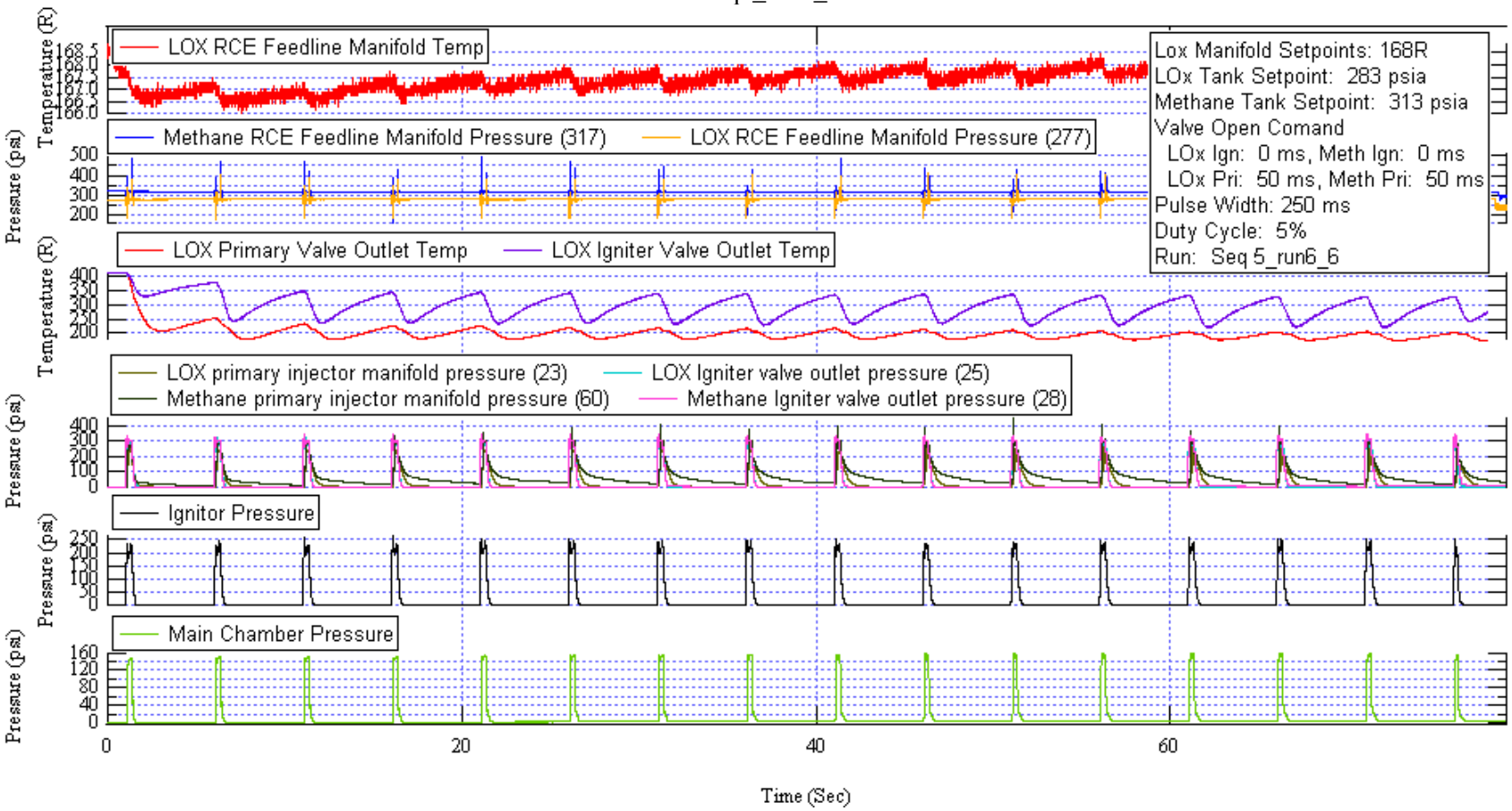
Seq5_run6_4


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (318)
LOX RCE Feedline Manifold Pressure (277)
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (26)
LOX Igniter valve outlet pressure (31)
Methane primary injector manifold pressure (38)
Methane Igniter valve outlet pressure (31)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Lox Manifold Setpoints: 173R
LOx Tank Setpoint: 283 psia
Methane Tank Setpoint: 314 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 50 ms, Meth Pri: 50 ms
Pulse Width: 250 ms
Duty Cycle: 5%
Run: Seq 5_run6_4
Time (Sec)

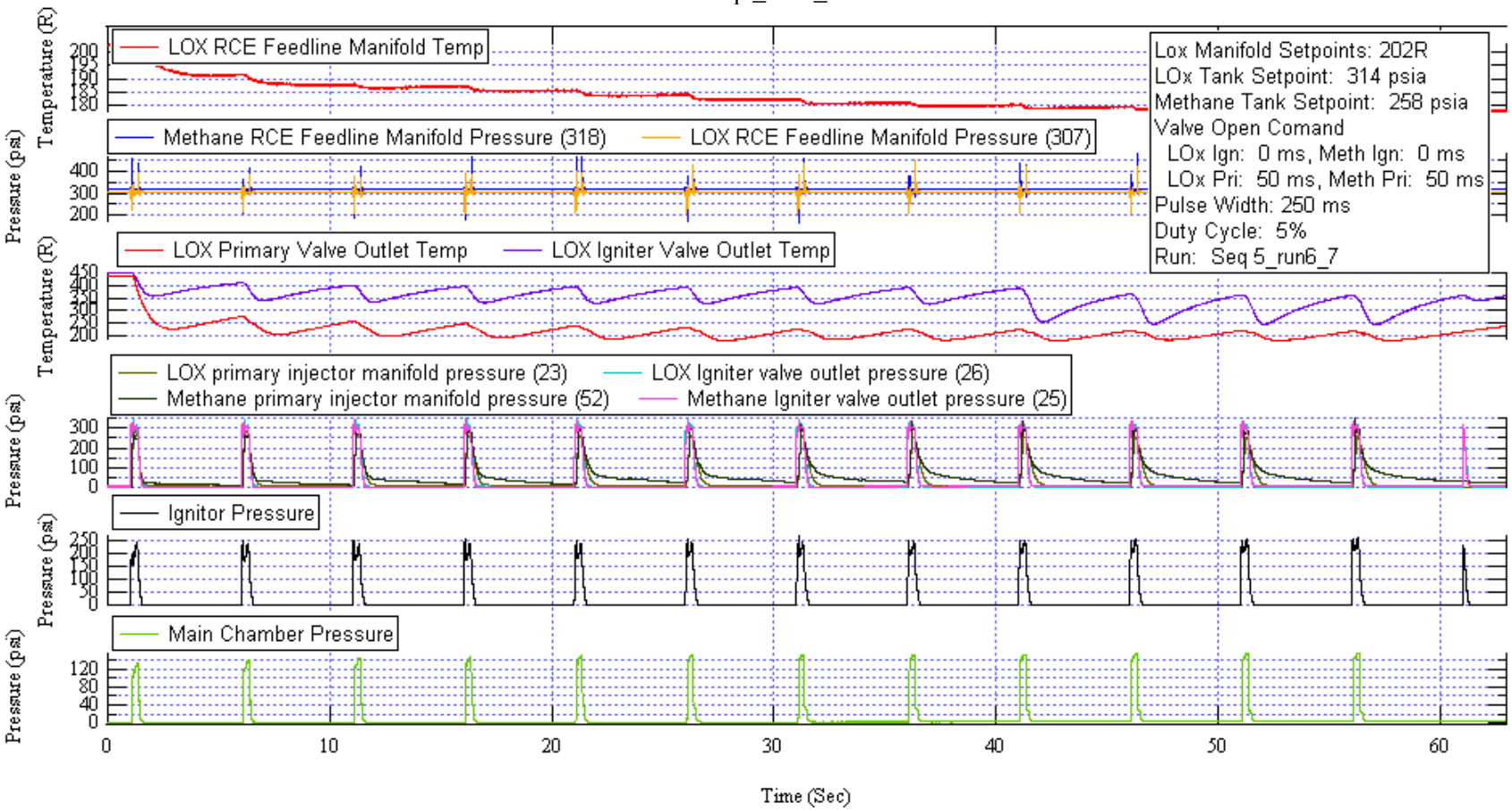
Seq5_run6_5


LOX RCE Feedline Manifold Temp
Temperature (R)
168.0
167.6
167.2
166.8
166.4
Methane RCE Feedline Manifold Pressure (318)
LOX RCE Feedline Manifold Pressure (277)
Pressure (psi)
400
300
200
Lox Manifold Setpoint: 168R
LOx Tank Setpoint: 283 psia
Methane Tank Setpoint: 314 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 50 ms, Meth Pri: 50 ms
Pulse Width: 250 ms then last 145 ms
Duty Cycle: 5%
Run: Seq 5_run6_5
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
400
350
300
250
200
LOX primary injector manifold pressure (24)
LOX Igniter valve outlet pressure (28)
Methane primary injector manifold pressure (41)
Methane Igniter valve outlet pressure (28)
Pressure (psi)
300
200
100
0
Ignitor Pressure
Pressure (psi)
250
200
150
100
50
0
Main Chamber Pressure
Pressure (psi)
120
80
40
0
0
2
4
6
8
10
12
Time (Sec)

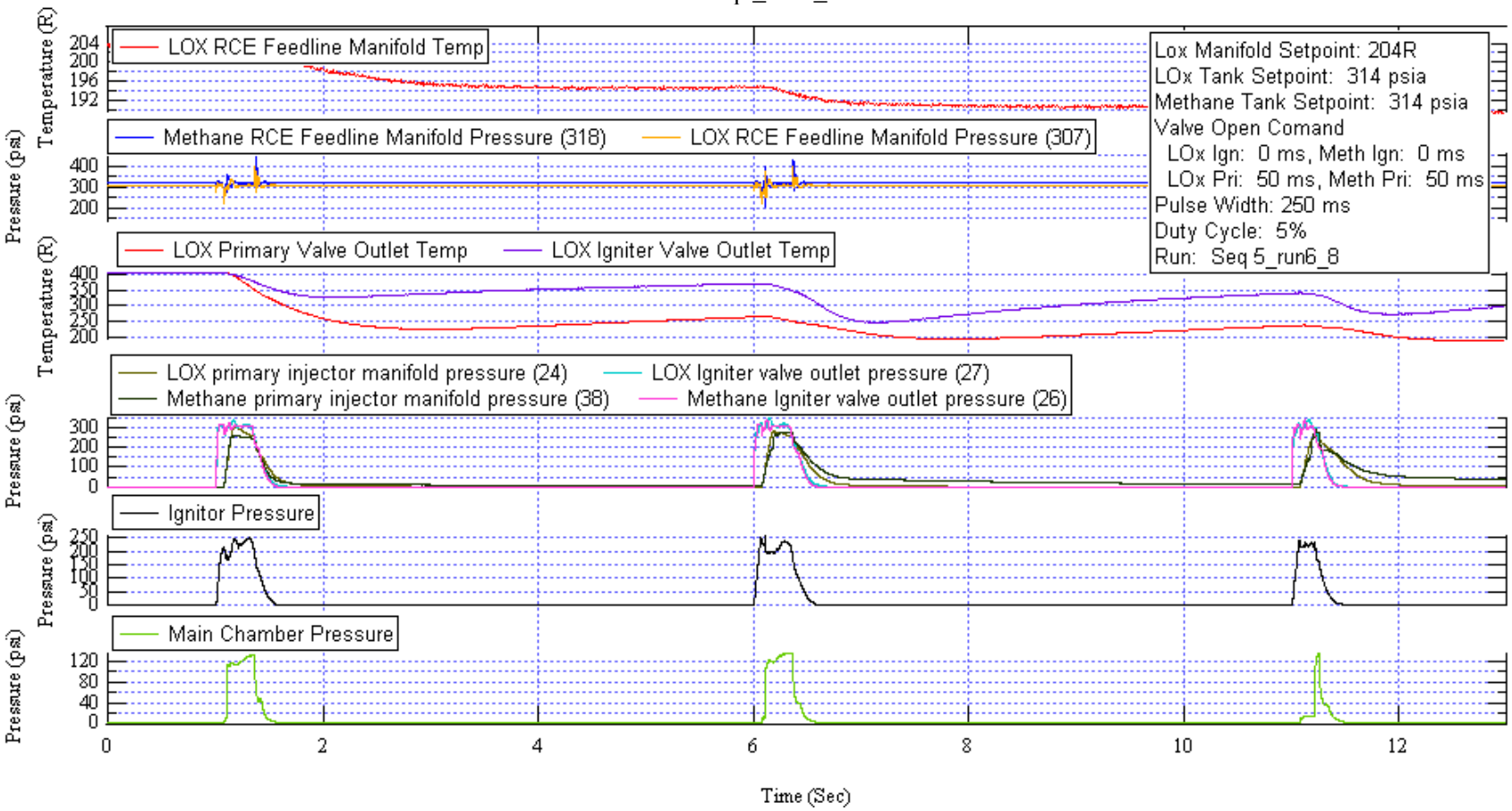
Seq5_run6_6


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (317)
LOX RCE Feedline Manifold Pressure (277)
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (23)
LOX Igniter valve outlet pressure (25)
Methane primary injector manifold pressure (60)
Methane Igniter valve outlet pressure (28)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Lox Manifold Setpoints: 168R
LOx Tank Setpoint: 283 psia
Methane Tank Setpoint: 313 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 50 ms, Meth Pri: 50 ms
Pulse Width: 250 ms
Duty Cycle: 5%
Run: Seq 5_run6_6
0
20
40
60
Time (Sec)

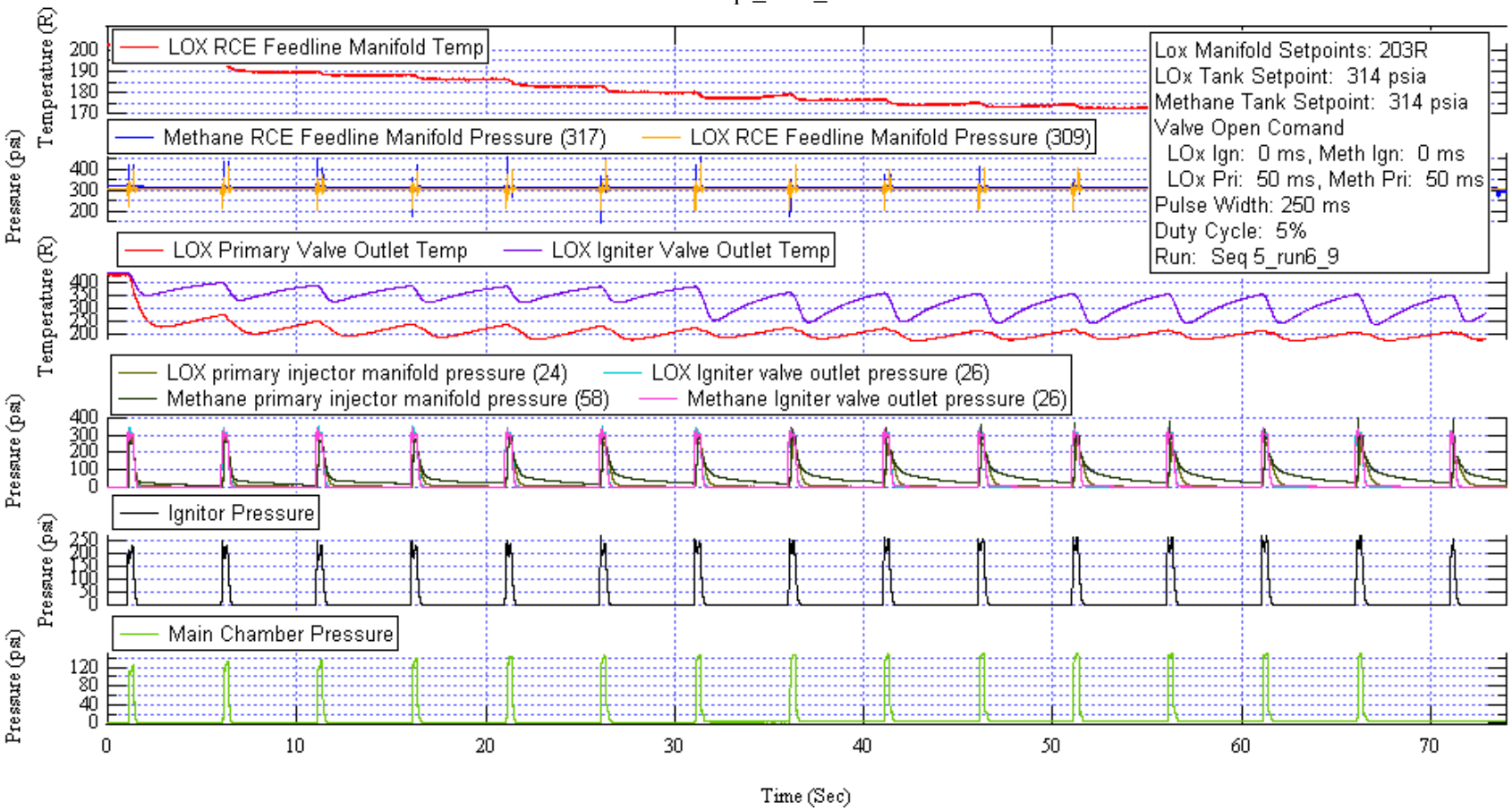
Seq5_run6_7


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (318)
LOX RCE Feedline Manifold Pressure (307)
Pressure (psi)
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (23)
LOX Igniter valve outlet pressure (26)
Methane primary injector manifold pressure (52)
Methane Igniter valve outlet pressure (25)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Time (Sec)
Lox Manifold Setpoints: 202R
LOx Tank Setpoint: 314 psia
Methane Tank Setpoint: 258 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 50 ms, Meth Pri: 50 ms
Pulse Width: 250 ms
Duty Cycle: 5%
Run: Seq 5_run6_7

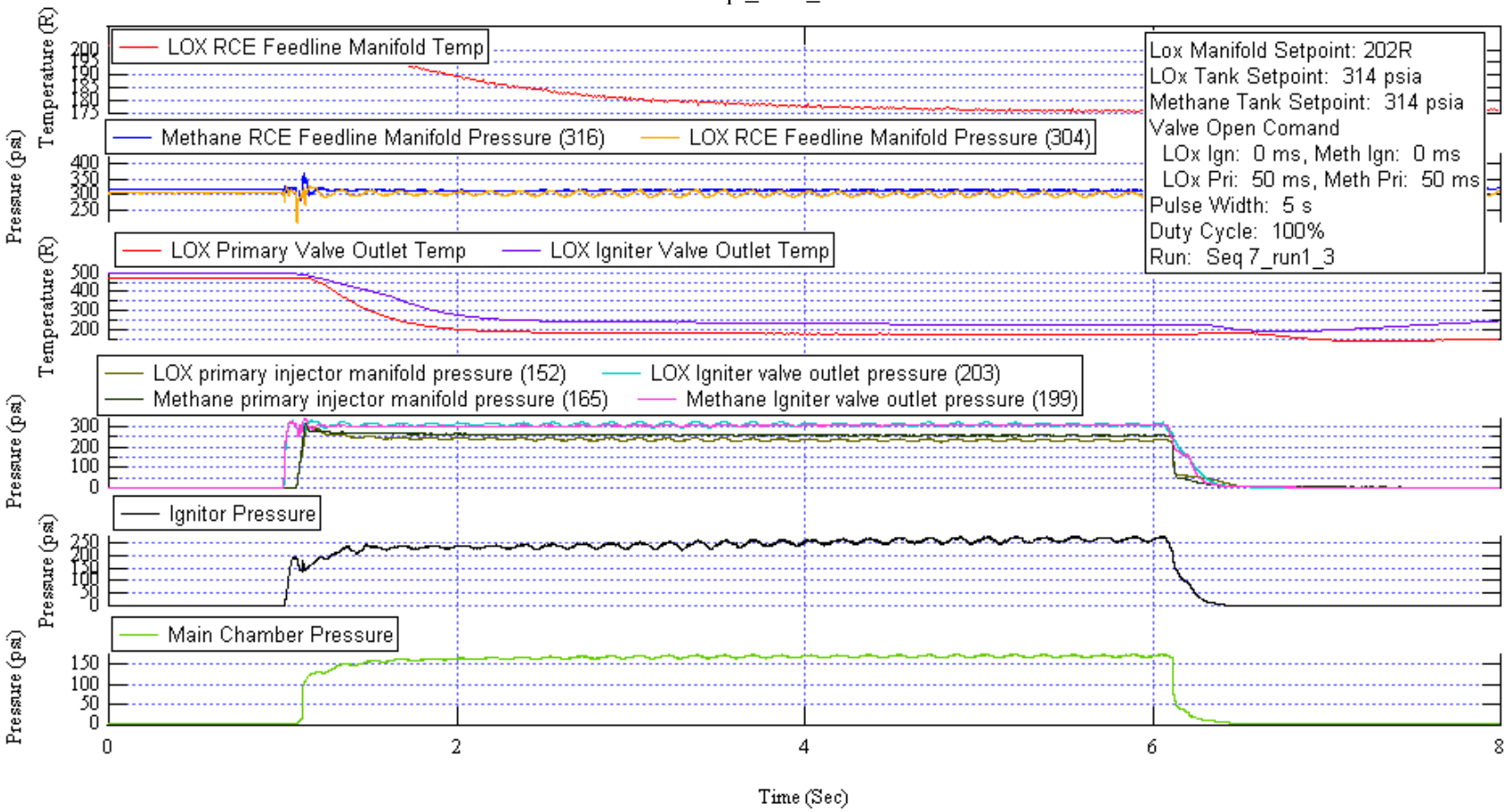
Seq5_run6_8


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (318)
LOX RCE Feedline Manifold Pressure (307)
Pressure (psi)
Lox Manifold Setpoint: 204R
LOx Tank Setpoint: 314 psia
Methane Tank Setpoint: 314 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 50 ms, Meth Pri: 50 ms
Pulse Width: 250 ms
Duty Cycle: 5%
Run: Seq 5_run6_8
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (24)
LOX Igniter valve outlet pressure (27)
Methane primary injector manifold pressure (38)
Methane Igniter valve outlet pressure (26)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Time (Sec)

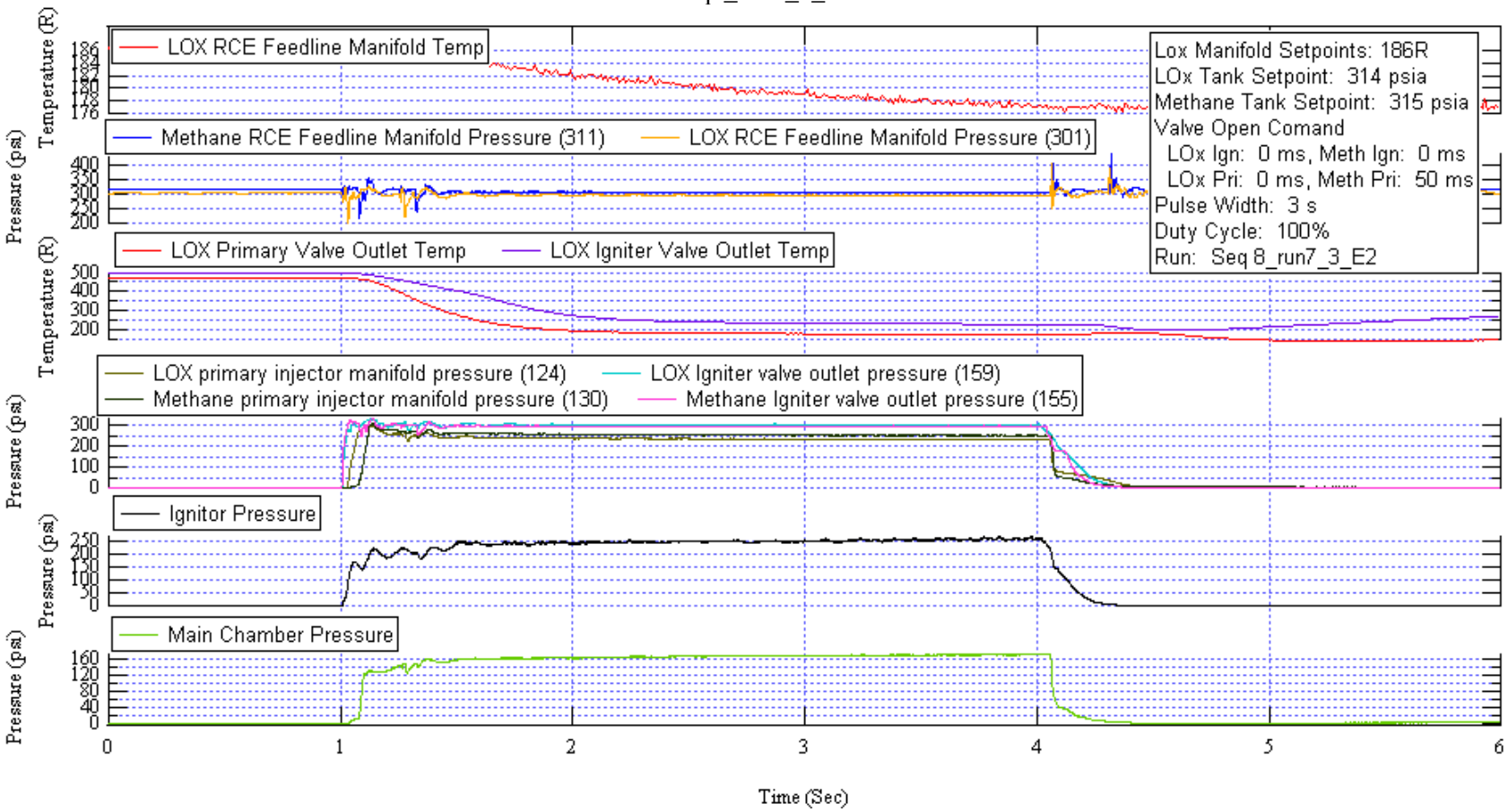
Seq5_run6_9


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (317)
LOX RCE Feedline Manifold Pressure (309)
Pressure (psi)
Lox Manifold Setpoints: 203R
LOx Tank Setpoint: 314 psia
Methane Tank Setpoint: 314 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 50 ms, Meth Pri: 50 ms
Pulse Width: 250 ms
Duty Cycle: 5%
Run: Seq 5_run6_9
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (24)
LOX Igniter valve outlet pressure (26)
Methane primary injector manifold pressure (58)
Methane Igniter valve outlet pressure (26)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Time (Sec)

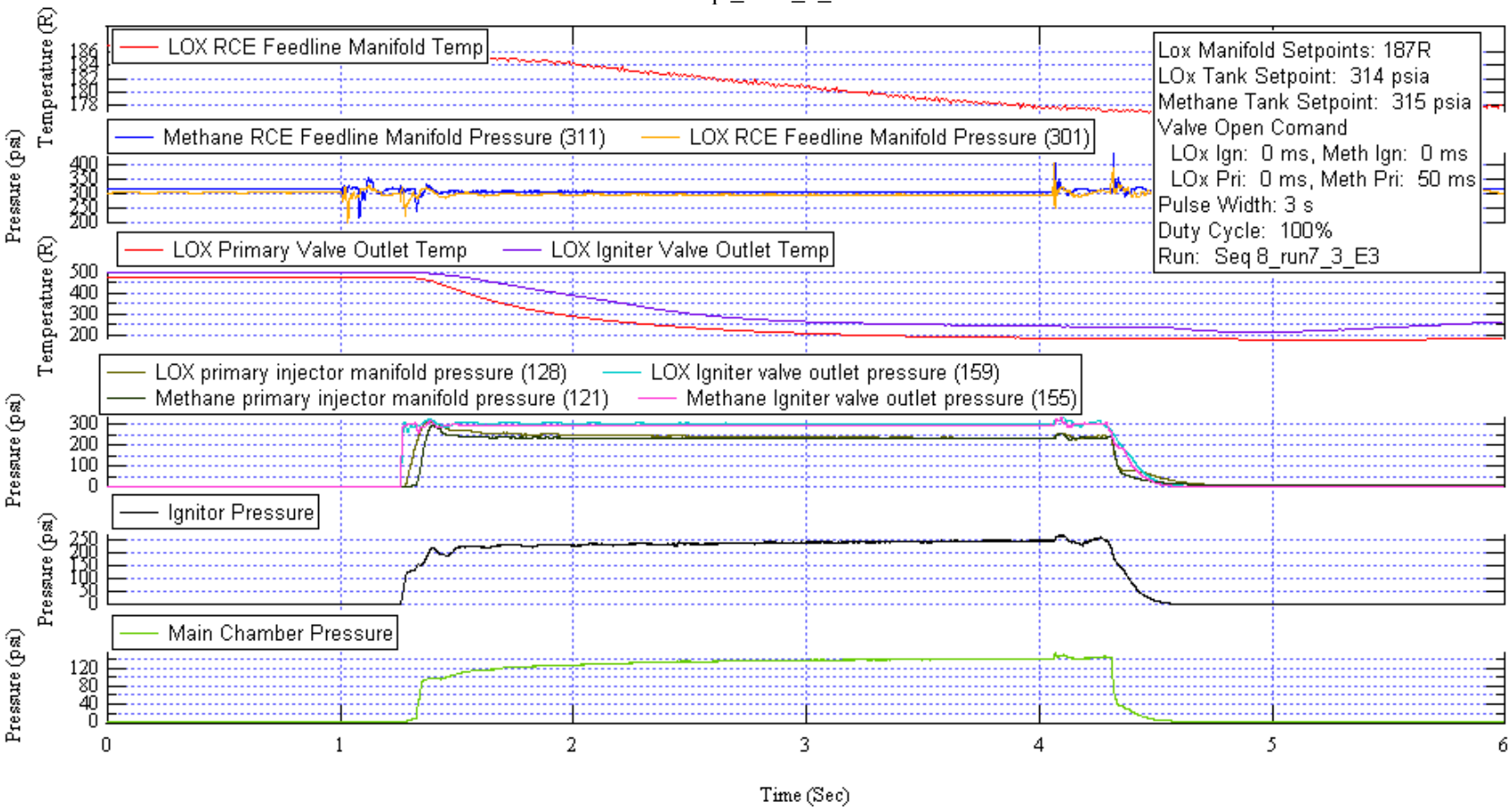
Seq7_run1_3


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (316)
LOX RCE Feedline Manifold Pressure (304)
Pressure (psi)
Lox Manifold Setpoint: 202R
LOx Tank Setpoint: 314 psia
Methane Tank Setpoint: 314 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 50 ms, Meth Pri: 50 ms
Pulse Width: 5 s
Duty Cycle: 100%
Run: Seq 7_run1_3
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (152)
LOX Igniter valve outlet pressure (203)
Methane primary injector manifold pressure (165)
Methane Igniter valve outlet pressure (199)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Time (Sec)

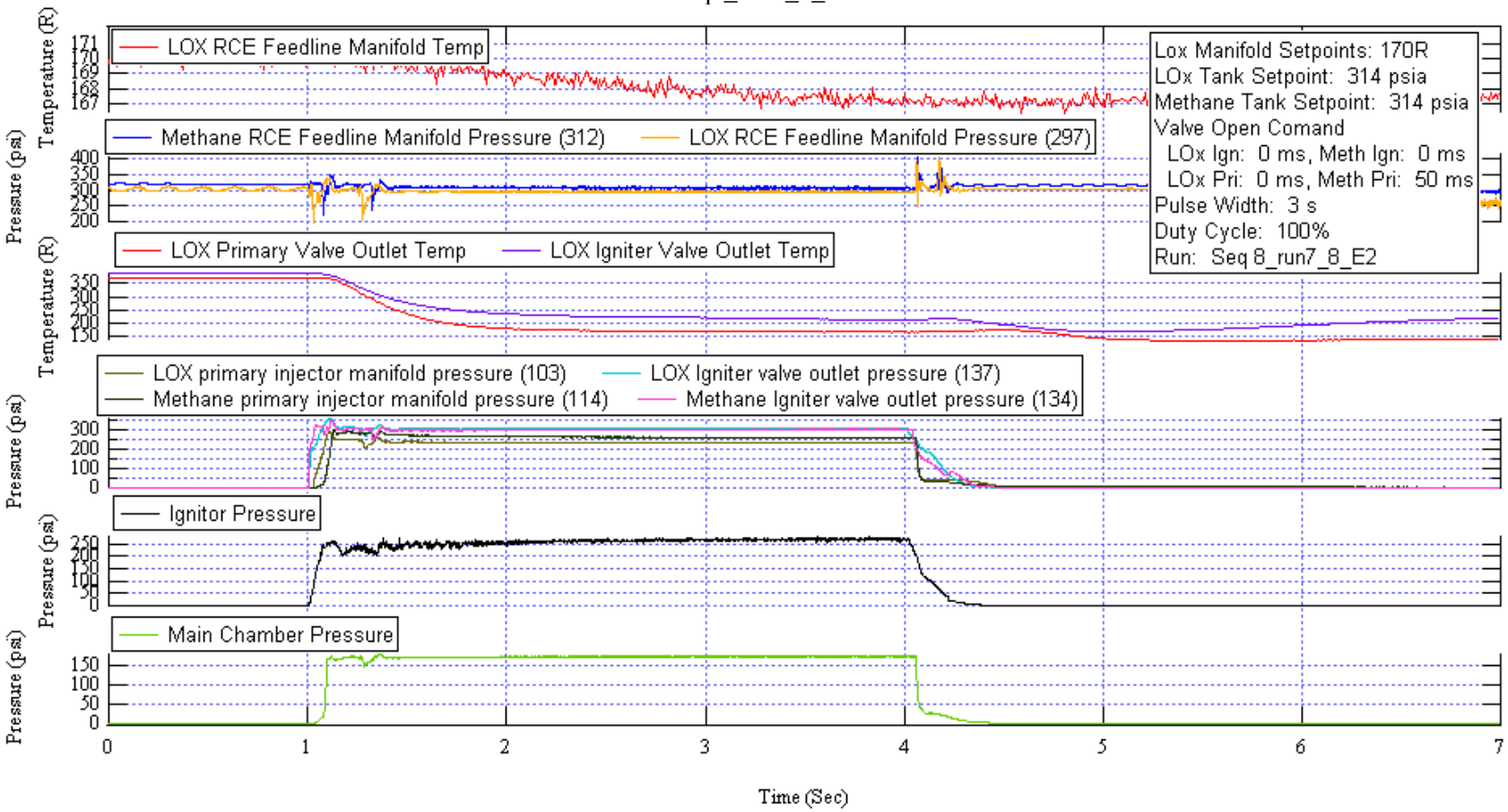
Seq8_run7_3_E2



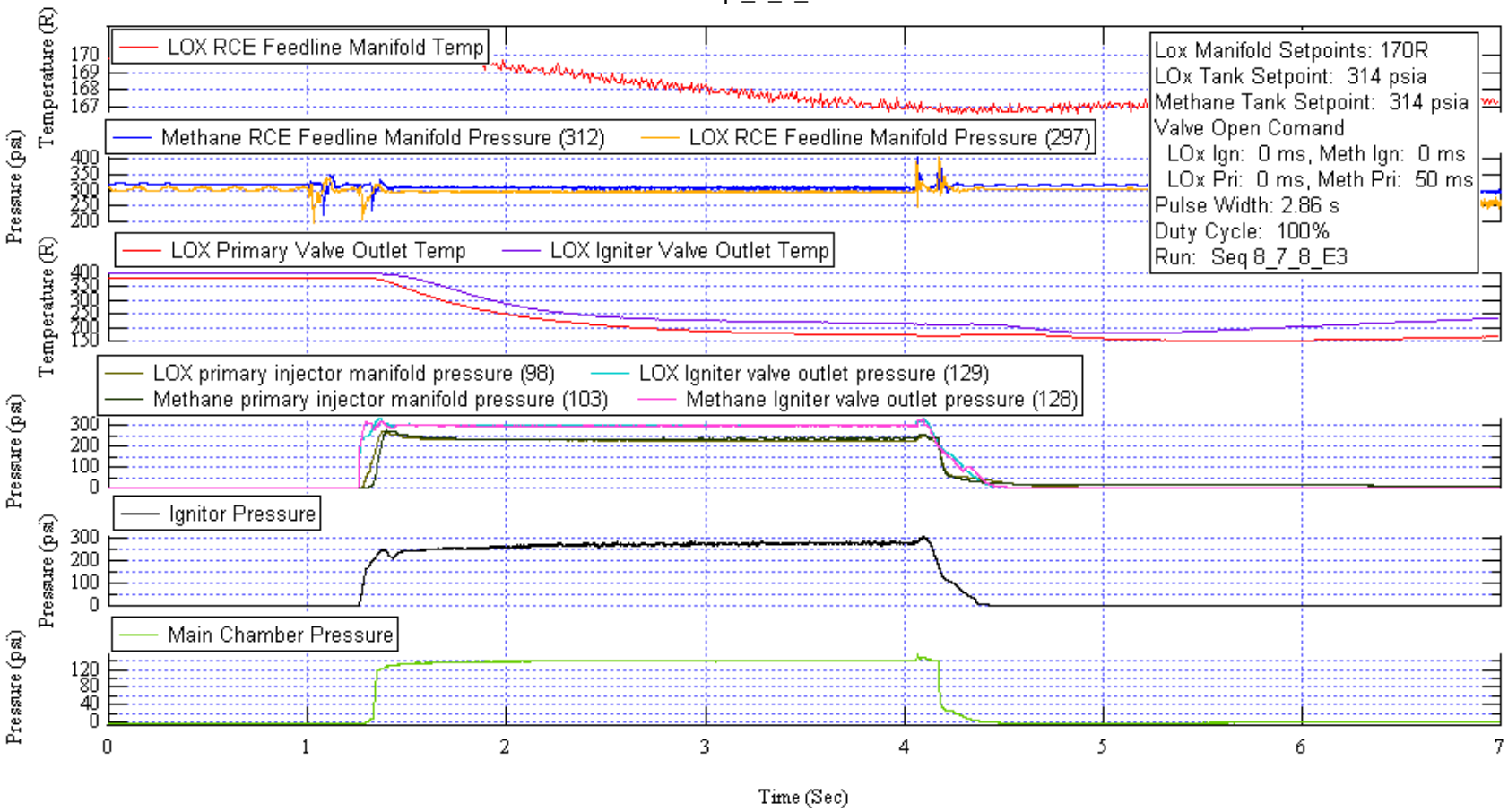
Seq8_run7_3_E3



Seq8_run7_8_E2



Seq8_7_8_E3


LOX RCE Feedline Manifold Temp
Temperature (R)
Methane RCE Feedline Manifold Pressure (312)
LOX RCE Feedline Manifold Pressure (297)
Pressure (psi)
Lox Manifold Setpoints: 170R
LOx Tank Setpoint: 314 psia
Methane Tank Setpoint: 314 psia
Valve Open Comand
LOx Ign: 0 ms, Meth Ign: 0 ms
LOx Pri: 0 ms, Meth Pri: 50 ms
Pulse Width: 2.86 s
Duty Cycle: 100%
Run: Seq 8_7_8_E3
LOX Primary Valve Outlet Temp
LOX Igniter Valve Outlet Temp
Temperature (R)
LOX primary injector manifold pressure (98)
LOX Igniter valve outlet pressure (129)
Methane primary injector manifold pressure (103)
Methane Igniter valve outlet pressure (128)
Pressure (psi)
Ignitor Pressure
Pressure (psi)
Main Chamber Pressure
Pressure (psi)
Time (Sec)

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13. ABSTRACT *(Maximum 200 words)*
Since 2001, the National Aeronautics and Space Administration (NASA) has worked to develop spacecraft reaction control systems (RCSs) that use nontoxic and cryogenic propellant combinations, such as liquid oxygen (LO2) and ethanol and LO2 and liquid methane (LCH4), as alternatives to common systems that rely on the highly toxic and more expensive hypergolic fuels. Compared with these propellants, cryogenics offer higher performance, easier ground handling, and can be generated in situ on the Moon or Mars. System studies have shown performance benefits for an integrated main engine and RCS that reduces mass and simplifies the system. However, advanced technology is required to store cryogenic propellants in liquid form and feed them to a pulsing RCS engine. Testing began with the firing of three 870-lbf (3870-N) thrust engines on a LO2/ethanol feed system; the engines were later modified and fired on a LO2/LCH4 feed system across a matrix of propellant inlet temperatures and pressures, engine duty cycles, and pulse times. 1,685 firings using LO2/ethanol propellants and 733 firings using LO2/LCH4 propellants were completed. The impulse bit pulse-to-pulse repeatability of both the LO2/ethanol and LO2/LCH4 thrusters was typically within 5%. Several problems related to igniter ignition reliability were uncovered and resolved, and it was determined that more oxygen in the main chamber was required for reliable main-stage ignition. The hardware proved durable given the number of off-nominal engine firings, and the cryogenic feed system and Thermodynamic Vent System (TVS) were able to maintain propellant temperatures within tight tolerances. Overall, LCH4 is a better match with LO2 than ethanol because of its lower freezing point and higher vapor pressure.

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