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EVALUATION OF FUTURE FUELS IN A HIGH PRESSURE COMMON RAIL SYSTEM
PART 1 – CUMMINS XPI

INTERIM REPORT
TFLRF No. 429

by
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Warren, Michigan

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EXECUTIVE SUMMARY

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FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period of April 2009 through October 2012 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank-Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-DP/MS110) served as the TARDEC contracting officer's technical representative. Ms. Patsy Muzzell of TARDEC served as the project technical monitor.

The authors would like to acknowledge the contribution of the TFLRF technical support staff along with the administrative and report-processing support provided by Dianna Barrera.

TABLE OF CONTENTS

Section **Page**

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

%	Percent
ASTM	American Society for Testing and Materials
˚C	Degrees Centigrade
CI/LI	Corrosion Inhibitor/Lubricity Improver
cSt	CentiStoke
ECM	Electronic Control Module
˚F	Degrees Fahrenheit
FT	Fischer-Tropsch
HDO	Heavy Duty Oil
HPCR	High Pressure Common Rail
mm	Millimeter
NATO	North Atlantic Treaty Organization
OEM	Original Equipment Manufacturer
psi	Pounds per square inch
RPM	Revolutions per minute
SAE	Society of Automotive Engineers
SPK	Synthetic-Paraffinic Kerosene
SwRI	Southwest Research Institute
TARDEC	Tank Automotive Research, Development and Engineering Center
ULSD	Ultra Low Sulfur Diesel
WSD	Wear Scar Diameter

1.0 BACKGROUND AND OBJECTIVE

As industries begin to incorporate renewable and synthetic fuel sources into global supply, it is in the interest of the U.S. Army to ensure satisfactory ground vehicle operation both now and in the future. With new aviation fuel properties differing from those of their petroleum-based counterparts, evaluations are required to validate performance in reciprocating engine fuel injection systems. As environmental regulations drive commercial Original Equipment Manufacturers (OEM) to reach lower emission levels, the high pressure common rail (HPCR) injection system has become broadly utilized. These systems can operate at pressure up to 30,000 psi to produce multiple highly atomized injection events per cycle. It is critical for the U.S. Army to determine the effect of various future fuels on these systems which are intended for operation on ultra low sulfur diesel. While many older vehicles in the military fleet do not utilize HPCR, it is likely that future commercial engines adapted for military use will.

2.0 APPROACH

2.1 TEST FUELS AND TEMPERATURES

The initial test plan included four fuels operated at two temperatures each. These fuels were to be Ultra Low Sulfur Diesel (ULSD), JP-8, a Fischer-Tropsch (FT) process Synthetic Paraffinic Kerosene (SPK) with a maximum treat rate of corrosion inhibitor/lubricity improver (CI/LI) of 22.5 ppm, and a 50% blend of the JP-8 and SPK test fuels. The temperatures evaluated were 60°C and 93.3°C at the inlet to fuel system components, giving an indication as to possible performance at elevated ambient conditions and high load. As testing progressed, results indicated that the system was less sensitive to low viscosity, low lubricity fuels than originally thought. Due to this, changes to the test plan were made to replace the high temperature ULSD and SPK tests from the original matrix with 60°C evaluations of Jet-A and SPK test fuels without lubricity improver. A summary of the fuels is shown in Table 1.

Table 1. Project Test Fuels

Fuel	Test Temp. (°C)	Viscosity @ Temp. (cSt)	Lubricity (Fresh), WSD (mm)	
			ASTM D5001	ASTM D6079
Ultra Low Sulfur Diesel	60	1.90	0.54	0.382
JP-8	60	0.89	0.67	0.647
JP-8	93.3	0.65	0.67	0.647
SPK (with CI/LI)	60	0.99	0.59	0.681
50% JP-8, 50% SPK (with CI/LI)	60	0.94	0.67	0.670
50% JP-8, 50% SPK (with CI/LI)	93.3	0.67	0.67	0.670
Jet-A	60	0.81	0.81	0.750
SPK (Neat)	60	0.95	1.01	0.663

2.2 TEST CYCLE

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, “load” was determined based upon the accelerator pedal percentage input supplied to the ECM. This value was read over the J1939 communications protocol. The pump was driven at the speed which it would turn if run on an engine, half that of the crankshaft. The operating modes for the cycle are shown in Table 2.

Table 2. NATO Cycle for XPI Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	400	0	0.5
2	1050	100	2
3	1155	0	0.5
4	788	100	1
*5	400 to 1050	0 to 100	2
6	630	100	0.5
7	400	0	0.5
8	1081	70	0.5
9	650	100	2
10	650	50	0.5

**Step 5 cycles between idle and rated conditions*

2.3 TEST STAND AND FUEL SYSTEM

2.3.1 Fuel Pump

The XPI system was developed jointly between Cummins, Inc. and Scania. Primarily targeted for Cummins midrange and Scania heavy duty applications, an oil-lubricated fuel pump allows the system to reach rail and injection pressures of up to 30,000 psi. It is operated at half engine speed to reach a rated condition of 1050 rpm (based upon the engine calibration used for testing). The XPI high pressure pump features a combination of low pressure gear pump and high pressure piston pump driven by a common shaft. The full pump is shown in Figure 1 and Figure 2. It should be noted that the pump shown was in a state of partial disassembly for information purposes and that photographs are of the pump used in low temperature ULSD testing.

Figure 1. XPI Pump – Drive Input

Figure 2. XPI Pump – Gear Pump Side

Power is provided to the pump via the tapered shaft located at the front. The shaft gear, not shown, meshes with the cam gear on the engine to provide speed and timing. Lubricating oil is provided through an orifice on the front of the pump from the engine oil galley and is allowed to drain out through the front bearing. The two cams on the shaft each feature three lobes which drive the high pressure pistons. The combination of two cams with three lobes each allows the pump to impart new fuel into the high pressure rail as each injector fires. Figure 3 shows the oil-lubricated portion of the pump with other components removed.

Figure 3. Main Pump Body

Each spring sits in a roller-follower tappet as shown in Figure 4. Oil flowing from the inlet orifice on the front of the pump passes through the roller on the bottom of the tappets to maintain lubrication throughout the pump housing.

Figure 4. Roller-Followers

These springs are compressed against the underside of the pump head to maintain contact with the pump camshaft. The underside of the pump head is shown in Figure 5.

Figure 5. High Pressure Pump Head

The two barrel retainers located on the underside of the pump head hold the ceramic plungers which develop the high pressures within the pump. The plungers are driven into the barrels by the tappets as the shaft turns. They are forced back out by fuel from the low pressure gear pump using a system of check valves located in the pump head. This is illustrated in Figure 6.

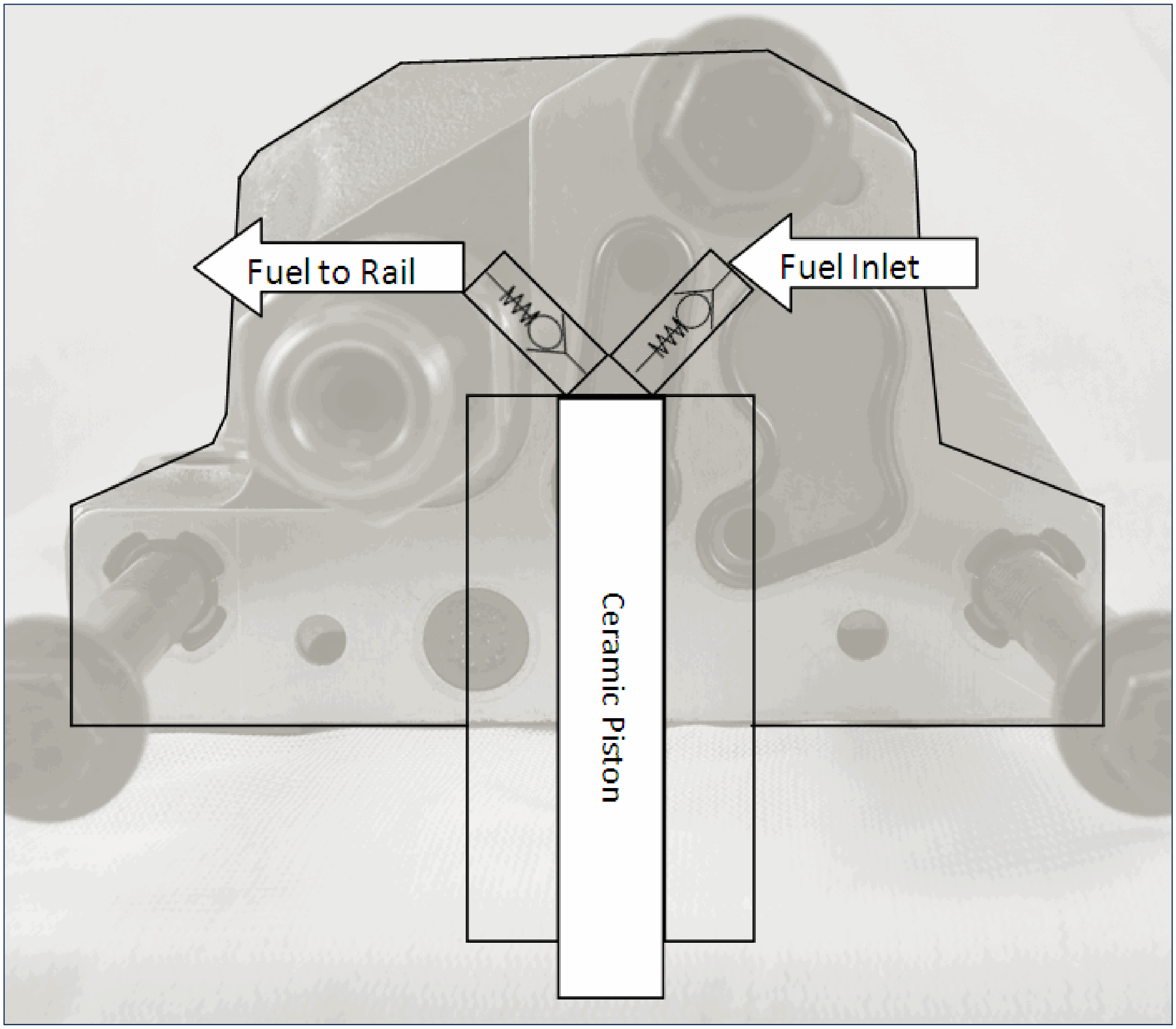


Figure 6. High Pressure Fuel Flow Path

Figure 7 shows the lower pressure, inlet check valves within the pump head.

Figure 7. Inlet Check Valves

Fuel enters this portion of the head through a volume control manifold located to the rear of the pump head. This can be seen in Figure 8. Figure 9 shows the gasket with fuel passage between the two sections of the pump.

Figure 8. Control Manifold Portion of Pump

Figure 9. Flow Control Gasket

The XPI system uses the electrically actuated control valve to direct fuel supplied by the low pressure side into the inlet of the pump head or to the bypass and return line. The low pressure gear pump, located on the rear of the pump body, draws fuel from the tank and pushes it through the final filter before entering the volume control area. Figure 10 shows the pump with the rear cover removed. While the low pressure pump is driven off of the main, oil lubricated shaft, the gears themselves are fuel-wetted surfaces.

Figure 10. Low Pressure Gear Pump

A pressure relief valve is located under the bolt on the top of the pump which prevents excessive downstream pressure from building at the filter. This valve is shown removed in Figure 11.

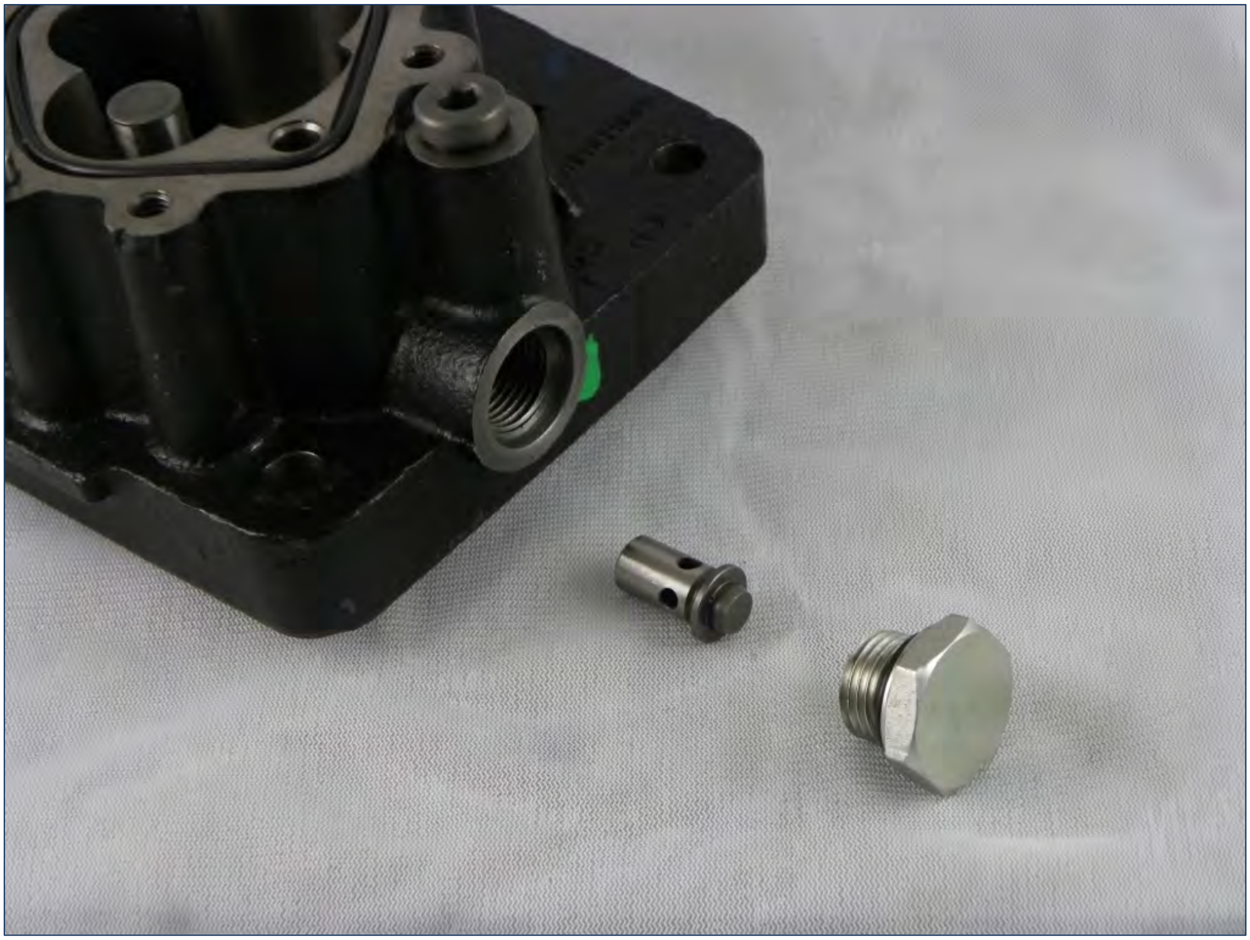


Figure 11. Gear Pump Pressure Relief Valve

2.3.2 Fuel Injectors

The XPI system injectors are solenoid controlled and able to provide multiple injection events per cycle. Figure 12 shows an injector with the hold-down clamp removed.

Figure 12. XPI Fuel Injector

High pressure fuel from the rail enters the injector via a quill tube through the cylinder head. The tube is held in place against a tapered hole in the side of the injector to form a high-pressure seal. Fuel enters the injector and fills internal passageways to act as a hydraulic fluid. From there, it is either directed through the injector tip into the cylinder, or allowed to flow out of the injector and back through the cylinder head as bypass fuel.

The injector body is made primarily of three sections. The lowest section holds injector tip and part of the needle. The upper half of the needle resides in the middle section of the injector body as can be seen in Figure 13. The needle, removed, can be seen in Figure 14.

Figure 13. Lower Injector Disassembled

Figure 14. Injector Needle

The middle section of the injector body also contains hydraulic components which allow the needle to lift. One of particular interest is a small ball which, when seated, prevents the flow of fuel and closes the injector. This part, in place, can be seen in Figure 15. Figure 16 shows the ball next to a common penny for size comparison.

Figure 15. Control Ball

Figure 16. Control Ball Size Comparison

When the control element is energized, the ball is allowed to lift off the lower seat and fuel flows past it from the lower section of the injector. This reduces the fuel pressure on the upper side of the needle and allows lift, letting fuel flow through the tip. When current is removed, the ball is moved back into place by a combination of spring force and fuel pressure in the upper section of the injector.

Fuel not injected into the cylinder passes through small orifices in the lower and middle body pieces as return fuel. Surrounding each injector in the cylinder head is an area, sealed by the injector at the bottom and an O-ring at the top, which fills with fuel. A passage through the cylinder head connects the six areas to a return line on the end of the head.

2.3.3 Stand Configuration

The pump and hardware was mounted on a test stand specifically configured for the XPI system. All temperature monitoring, control, and data acquisition was conducted by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Cummins CM2150 engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The evaluation was conducted using a 55-gallon drum as remote fuel source for the stand. A diaphragm air pump supplied the fuel to a smaller day tank located on the stand. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. A MIL-PRF-2104G 15W-40 was used in the oil-lubricated portion of the system. Once primed, the gear pump supplies fuel through a high efficiency filter and on to the high-pressure cam driven pump. Fuel then flows to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was combined and returned to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled, and returned to the remote drum. A schematic of the stand layout is shown in Figure 17.

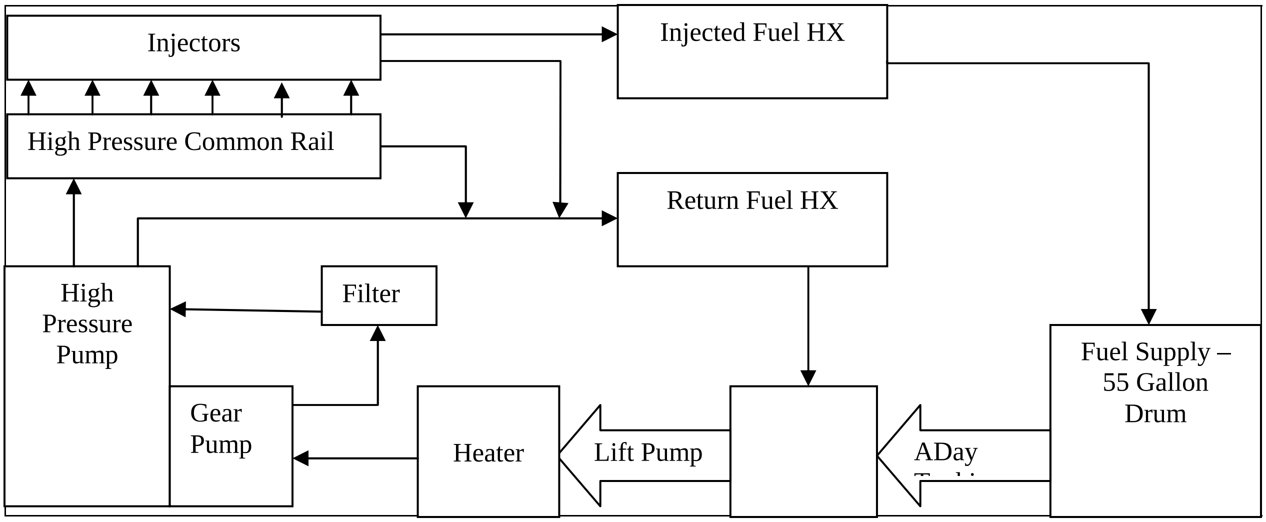


Figure 17. XPI Test Stand Layout

The stand was designed and constructed as part of the project with the goal of flexibility in testing. Two shelves provide almost 48 sq. ft. of surface for component mounting. Each shelf has a 1” lip and multiple drain ports to provide containment in the event of spills or leaks. To improve adaptability of the stand for future fuel systems, the drive motor was located on the lower shelf and transferred power to the upper table via a synchronous belt. This allowed the upper table drive components to fit into a smaller footprint, leaving more space for test components. The majority of cooling and heating equipment was located on the lower shelf of the table along with fuel and oil reservoirs. High pressure test components were located on the upper table and surrounded by a ½” Lexan shield for safety purposes. The electronic control devices were mounted on the opposite end of the stand from the drive hardware on elevated isolation mounts. This prevented harm from vibration during testing or liquid accumulation in the containment area. Additional discussion on the creation and layout of the test stand is provided in Appendix A. Figure 18 shows the completed test stand.

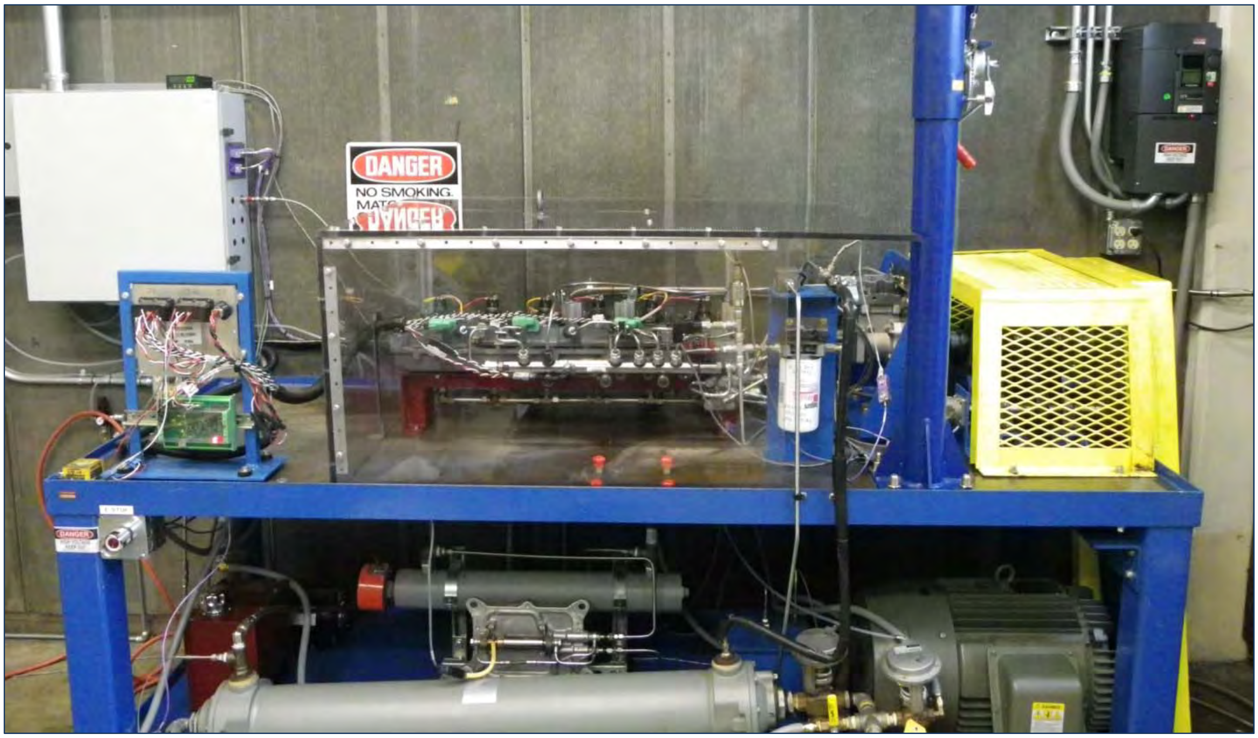


Figure 18. Completed Test Stand

2.3.4 Test Components

For each test, the fuel pump, injectors, quill tubes, and fuel filter were replaced with new parts. Other lines on the system were drained of fuel and rinsed with iso-octane. The larger components on the stand, such as heaters and heat exchangers, were drained and flushed with new test fuel. Typical flush volumes were 20 gallons to ensure the previous fuel was thoroughly rinsed through the system. During testing, a 55-gallon drum was used as the stand fuel source. Every 100-hours of test time, or 10 cycles, the drum was replaced with fresh fuel. For the high temperature tests, the lubricating oil, MIL-PRF-2104H SAE 15W-40, was also changed at this point in response to a decreased viscosity due to fuel dilution.

3.0 EVALUATION RESULTS

This section contains a comparison of performance from all completed testing. Individual test reports are attached as Appendix A through Appendix I.

3.1 SYSTEM PERFORMANCE AND OPERATION

Data from the two-hour "peak power" step, Mode 2, was evaluated as an indicator of overall system health and performance. The figures that follow show various measured parameters over the 40 cycles of each test in comparison. Data logging was at a rate of every 60 seconds and the first two data points from each cycle were eliminated to allow for stabilization before taking the mean value for the remaining 118 minutes. Tests conducted at 93.3°C are listed as "HT" for high-temperature.

3.1.1 Rail Pressure

The fuel rail pressure, Figure 19, was controlled by the ECM based upon the system speed and throttle input. A high pressure transducer provided a voltage signal to both the ECM and the data acquisition software. Rail pressure remained steady throughout all but the Jet-A test. This evaluation showed an increase of roughly 450 psi, about 1.5%, over the previous evaluations for the first twenty six cycles. This change was likely due to the replacement of the high pressure rail and supply line. It was found that a small blockage was located in the high pressure supply line where it fed into the rail. After the 26th cycle, the pressure returns to the same value as was seen prior to, and following the Jet-A test. No fuel based performance issues can be derived from the system rail pressure for any of the eight evaluations.

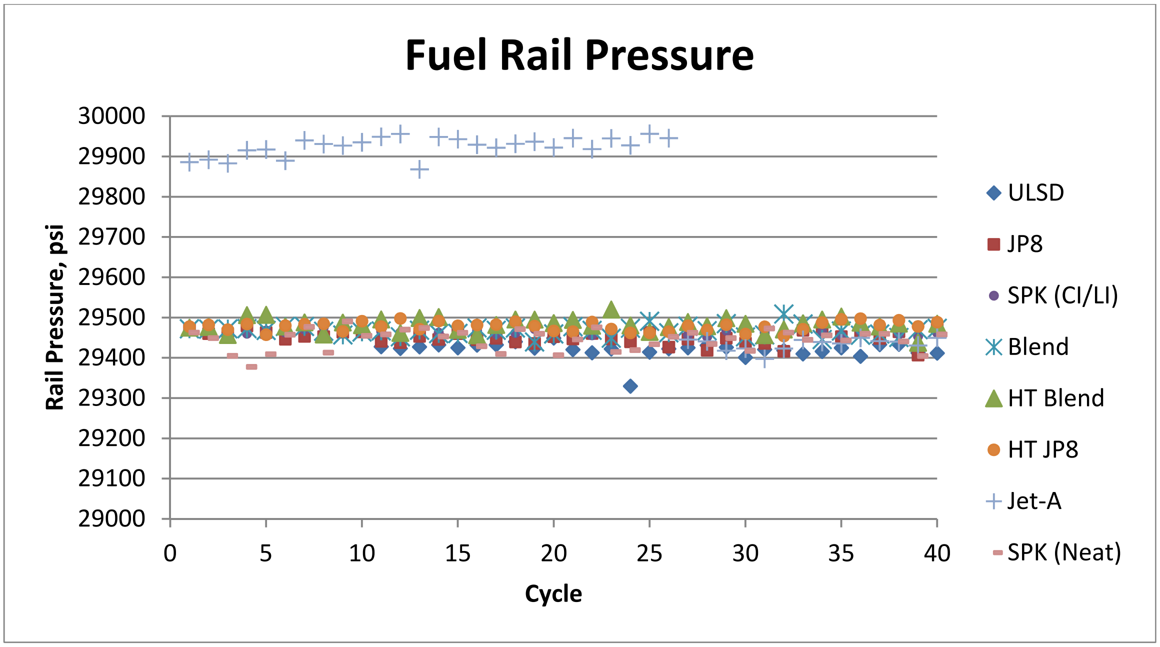


Figure 19. Fuel Rail Pressure

3.1.2 Gear Pump Outlet Pressure

The gear pump outlet pressure, Figure 20, was measured prior to the final filter element. A severe decrease in outlet pressure could be an indication of wear on the fuel-wetted gear teeth in the pump causing leakage. Over the course of the project, there was a tendency for a decline in pressure early in the test followed by primarily steady operation. This would indicate that the pumps were undergoing a break-in period after which they stabilized. Other factors which may influence the pressure at this point of the system include a relief valve on the downstream side of the pump, the filter condition, and injected and return fuel flow rates. The relief valve likely has the largest impact on this pressure out of these factors.

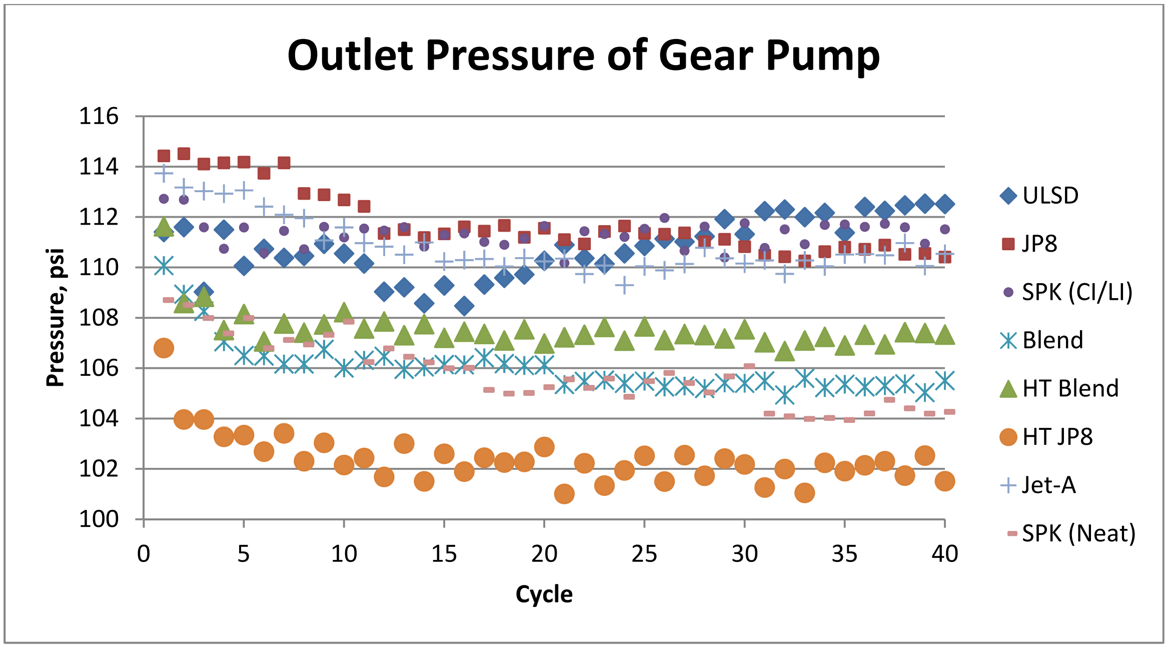


Figure 20. Outlet Pressure of Gear Pump

3.1.3 Injected Fuel Flow Rate

Injected fuel was collected for all six of the injectors in a common manifold before being returned to the remote fuel source. Data is not available for the first 10 cycles of the ULSD test. During this time, an oval gear flow meter was being used which was later determined to be incompatible with the temperatures experienced during the test. Since the temperature of the fuel impacts the volumetric flow, a coriolis meter was installed to measure mass flow and density. This allowed the fuel to be cooled without impacting the flow measurement. Once the new style flow meter and proper cooling equipment were installed, no meaningful changes in flow rate were seen for the ULSD evaluation. The lower temperature JP-8 evaluation was the only test to show a substantial change in injected flow rate. Early in the test, a decrease in flow was seen followed by a sharp drop off. Following this reduction, the flow rate remained stable for the remaining 28 cycles. Post test inspection of the injectors indicated that there may have been a failure in the solenoid of the #4 injector. A plunger appeared seized in a way that prevented the needle from lifting. Based upon the assumption that five out of six injectors were functioning, a “projected” flow rate was added to the figure which falls closely in line with the other fuels tested. The lack of wear or debris in the other five injectors, or high temperature evaluation of the JP-8 fuel, along with how early in the test the failure occurred indicate that the issue was likely an isolated component failure rather than a fuel influenced one. The failure is discussed further in the “Injectors” section of the report. All other fuels and temperatures evaluated for this project produced results with very little change over the course of the 400-hour test. It was noted that the ULSD, with a test viscosity of 1.9 cSt, had a lower flow rate than any other fuel. This type of change in flow rate has been seen in other HPCR applications and was somewhat expected. When the same fuel was tested at two temperatures, the JP-8 and Blended fuels, the higher temperature and lower viscosity fuel produced an increased flow rate compared to the lower temperature test.

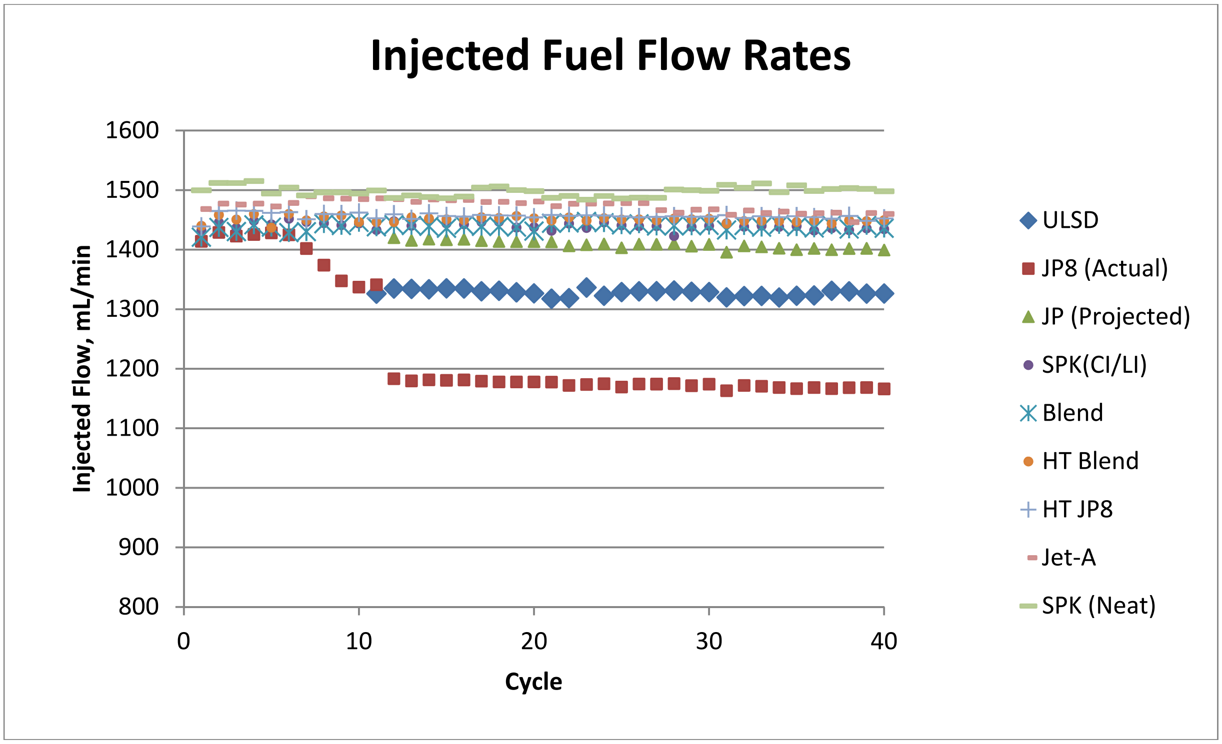


Figure 21. Injected Fuel Flow Rates

3.1.4 Bypass and Return Fuel Flow Rate

The bypass and return fuel flow is a combination of high pressure fuel that is not used by the injectors, what is diverted by the pump before being pressurized, and what, if any, comes through the high pressure relief valve on the fuel rail. The combined return flow rate for each test is shown in Figure 22. The step change in return flow for the Jet-A evaluation can be traced back to the same high pressure supply line issue that impacted the rail pressure. Again, this does not seem to have had an impact on system performance related to component wear or fuel compatibility.

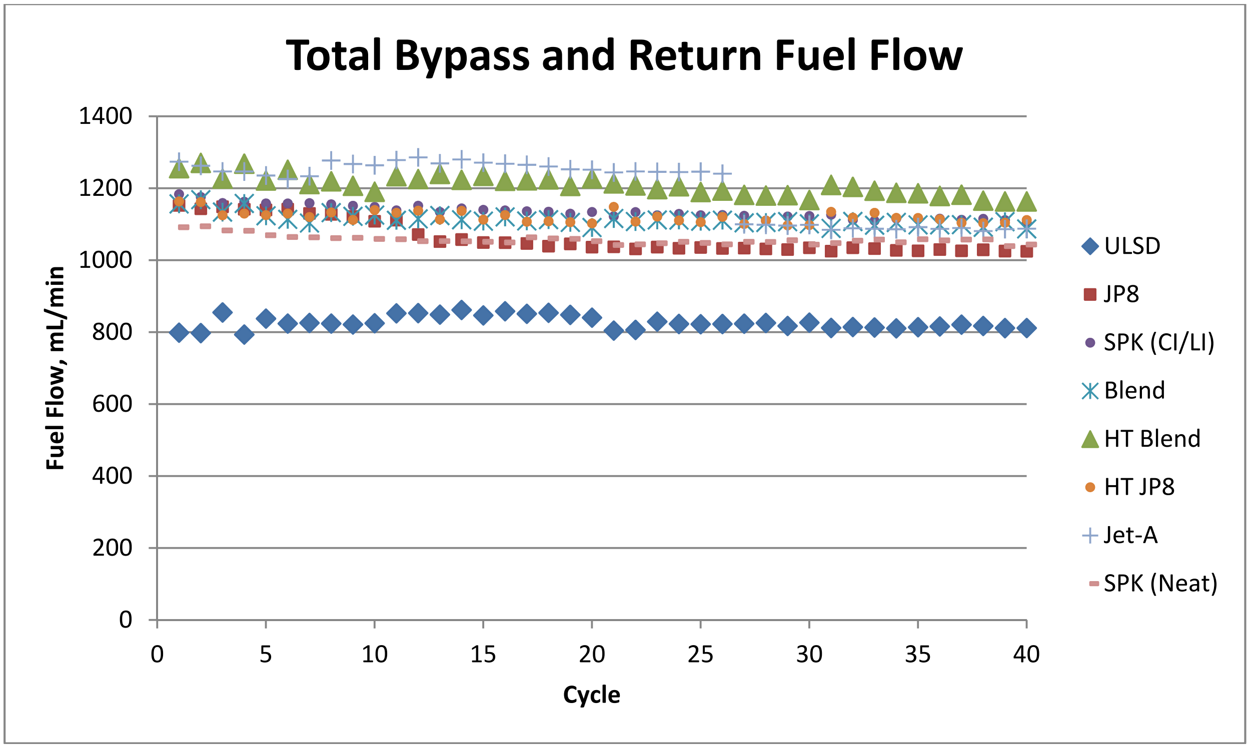


Figure 22. Bypass and Return Flow

Since there are multiple sources for this fuel to come from, the number of components which may impact the flow rate are high. Wear in the low pressure gear pump may lead to additional leakage, less total flow, and therefore less fuel diverted around the high pressure system and into the return lines. Combined with the data from the outlet of the gear pump, the reduction in return flow over the course of testing is likely tied to this. Increased wear in the injectors could allow additional fuel to pass through tight clearances and increase the total volume returned. Component inspection gave no indication to believe this was the occurring. Since the rail pressure throughout all tests was controlled successfully, it can be assumed that the relief valve was not unexpectedly opening and increasing the return flow. The relatively high viscosity of the ULSD fuel is likely the reason for the distinctly lower return flow rate. Since the clearances in the injectors which return fuel passes through are typically very tight, a lower flow rate would be expected to come out of the injector returns.

3.1.5 Drive Motor Power Output

The combination high pressure and gear pump was driven by an electric motor through a variable frequency drive. This drive offered the ability to monitor power output to the motor. While this does not take into account drive system losses, such as bearing friction or coupling inefficiencies, these losses can be expected to be relatively small and to remain consistent between tests. The measured power output to the motor is shown in Figure 23.

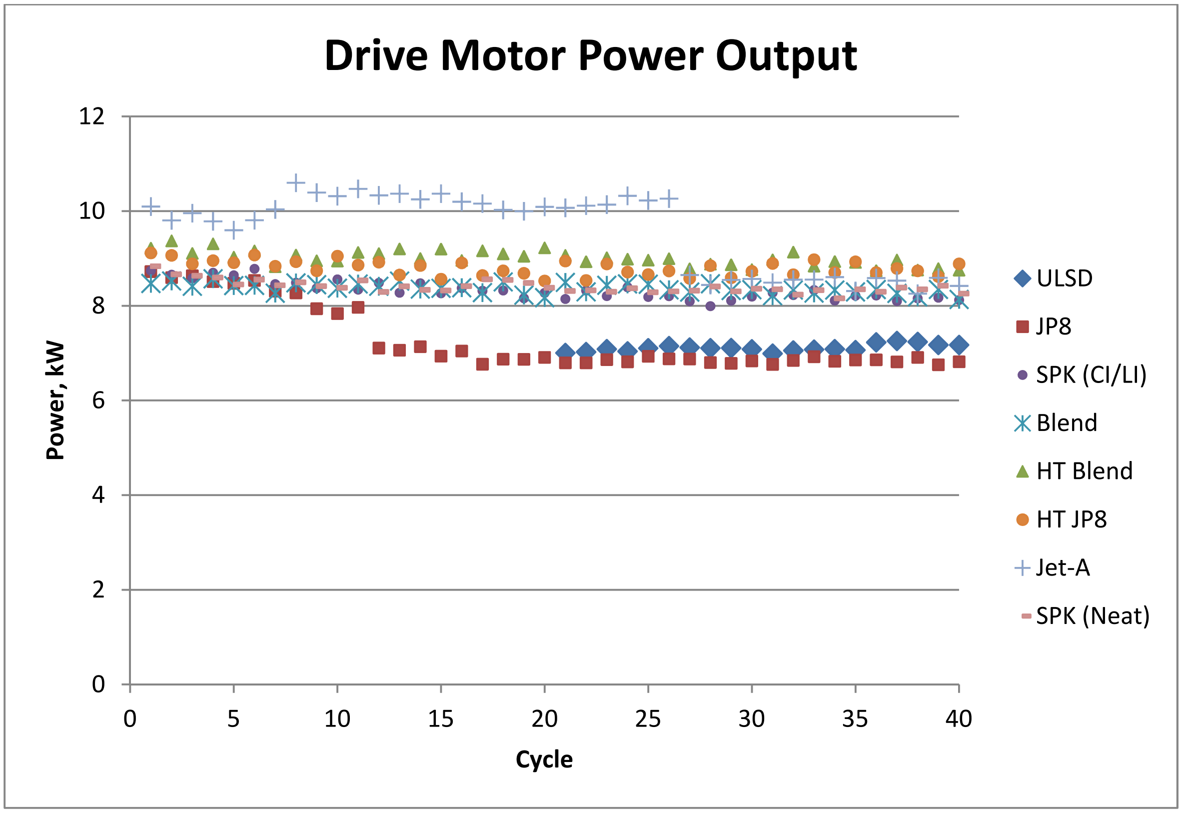
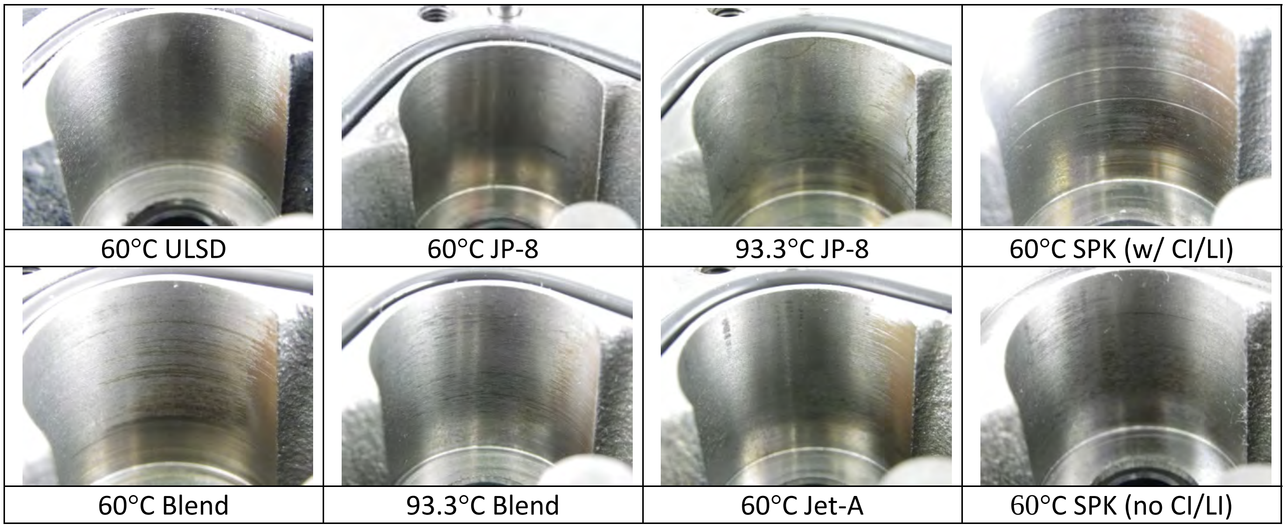


Figure 23. Drive Motor Power Output

Once again, the impact of the blockage can be seen for the Jet-A evaluation. Since the pump being controlled by the ECM developed a slightly higher pressure, the power output of the motor to maintain the desired speed was also higher. As the pressure, and total return flow, of the test decreased after the 26th cycle, the motor's power draw returned to typical levels. The assumed failure of the injector during the low temperature JP-8 evaluation can also been seen in the motor power. As the injector begins to seize and fuel flow dropped, the pump was able to produce the required pressure with less power input. For the ULSD test, the low flow rate compared to other tests is consistent with the reduced amount of high pressure fuel for injection supplied by the pump.

3.2 LOW PRESSURE GEAR PUMP HOUSING

The side walls which the teeth of the gear contact are shown in Figure 24. It can be seen in the figure that each test, including the ULSD baseline, experienced some degree of abrasive wear from the gear teeth sliding along the housing wall. Some level of this is expected as the gear teeth remove material from the housing until a seal is formed. This area is where the gear tooth is coming into contact with the housing the on the suction side of the pump (right side of the images). Some variation in the extent of this wear is expected due to manufacturing tolerances between the pumps and individual gears.

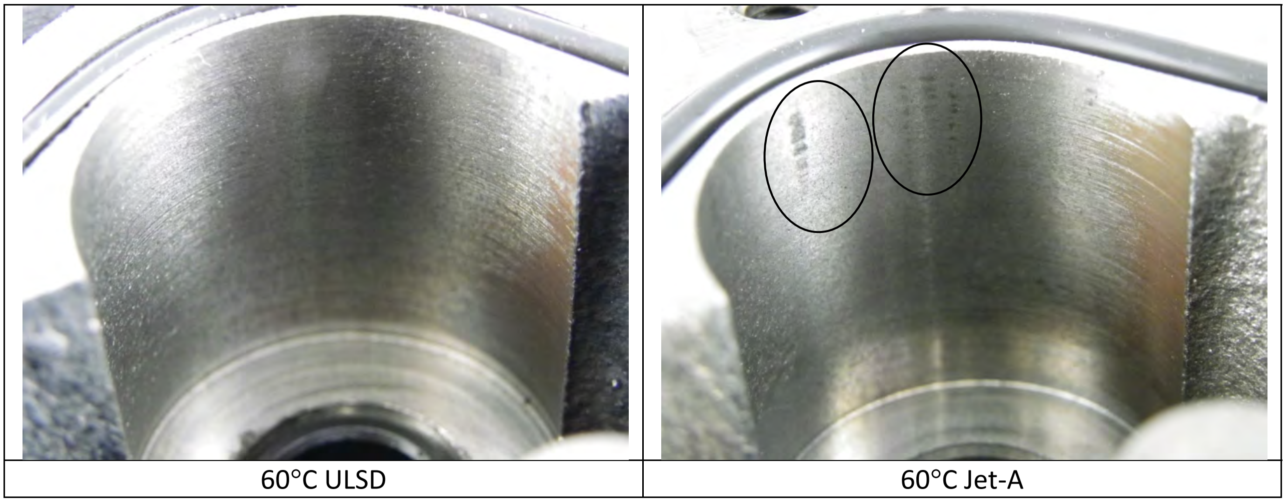


60°C ULSD | 60°C JP-8 | 93.3°C JP-8 | 60°C SPK (w/ CI/LI)

60°C Blend | 93.3°C Blend | 60°C Jet-A | 60°C SPK (no CI/LI)

Figure 24. Low Pressure Pump Housing Wall

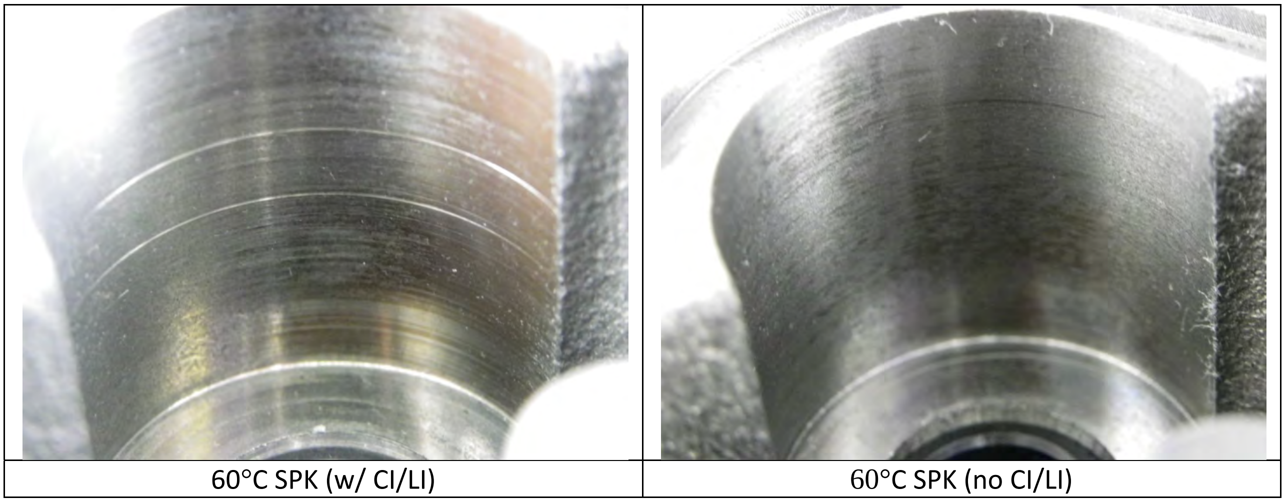
While the majority of the tests produced results similar to the baseline, there were a few instances which require further examination. These are shown in Figure 25, an enlarged view from four of the above tests. The Jet-A evaluation, viscosity of 0.81 cSt at 60°C and ASTM D5001 WSD of 0.81mm, produced marks not observed in other tests. These are a group of markings perpendicular to the direction of travel between the two surfaces. The appearance of these in distinct locations around the housing wall may indicate formation at either a shut down or start up event rather than while the pump was rotating. As a 400-hour test, run 100-hours each week, the marks may have been the result of the stand sitting idle for two days at a time before restarting. While this cannot be verified, the width of the mark is similar in width to the gear tooth, making it a possible explanation.


60°C ULSD

60°C Jet-A

Figure 25. Housing Wall – ULSD and Jet-A

A comparison of the SPK test fuel with and without additive is shown in Figure 26. The two deeper groves that appear in the test with the additive are likely due to debris rather than fuel related wear. If the lubricity of the fuel were an issue for the test, it would be expected that the groves or lines would have formed more uniformly across the contact surface rather than in two distinct locations.

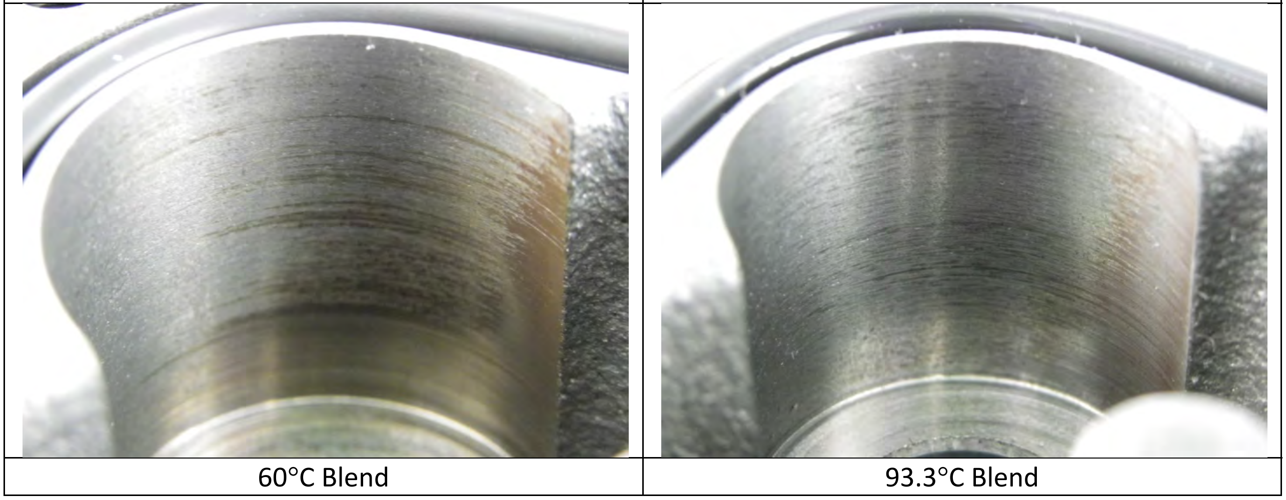


60°C SPK (w/ CI/LI)	60°C SPK (no CI/LI)

Figure 26. Housing Wall – SPK

The influence of temperature of the pump wear characteristics is seen in Figure 27. For the JP-8 tests an increased level of polishing along with limited scoring is seen in the high temperature test. In the blended fuel the increased level of scoring is seen in some spots, however the lower temperature test shows a larger area of polished material. It should be noted that while the scoring marks found in each of the higher temperature evaluations are spread uniformly, they do not have the depth observed in the 60°C SPK (w/ CI/LI) pump.

60°C JP-8 93.3°C JP-8

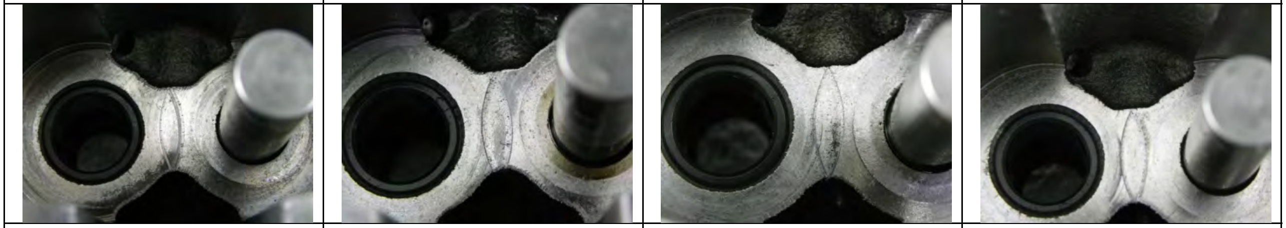


60°C Blend 93.3°C Blend

Figure 27. Housing Wall - Temperature Comparison

The bottom of the pump housing, the surface which the gear ends rotate on, is shown in Figure 28. The edges of the gear teeth, in most cases, cut noticeable grooves into the metal of the housing. These grooves have a noticeable depth to them, rather than just a visible appearance. It should be noted that while these grooves exist, there does not seem to be a strong connection between fuel selection and wear development in this location. The best lubricity fuel, ULSD at 60°C, produced a groove very similar to Jet-A, one of the worst lubricity fuels. While there is a large contrast between the JP-8 fuel low and high temperature tests, the same cannot be said for the blended fuel. A large influencer of the depth of groove is likely the shaft, visible in the photos, which the second of the gears rotates on. If the shaft is not completely perpendicular to the face the grooves appear on, the gear teeth would have increased pressure applied at the ends of the teeth rather than evenly across the end of the gear.

60°C ULSD | 60°C JP-8 | 93.3°C JP-8 | 60°C SPK (w/ CI/LI)

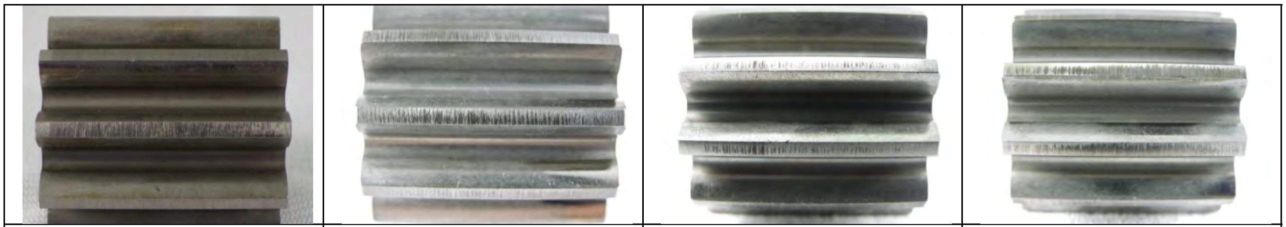


60°C Blend | 93.3°C Blend | 60°C Jet-A | 60°C SPK (no CI/LI)

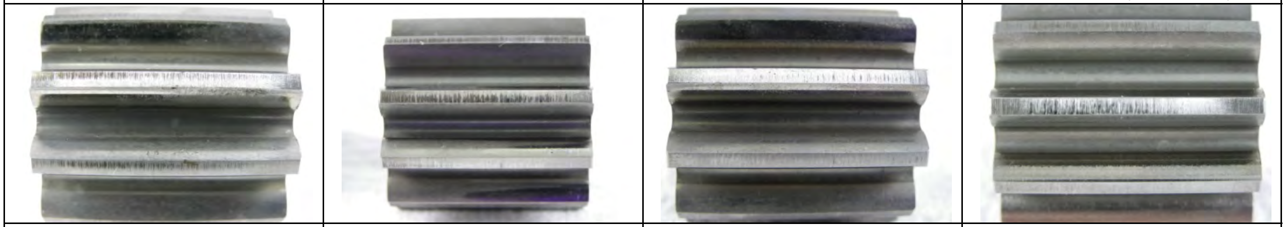
Figure 28. Low Pressure Gear Pump Bottom

3.3 GEAR TEETH

The seal between the top land of the gear teeth and the pump housing wall is an important one in developing the supply pressure to the high pressure system. Leakage past this interface would result in lower supply pressure and reduced fuel flow. A comparison between the gears removed from each of the tests show very similar and uniform finish and wear patterns. The gears are likely harder than the cast pump housing, and therefore show less wear due to the surface contact. The gears themselves do not appear to be heavily impacted by fuel viscosity or lubricity, as shown in Figure 29.



60°C ULSD | 60°C JP-8 | 93.3°C JP-8 | 60°C SPK (w/ CI/LI)



60°C Blend | 93.3°C Blend | 60°C Jet-A | 60°C SPK (no CI/LI)

Figure 29. Gear Teeth Wear

3.4 LOW PRESSURE RELIEF VALVE

A relief valve in the gear pump prevented excess downstream pressure from building at the filter element. The two locations which showed polish and wear are displayed in Figures 30 and 31. A spring, held in place by the plug on top of the pump, keeps the valve seated until there is sufficient downstream pressure to overcome the spring force. When operating, the valve likely spends a substantial amount of time fully or partially open, vibrating in place as the spring and pressure forces balance each other. While this is occurring, two spots on the cylinder developed substantial polishing in most cases. The locations were on opposite sides of the piece for each test, indicating that the component moved through its bore at a slight angle. For the two tests conducted at elevated temperatures, a lesser degree of wear was noted on this component. One possible explanation for this is that the lower viscosity fluids relieved more pressure through leakage which then resulted in a reduced actuation of the relief valve. The two tests using the SPK test fuel, additized and neat, produced very similar polish patterns despite the difference in lubricity.

60°C ULSD
60°C JP-8
93.3°C -8
60°C SPK (w/ CI/LI)
60°C Blend
93.3°C Blend
60°C Jet-A
60°C SPK (no CI/LI)

Figure 30. Pressure Relief Valve Side A

60°C ULSD
60°C JP-8
93.3°C JP-8
60°C SPK (w/ CI/LI)
60°C Blend
93.3°C Blend
60°C Jet-A
60°C SPK (no CI/LI)

Figure 31. Pressure Relief Valve Side B

Although each test uses six injectors, only one example is shown per evaluation. When noticeable differences were seen between injectors in a test, the worst case example is presented.

3.5 INJECTOR NEEDLE TIP

The tip of the needle is an area of importance in the injector. If the tip is not seating and sealing properly, the high pressure fuel will continuously flow into the cylinder. A comparison of the injector tips from the eight evaluations is shown in Figure 32. No visual indications were seen on the tips of the injector needles to indicate a fuel related issue or change.

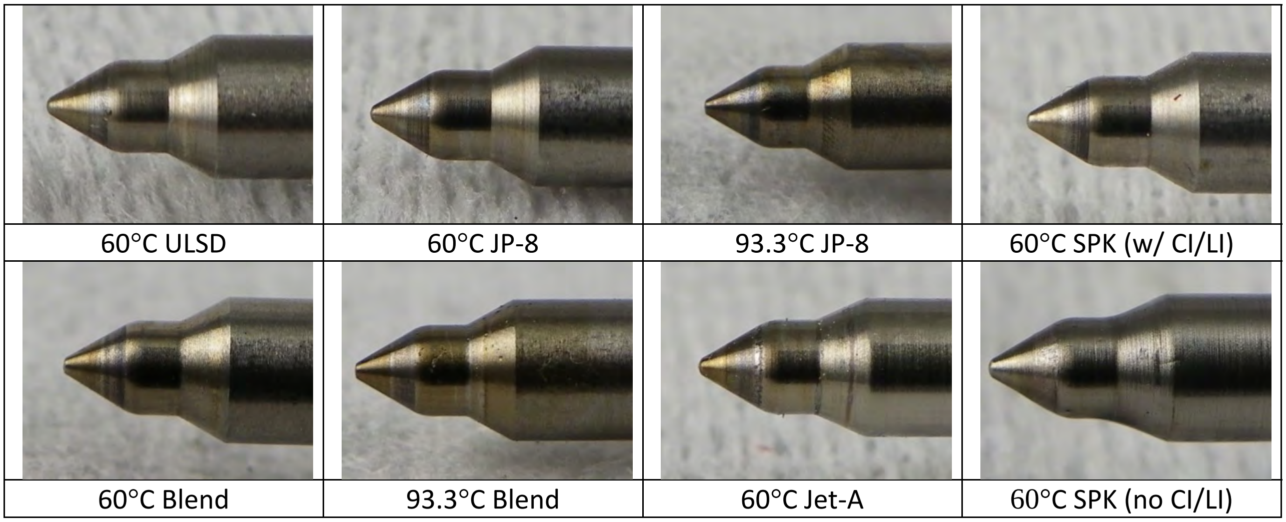
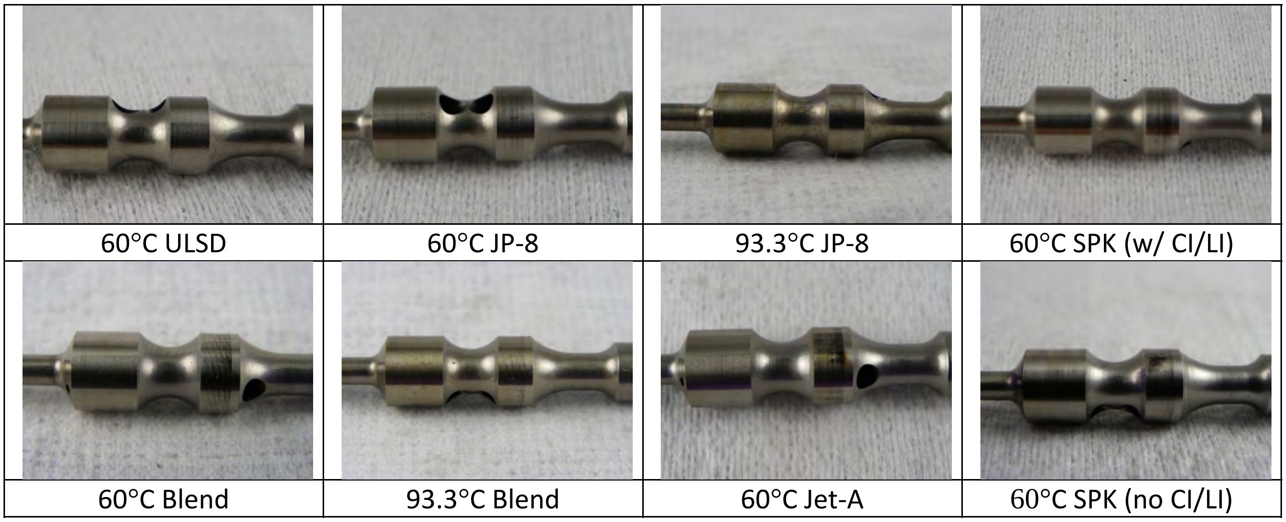

60°C ULSD
60°C JP-8
93.3°C JP-8
60°C SPK (w/ CI/LI)
60°C Blend
93.3°C Blend
60°C Jet-A
60°C SPK (no CI/LI)

Figure 32. Injector Needle Tip

3.6 INJECTOR NEEDLE MID-SECTION

The middle of the needle helps with alignment in the bore of the injector tip. It also acts as the passageway for fuel to reach the injector tip. By passing fuel through the needle itself, the overall injector diameter can be held smaller. All tests, including the ULSD baseline, showed some degree of marking on the needle. For the ULSD, 60°C JP-8, and 60°C SPK (w/ CI/LI) tests these markings appeared as radial rings along the sections in contact with the needle bore. This is somewhat unexpected since they are perpendicular to the direction of motion for the needle when the injector fires. It would appear that the needle was rotating in its bore in addition to the travel required to open the fuel flow path. The two blended fuel tests and the 93.3°C JP-8 test show a diagonal wear pattern indicating that the markings were formed during a combination of rotation and linear movement. While there was some concern that the slanted marks were formed during disassembly of the injector, the pitch is substantially different from that of the housing threads.

The final two tests, Jet-A and SPK (no CI/LI) showed a combination of radial and axial markings. Additionally, dark spots of heavy wear were seen in both of these tests, something not observed in any of the previous evaluations. Over time, wear in this location could potentially cause an injector needle to seize when fired. If seized in a closed position, this would result in a loss of power and vehicle performance, while seizing in an open position would result in continuous fuel flow through the injector. It should be noted that for both the Jet-A and SPK (no CI/LI) tests, the addition of even a small amount of lubricity improver appears to have improved the fuel properties to levels acceptable for increased injector life. These test results are shown in Figure 33.



60°C ULSD

60°C JP-8

93.3°C JP-8

60°C SPK (w/ CI/LI)

60°C Blend

93.3°C Blend

60°C Jet-A

60°C SPK (no CI/LI)

Figure 33. Injector Needle – Mid-Section

3.7 JP-8 TEST INJECTOR FAILURE

During the first 100-hours of the 60°C JP-8 test, it was noted that the injected flow rate had an unexpected decrease. While performing post-test component teardown, it was found that the injector from cylinder #4 had a seized plunger in the solenoid. Upon removal, numerous metallic shards were found within the bore. While wet with fuel, the material appeared to form spikes from the component, follow the residual magnetic field lines. The component, at removal, is shown in Figure 34.

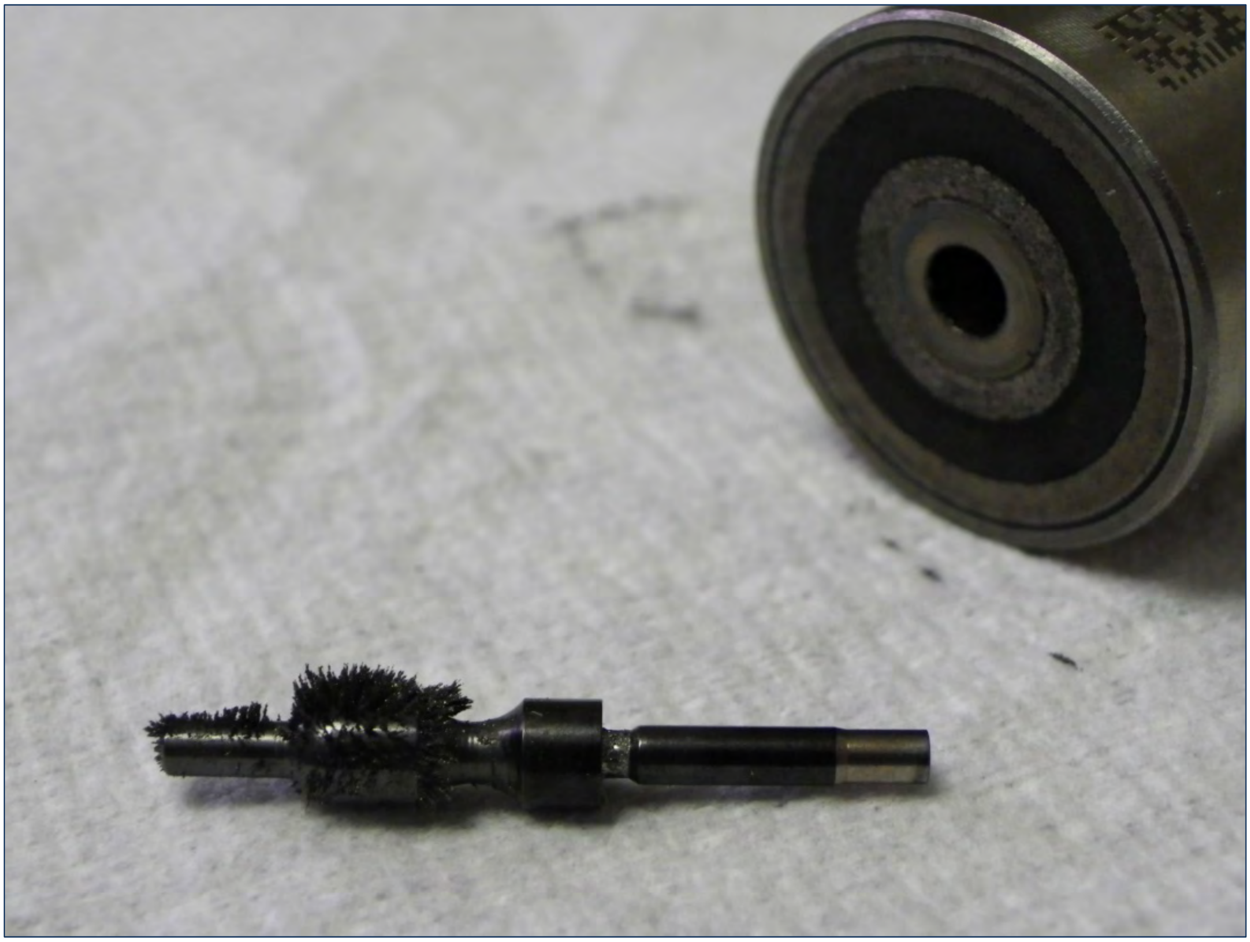
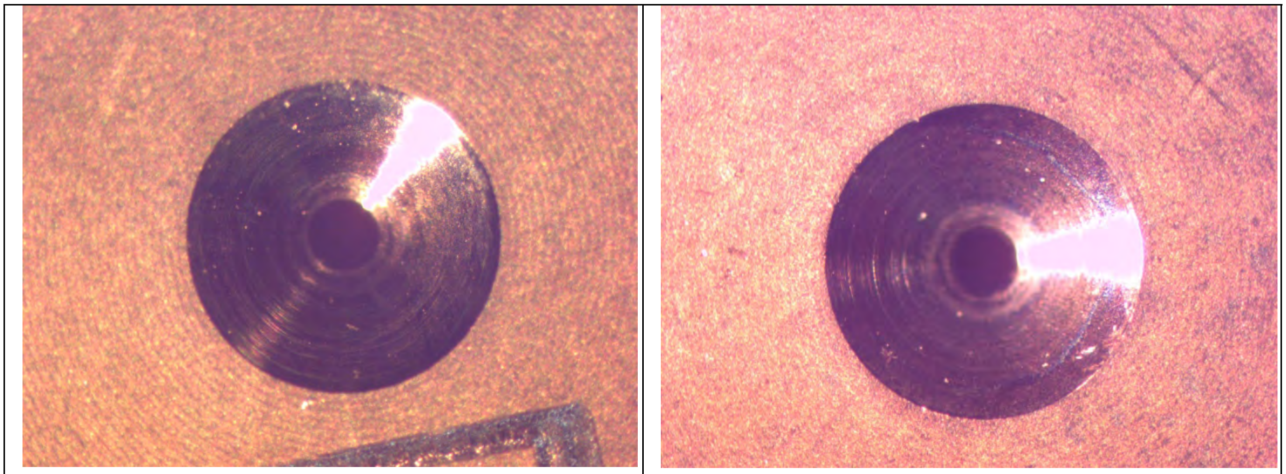


Figure 34. Solenoid Plunger Removed with Debris

The plunger was washed with iso-octane and the particles collected on filter paper. Examination of the other components within the injector indicated that the wear was occurring near the same location it was collecting at, the solenoid. The lower seat which the small control ball rests in was one sign of this. A comparison between the suspect injector and one of the other five is shown in Figure 35 under magnification.



Suspected Failed Injector

Normal Injector

Figure 35. Control Ball Seat

If the wear particles had been forming in the high pressure pump, or anywhere else upstream, before collecting in the solenoid bore, there would likely be gouges or scoring from the center hole of the seat to the outer edge. However, the only visible marks are the original machining lines and the location on the non-failed example where the ball seats, both radial in form.

The location likely responsible for the particles is the bottom side of the solenoid. Figure 36 shows the difference in appearance between the suspect injector (left) and normal injector (right) at the end of the test.

Figure 36. Solenoid Comparison – Suspected Failed (Left) and Typical (Right)

The metal immediately inside of the black insulating material is substantially rougher in texture in the failed component. While this is a location that should not come into direct contact with the component below it, matching wear marks indicate that some degree of contact did occur. Also, the color of the particles collected from the plunger are consistent with the area in question. The only way for this to have happened would be for the plunger within the solenoid to have been forced further in than it normally travels, not an issue likely related to fuel viscosity or lubricity effects. Additionally, the timing of the failure, early in the test, coupled with the lack of repeated occurrence within the other injectors of this and other tests, lead to the conclusion that it was an isolated incident related to the components themselves rather than the fuel used.

4.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Over the eight sets of components and six fuel types, only one injector failure was noted and that was not related to the test fluid. Overall, the indications are that the XPI system is robust with regards to fuel lubricity and viscosity even in relatively extreme combinations such as the unadditized Jet-A and SPK test fuels. While little was seen based upon performance data for flow rates, pressures, etc., it should be considered that an electronically controlled engine may be making adjustments and compensations without operator awareness. Monitoring the motor power being fed into the pump attempted to quantify this to some extent, however it would not be able to capture things such as minor high-speed changes in the behavior of injector needle lift. Visual indicators of wear were noted within the injectors on the final two tests. While these were not severe enough to cause an issue over the 400-hour duration of the NATO cycle, if ran long enough, it is unknown what may have occurred. If the XPI fuel system is proliferated through the Tactical Wheel Vehicle Fleet through Cummins ISC, ISL, ISX and other engines, additional testing should be conducted with military fuels. Evaluating system performance over the expected economical useful life of a vehicle, 15-20 years, would prove the apparent ruggedness of the system in a more appropriate time frame. For this, a three or four repetition NATO test might be appropriate. Other limitations of bench testing include the actual engine power output and deposit formation, although the increased volumetric flow rate may help to compensate for any loss of power due to fuel type. While the fuel utilized for the project had challenging lubricity and viscosity properties, it was also kept to high cleanliness and filtration standards. The effect of dust, dirt, water, or silt which may be present in field operation and be limited in high lubricity diesel fuel, could potentially be compounded by the fluids evaluated in this project. In future work, it may be beneficial to examine the combined impact of particle size with fuel lubricity to determine if a synergistic impact on component durability exists.

5.0 REFERENCES

ASTM Standard D6079, 2011, “Standard Test Method for Evaluating Lubricity of Diesel Fuels by the High-Frequency Reciprocating Rig (HFRR)[1],” ASTM International, West Conshohocken, PA, 2011, DOI: 10.1520/ASTM D6079-11

ASTM Standard D5001, 2010, “Standard Test Method for Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE)[1],” ASTM International, West Conshohocken, PA, 2010, DOI: 10.1520/ASTM D5001-10

ASTM Standard D445, 2011, “Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)[1],” ASTM International, West Conshohocken, PA, 2011, DOI: 10.1520/ASTM D6079-11

Cummins Inc., *Parts Catalog: ISC/ISL with CM2150 Control Module.* 2007

Cummins Inc., *Service Manual ISLe CM2150 Volume 1 & 2.* 2009

Lubricating Oil, Internal Combustion Engine, Combat/Tactical Service, MIL-PRF-2104H, 1997

APPENDIX - A

Test Stand Development

The test stand, with components installed is shown in Figure A-1.

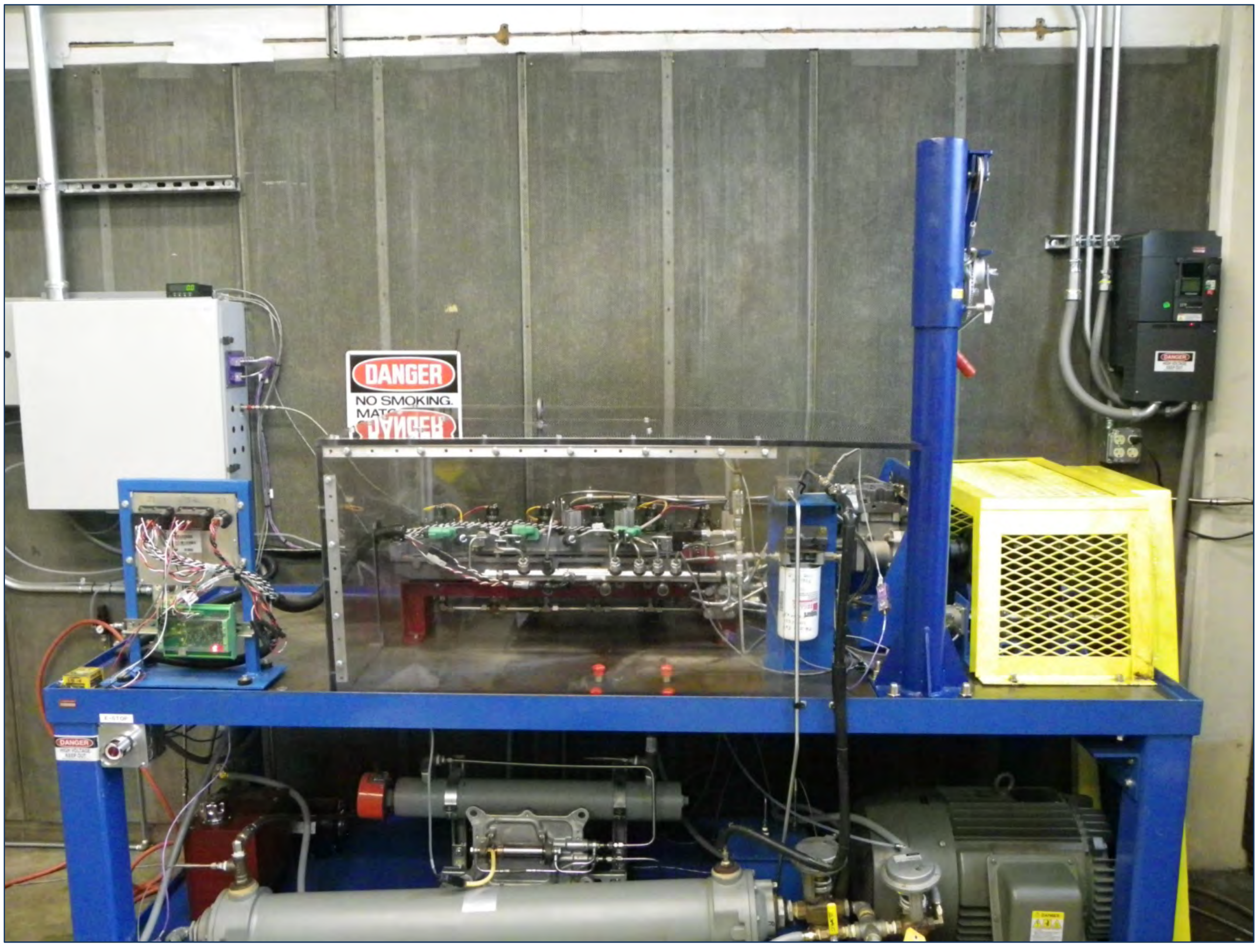


Figure A-1. XPI Test Stand

The table consists of two 8’x3’ steel plates, the top being one inch thickness and the bottom ½”. A lip surrounds both the top and bottom surfaces to create containment areas with drain plugs located in the corners. A 400-lbs capacity hoist was located on the stand to facilitate the movement of test components and safety equipment. The test pump was driven by a 30hp electric motor controlled via a variable frequency drive. A cog belt connected the motor, lower shelf of the table, to the drive assembly on the top. This required less space dedicated to the drive portion of the test stand and allowed for a full cylinder head to be utilized in testing. The oil lubricating system of the stand consisted of a ½ hp gear pump, 2 gallon reservoir, and heat exchanger for return lubricant. Oil was sent through ½” tubing along the back side of the table to a port near the test article. After passing through the pump, it returned along the same path, was cooled via a liquid-to-liquid heat exchanger, and flowed back into the reservoir. Fuel entered the test cell via stainless lines from a remote drum rack. A pressure regulator controlled the supply to the on-stand day tank at no more than six psig. This prevented the float valve in the day tank from being over pressurized and spilling. The fuel temperature at the inlet to the test parts was controlled using a circulation heater. Based upon the outlet temperature of the fuel from the heater, the power to the heater was adjusted to obtain the desired value. After injection, the hot fuel was run through a large liquid-to-liquid heat exchanger prior to measuring flow. This did not impact volumetric flow; the meter was a coriolis mass-flow style, but prevented damage due to high temperature fuel. After flow was measured, the fuel was routed back to the remote drum rack. Bypass and return fuel was also measured for flow and cooled before being returned to the on-stand day tank. The heat exchanger for this fuel was controlled to maintain an elevated, but below flashpoint, temperature within the day tank. Speed signals, for both the system ECM and data acquisition software, came from a 3600 pulse-per-revolution rotary encoder. A table summarizing the major components of the stand is provided in Table A-1.

Table A-1. Test Stand Components

Component	Description	Supplier
Circulation Heater	4.5kW, CFMNA25J10S	Watlow
Injected Fuel HX	6” Diameter, 48” Length, Stainless Steel shell and tube	ITT Standard
Return Fuel and Oil System HX	3” Diameter, 14” Length, Stainless Steel shell and tube	ITT Standard
Drive System Bearings	VPS-216 Pillow Block Bearing	Browning
Pump Coupling	PN 6A52: Clamp Style 2” Bore w/ Keyway x Blank Set Screw A-hub	Zero-Max
Motor	30HP, 230/460V, 286TS, 2-POLE Motor, PN 0302FTSA31B-P	Toshiba
VFD	30HP, 460VAC, 40AMPS, NEMA 1, PN VT130H9U4330	Toshiba
Rotary Encoder	XH25D-SS-3600-ABZC-28V/V-SM18	BEI Industrial
Oil System Pump	½ hp Rotary Gear Pump	McMaster-Carr
Oil System Reservoir	2-gallon High Temperature Oil Tank	McMaster-Carr

APPENDIX - B

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: Ultra Low Sulfur Diesel
Test Number: ULSD-AF7469-60C-XPI

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Cummins XPI Fuel System

Test Fuel: Ultra Low Sulfur Diesel
Test Number: ULSD-AF7469-60C-XPI
Start of Test Date: November 29, 2010
End of Test Date: February 10, 2011
Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

TABLE OF CONTENTS

Section **Page**

LIST OF TABLES

LIST OF FIGURES

Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) is working on a project with the U.S. Army TARDEC on synthetic and alternative fuels. The project goal is to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, JP-8, and FT SPK, manufactured by Syntroleum as S-8, treated with corrosion inhibitor/lubricity improver (CI/LI), and a 1:1 blend of the JP-8 and the synthetic fuels. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Four tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and up to four at 93.3°C (200 °F), for a total of eight tests. The lower temperature ULSD test is considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the Cummins XPI fuel system. This system was developed jointly between Cummins, Inc. and Scania. Primarily targeted for Cummins midrange and Scania heavy duty applications, an oil-lubricated fuel pump allows the system to reach rail and injection pressures of up to 30,000 psi. The pump consists of a low pressure gear pump and high pressure piston pump. It is operated at half of the engine angular velocity for a rated condition speed of 1050 rpm. On the high pressure side of the pump, the camshaft drives two plungers which pressurize the fuel entering the rail. Each plunger is driven by three lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure side of the system consists of a gear pump which passes fuel through the final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand specifically configured for the XPI system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Cummins CM2150 engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The fuel pump consisted of a low pressure gear pump to push fuel through a high efficiency filter and send it to the high-pressure cam driven pump. Fuel then flows to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled below its flash point, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each100 hour segment. A schematic of the stand layout is shown in Figure B-1.

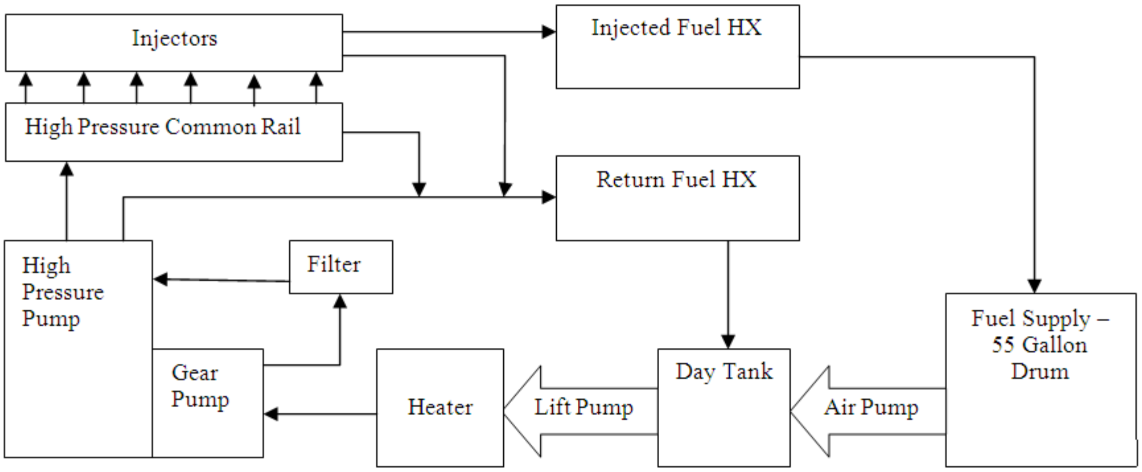


Figure B-1. XPI Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table B-1.

Table B-1. NATO Cycle for XPI Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	400	0	0.5
2	1050	100	2
3	1155	0	0.5
4	788	100	1
5*	400 to 1050	0 to 100	2
6	630	100	0.5
7	400	0	0.5
8	1081	70	0.5
9	650	100	2
10	650	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

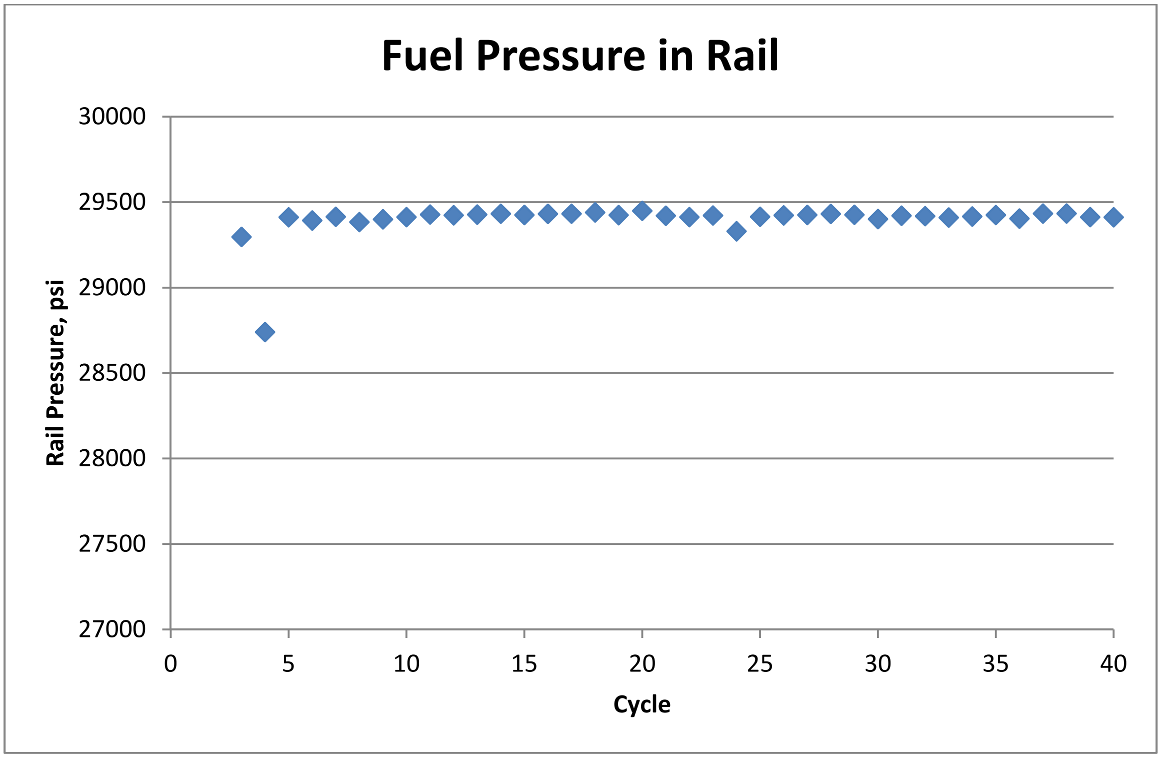


Figure B-2. Fuel Rail Pressure

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Cummins ECM for monitoring purposes. Data for the first two cycles is not available due to test point calibration issues. The test stand did not experience any unusual performance issues related to rail pressure during this, or any other, time.

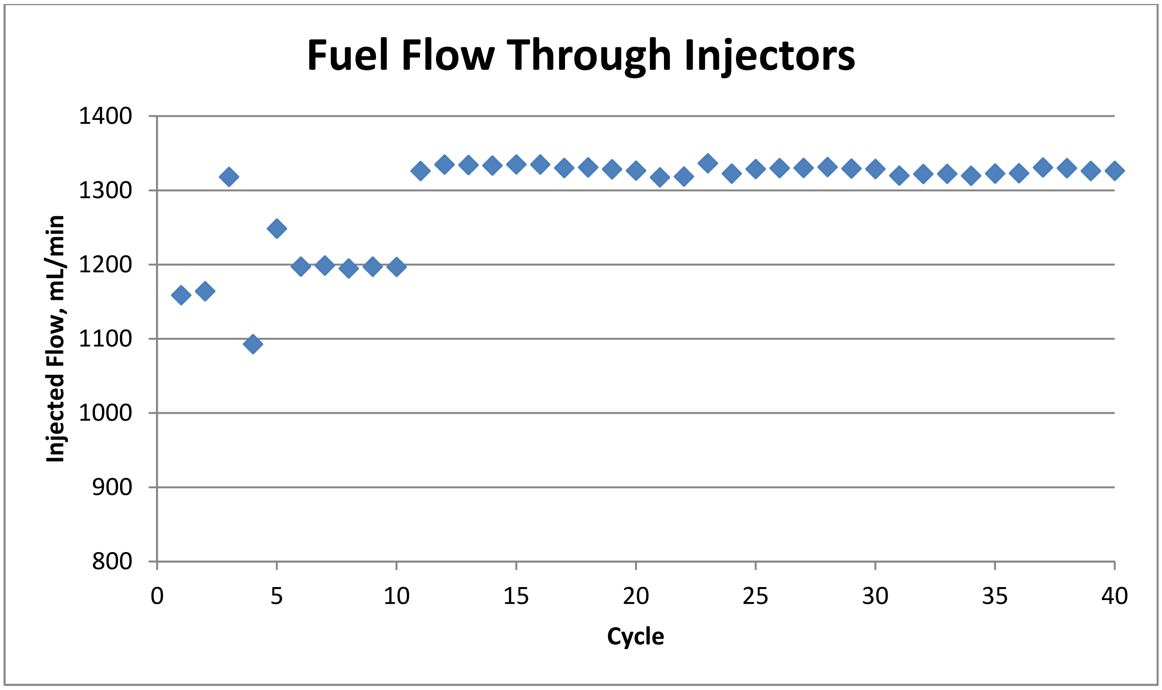


Figure B-3. Injected Fuel Flow

Fuel flow over the first 10 hours of testing was recorded using an oval gear style flow meter. As testing continued, it was determined that the electronic components of this meter were not capable of withstanding the temperature of the injected fuel and a new-styled meter was installed. This is the cause of the discrepancy in flow rate between Cycles 9 and 10. Following this change, the injected flow remained stable over the remaining 30 Cycles.

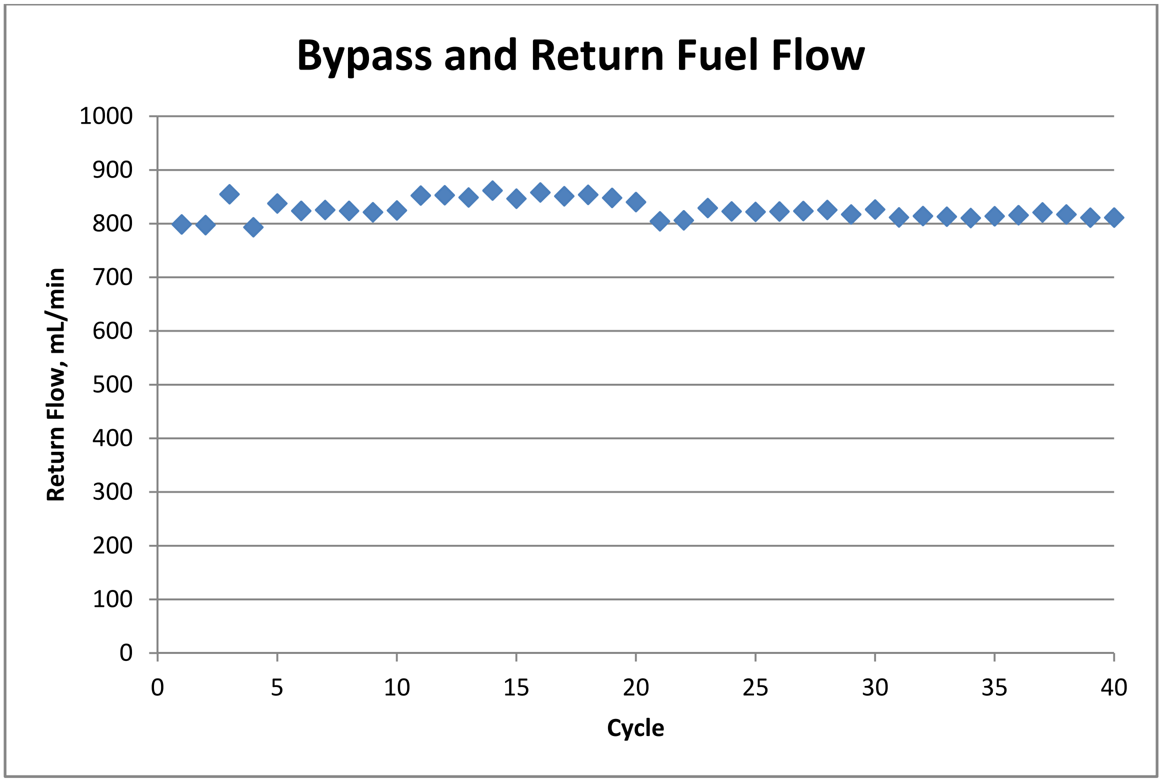


Figure B-4. Return Fuel Flow

Bypass and return fuel flow is the combined fuel from the high pressure pump relief valve, rail protection check valve, and injectors bypass/cooling flow.

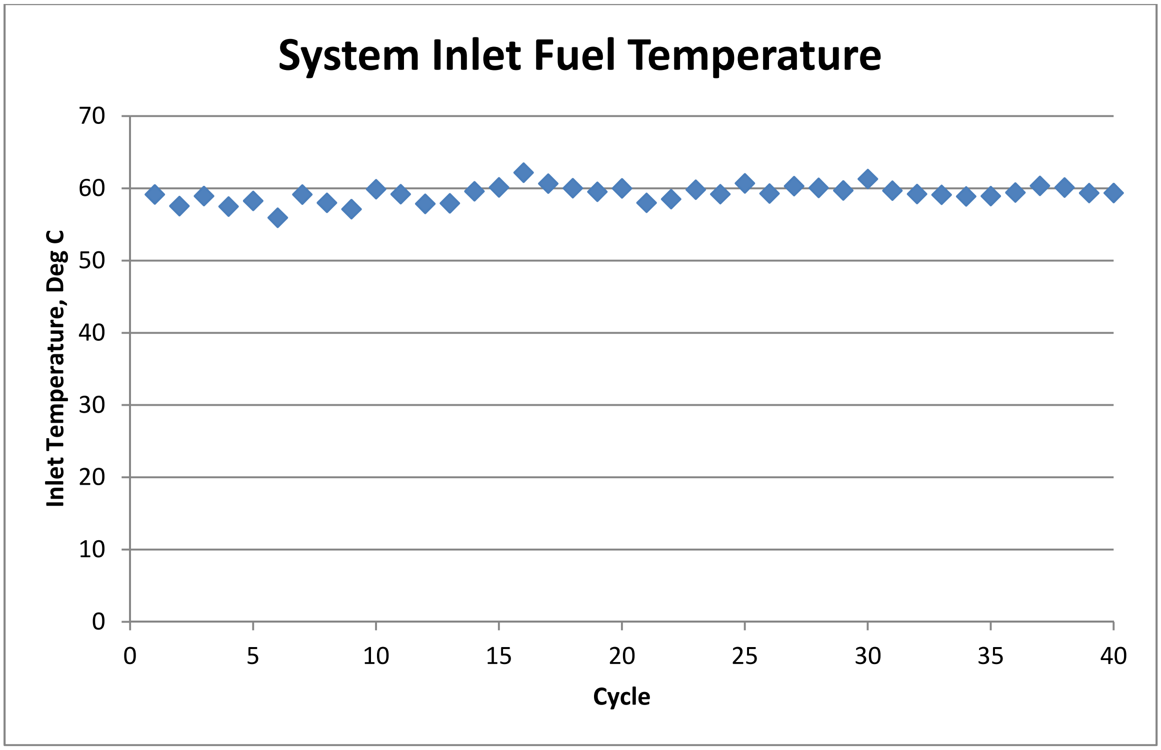


Figure B-5. System Inlet Fuel Temperature

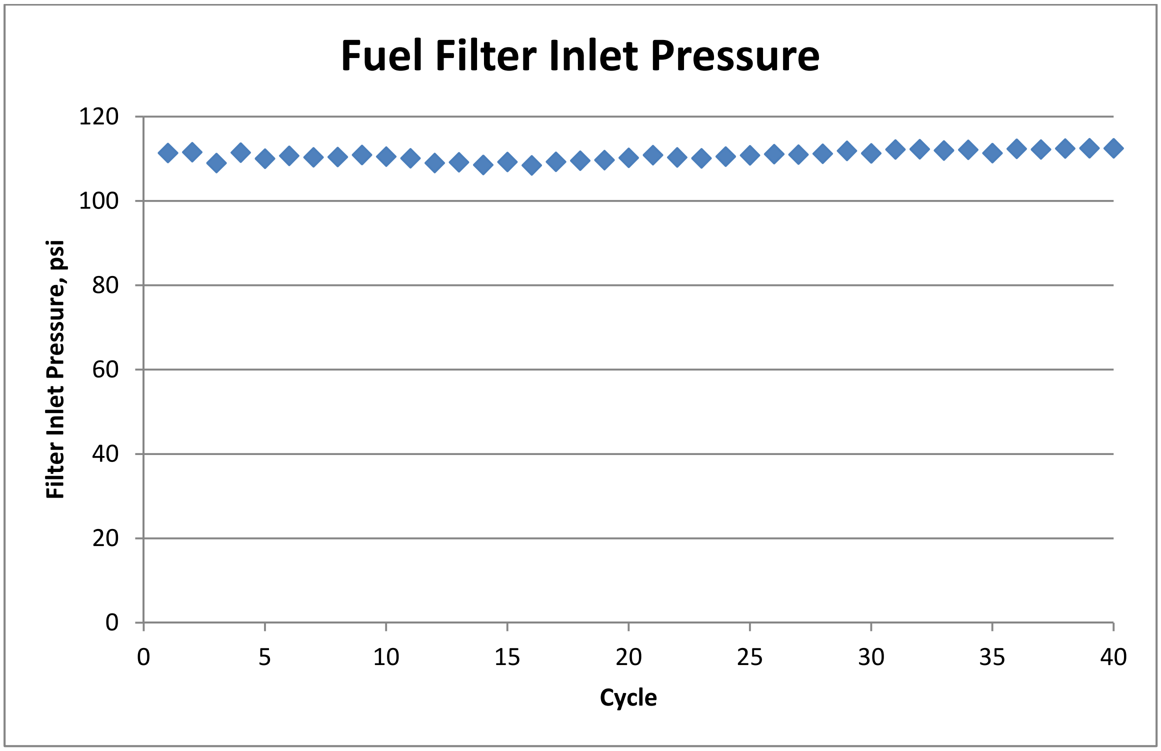


Figure B-6. Fuel Filter Pressure

Fuel filter inlet pressure is a measure of the pressure being developed by the gear pump portion of the XPI fuel pump. It is influenced by a combination of pump speed and an internal pressure relief valve.

Shown in Table B-2 are operating conditions for each 100 hours of test time.

Table B-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	58.1	2.2	48.1	66.1
Injected Fuel Temperature, deg C	146.8	6.8	73.8	149.6
Rail Pressure, psi	29308	487	20088	29629
Injected Flow Rate, mL/min	1197.3	85.6	658.3	1391.6
Return Fuel Flow Rate, mL/min	820	26.0	717.2	1041.9
Fuel Filter Inlet Pressure, psi	110.7	1.2	98.7	113.6
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	59.7	1.5	53.7	64.2
Injected Fuel Temperature, deg C	149.2	2.1	118.9	149.6
Rail Pressure, psi	29431	79	29067	29742
Injected Flow Rate, mL/min	1331.6	32.5	1177.9	1403.8
Return Fuel Flow Rate, mL/min	851	13.3	799.9	903.2
Fuel Filter Inlet Pressure, psi	109.4	0.9	103.1	112.8
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	59.7	1.9	50.5	64.3
Injected Fuel Temperature, deg C	148.2	6.1	46.3	149.6
Rail Pressure, psi	29410	328	18573	29642
Injected Flow Rate, mL/min	1327.4	29.1	487.7	1375.0
Return Fuel Flow Rate, mL/min	820	16.7	693.0	876.6
Fuel Filter Inlet Pressure, psi	111.0	1.7	63.5	114.1
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	59.1	1.8	47.6	63.7
Injected Fuel Temperature, deg C	148.1	4.7	83.2	149.6
Rail Pressure, psi	29418	77	29131	29710
Injected Flow Rate, mL/min	1319.6	28.2	1062.8	1358.0
Return Fuel Flow Rate, mL/min	813	10.9	762.7	845.9
Fuel Filter Inlet Pressure, psi	112.4	0.9	105.4	116.9

Fuel Analysis

Fuel was evaluated for lubricity at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Because the ULSD fuel was from two separate shipments, there are two “fresh” samples, one for the first two hundred hours and one for the last two hundred. It should be noted that the difference in WSD for fresh samples in the HFRR test type is within the repeatability of the procedure. Results from ASTM D5001 and D6079 are shown in Figures B-7 and B-8. Test results indicate that over the duration of the test the system did not encounter fuel with unusually high lubricity. Figure B-9 shows the Certificate of Analysis received from the supplier for the fuel used in this test. It should be noted that the value for HFRR is outside of the ASTM D975 specification of 0.52 mm according to the CoA, but within the limits when tested at SwRI.

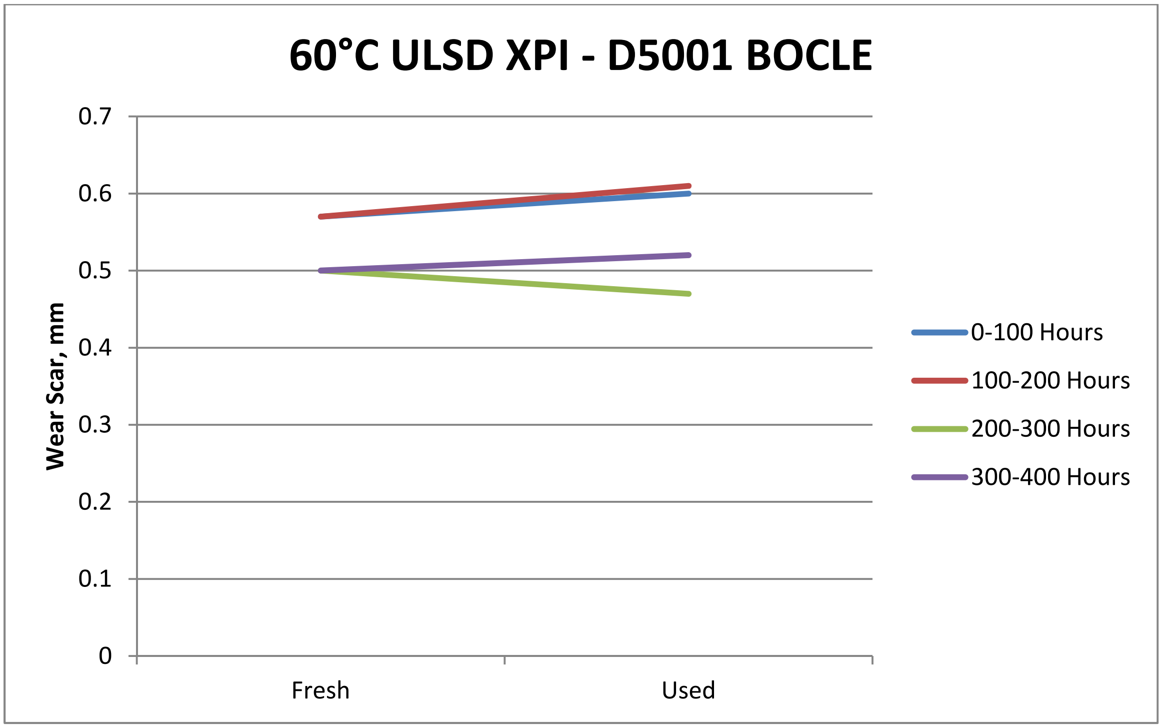


Figure B-7. ASTM D5001 BOCLE

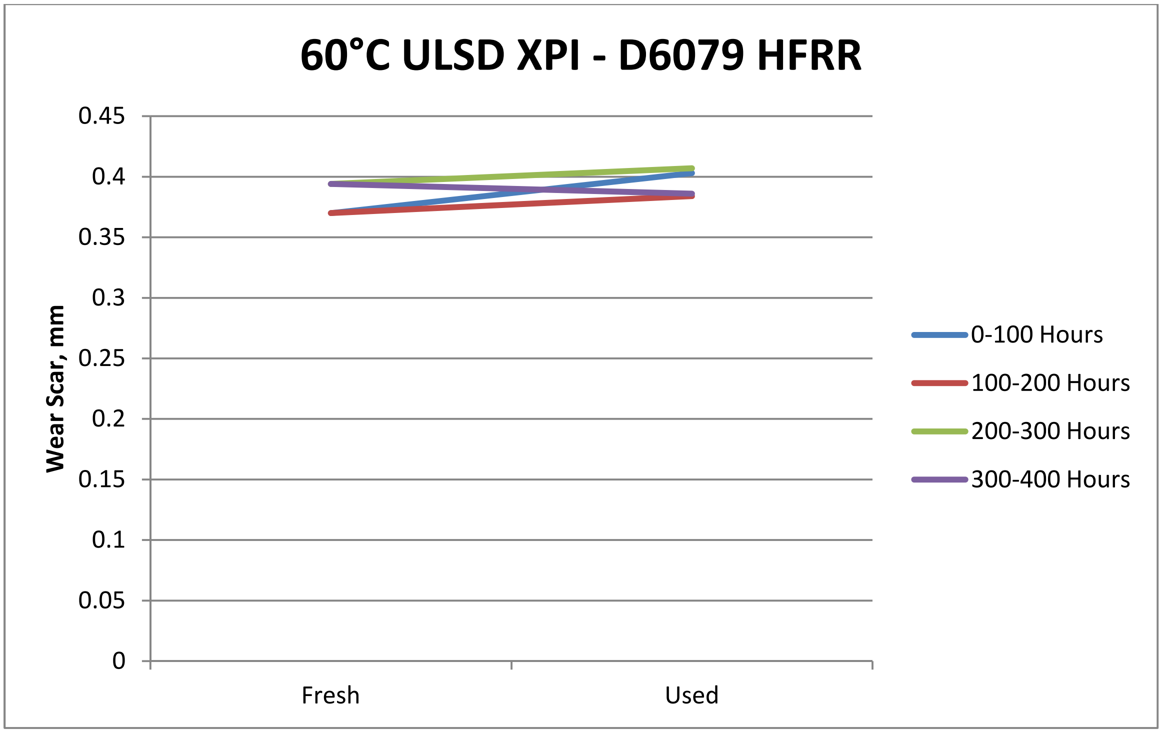
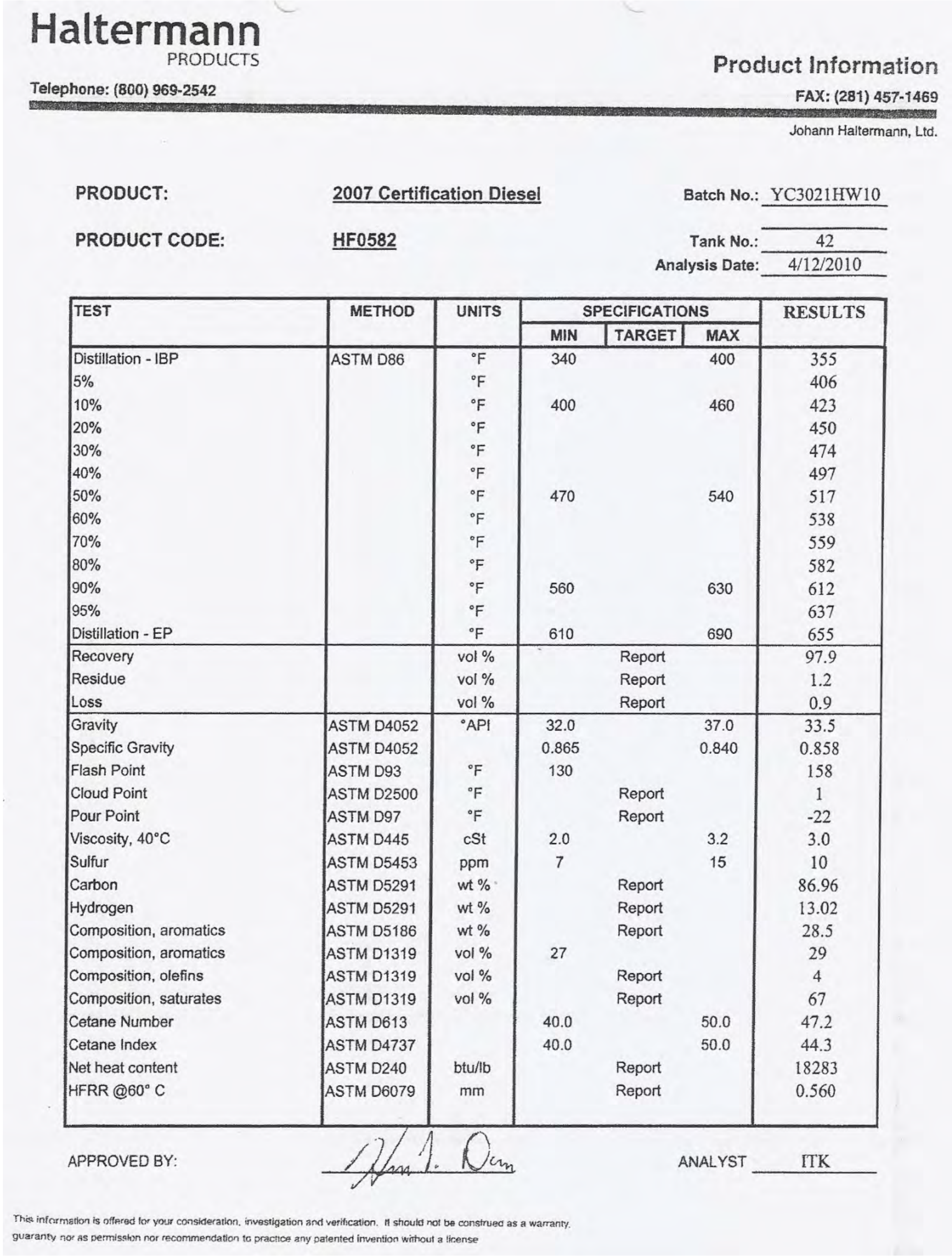


Figure B-8. ASTM D6079 HFRR



Haltermann
PRODUCTS

Telephone: (800) 969-2542

Product Information

FAX: (281) 457-1469

Johann Haltermann, Ltd.

PRODUCT: **2007 Certification Diesel**

Batch No.: YC3021HW10

PRODUCT CODE: **HF0582**

Tank No.: 42

Analysis Date: 4/12/2010

TEST	METHOD	UNITS	SPECIFICATIONS			RESULTS
			MIN	TARGET	MAX	
Distillation - IBP	ASTM D86	°F	340		400	355
5%		°F				406
10%		°F	400		460	423
20%		°F				450
30%		°F				474
40%		°F				497
50%		°F	470		540	517
60%		°F				538
70%		°F				559
80%		°F				582
90%		°F	560		630	612
95%		°F				637
Distillation - EP		°F	610		690	655
Recovery		vol %		Report		97.9
Residue		vol %		Report		1.2
Loss		vol %		Report		0.9
Gravity	ASTM D4052	°API	32.0		37.0	33.5
Specific Gravity	ASTM D4052		0.865		0.840	0.858
Flash Point	ASTM D93	°F	130			158
Cloud Point	ASTM D2500	°F		Report		1
Pour Point	ASTM D97	°F		Report		-22
Viscosity, 40°C	ASTM D445	cSt	2.0		3.2	3.0
Sulfur	ASTM D5453	ppm	7		15	10
Carbon	ASTM D5291	wt %		Report		86.96
Hydrogen	ASTM D5291	wt %		Report		13.02
Composition, aromatics	ASTM D5186	wt %		Report		28.5
Composition, aromatics	ASTM D1319	vol %	27			29
Composition, olefins	ASTM D1319	vol %		Report		4
Composition, saturates	ASTM D1319	vol %		Report		67
Cetane Number	ASTM D613		40.0		50.0	47.2
Cetane Index	ASTM D4737		40.0		50.0	44.3
Net heat content	ASTM D240	btu/lb		Report		18283
HFRR @60° C	ASTM D6079	mm		Report		0.560

APPROVED BY:

ANALYST ITK

This information is offered for your consideration, investigation and verification. It should not be construed as a warranty, guaranty nor as permission nor recommendation to practice any patented invention without a license

Figure B-9. Test Fuel Certificate of Analysis

Component Wear

Post-test disassembly of the pump and injectors was performed to establish a baseline for typical wear operating on ULSD. Only fuel wetted components are shown in the figures that follow. The most predominant wear following the ULSD test was located on the teeth of the oval gears. This is somewhat expected as this surface slides along the pump housing to produce the low pressure fuel pressure.

Fuel Pump

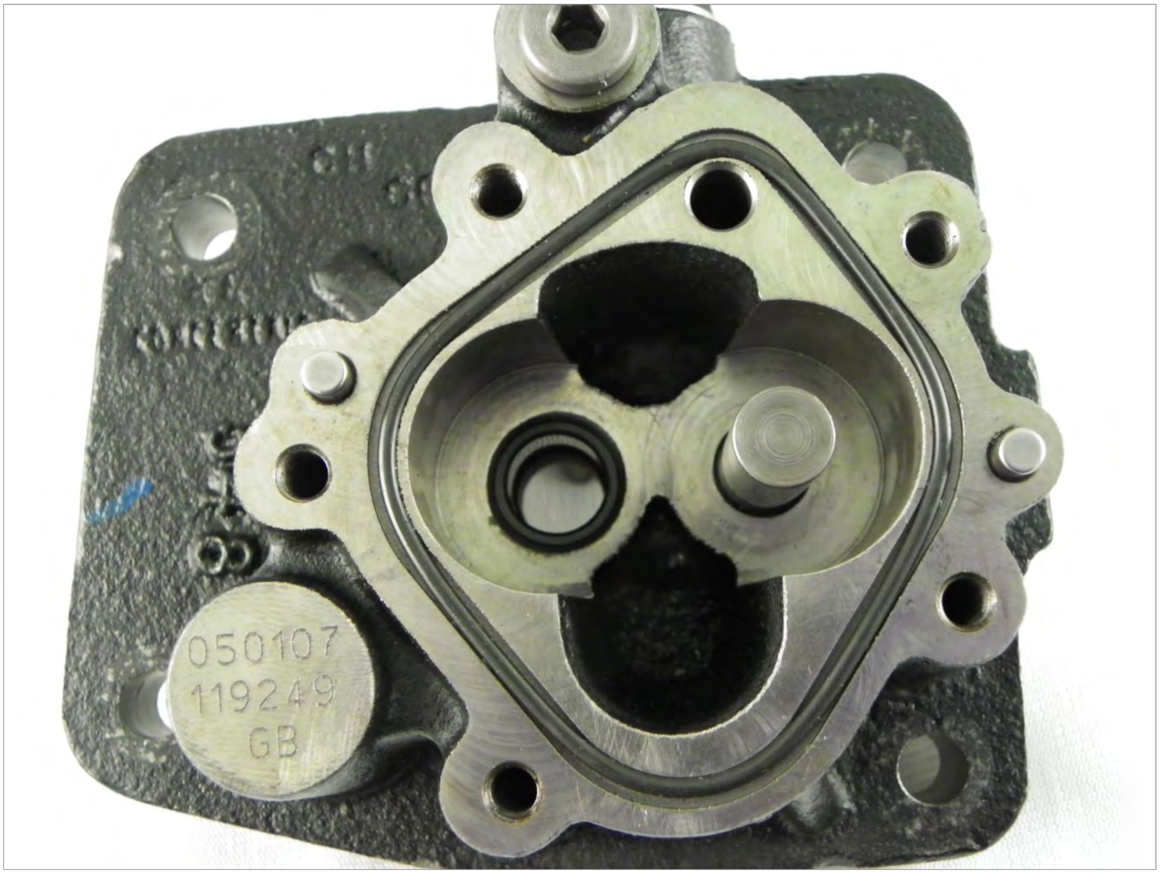


Figure B-10. Low Pressure Gear Pump Housing

Figure B-11. Gear Pump Pressure Relief Valve

Figure B-12. Pump Gears

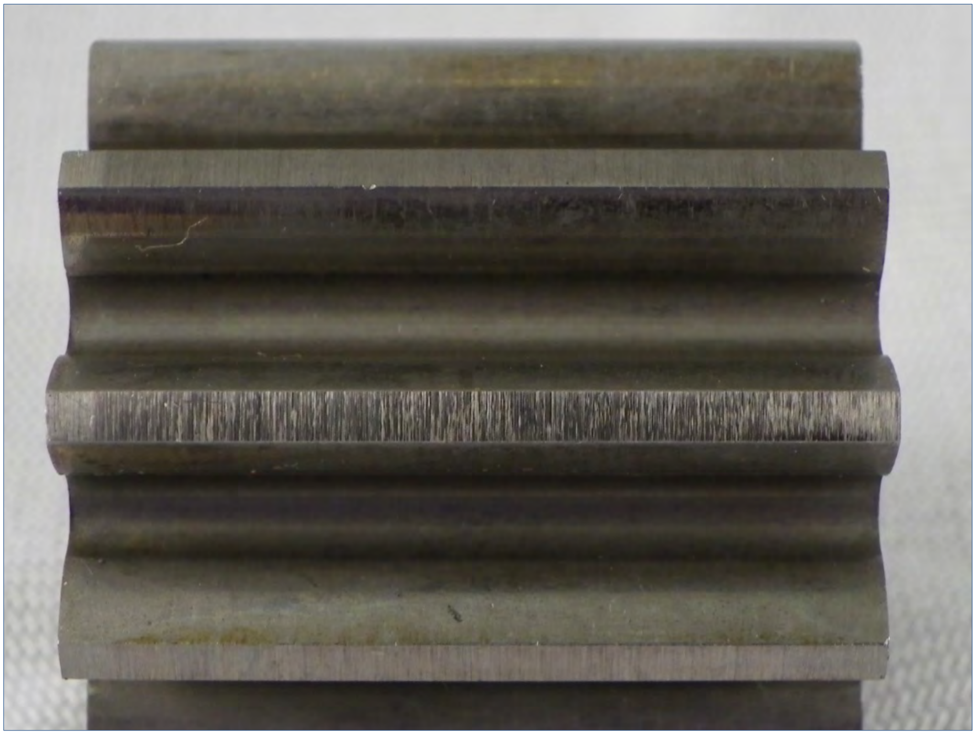


Figure B-13. Gear Tooth Wear

Figure B-14. High Pressure Check Valve

Fuel Injector

Figure B-15. Upper Injector Components

Figure B-16. Solenoid Plunger

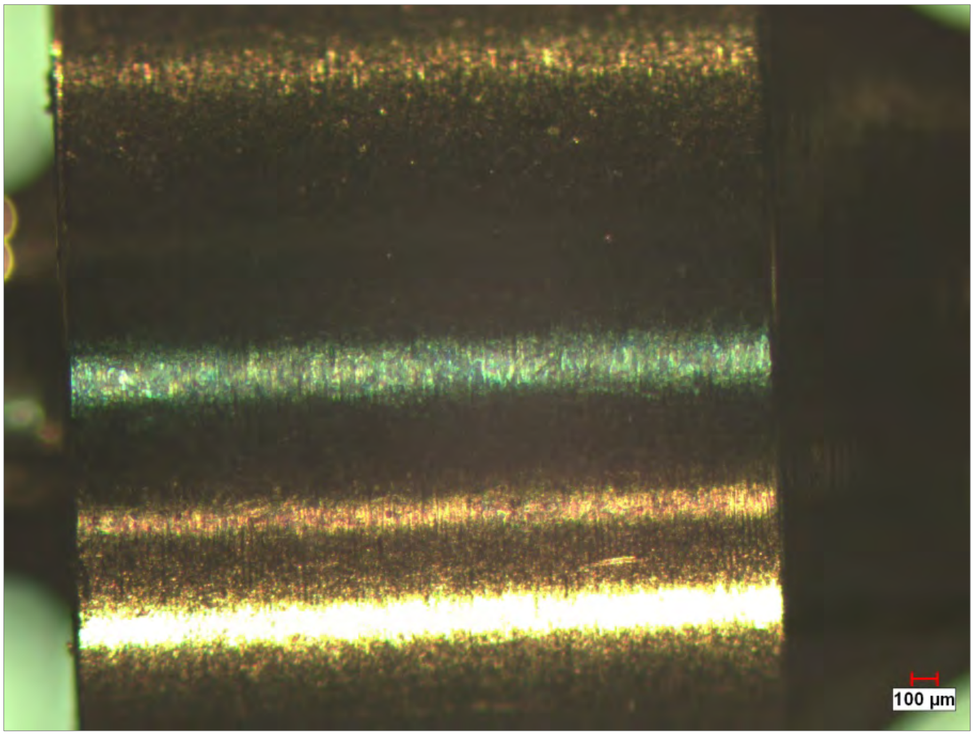


Figure B-17. Solenoid Plunger Close-Up

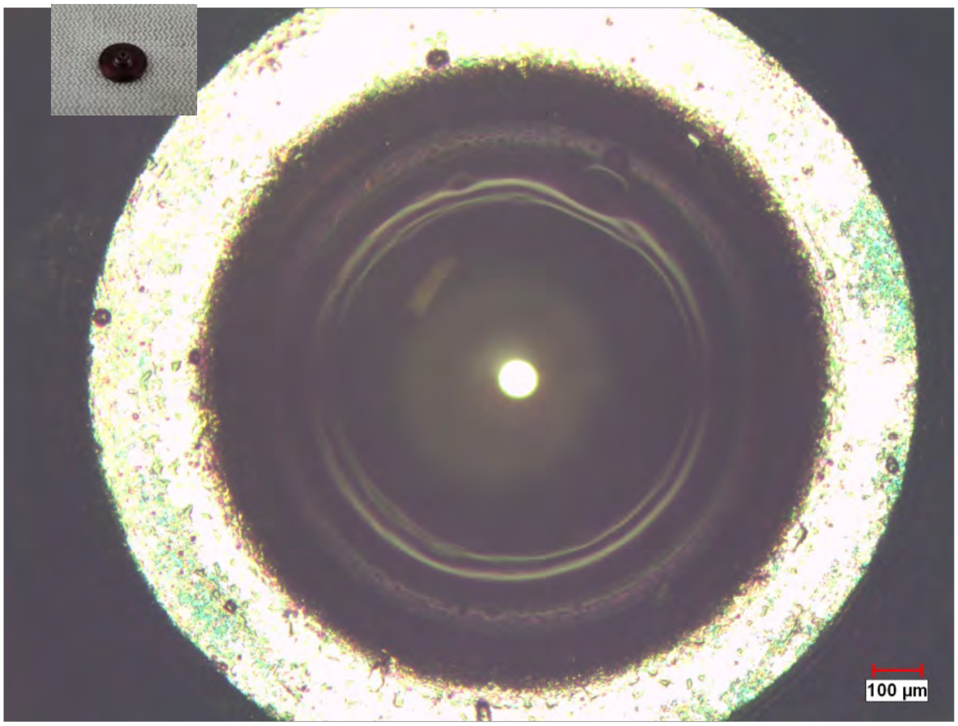


Figure B-18. Upper Ball Seat

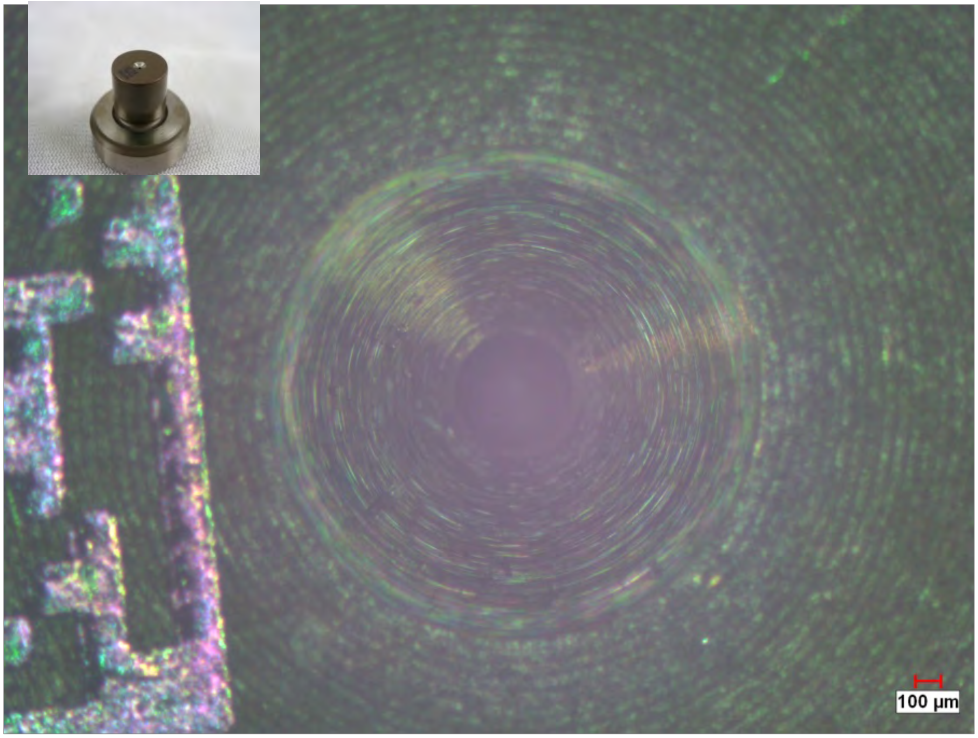


Figure B-19. Lower Ball Seat

Figure B-20. Injector Needle

Figure B-21. Injector Needle Scuffing

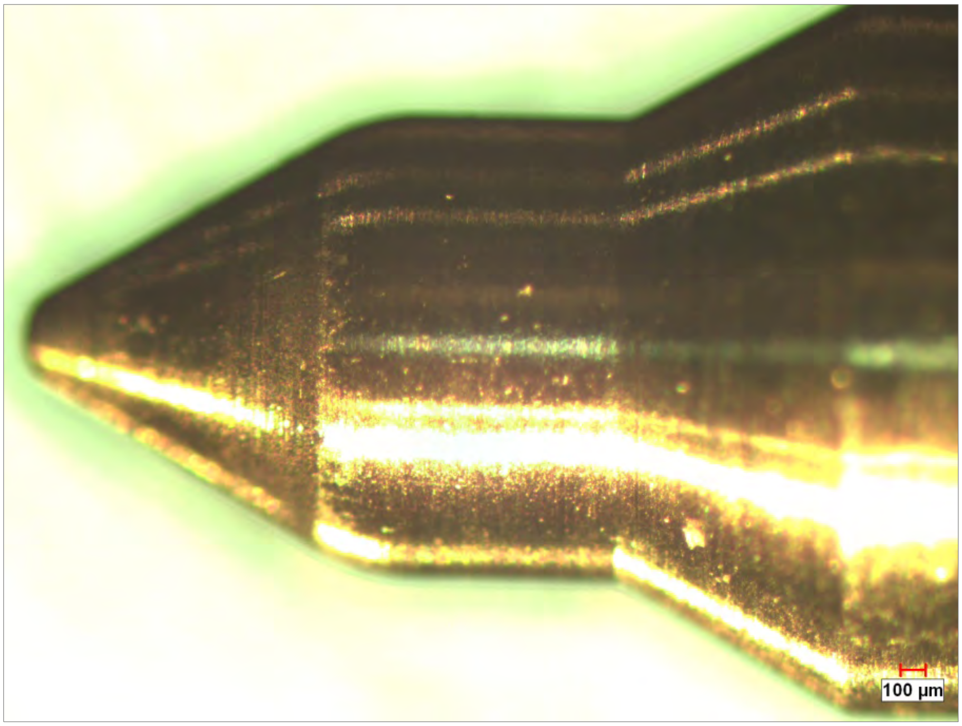


Figure B-22. Injector Needle Tip

APPENDIX - C

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: JP-8
Test Number: JP-8-AF7832-60C-XPI

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Cummins XPI Fuel System

Test Fuel: JP-8
Test Number: JP8-AF7832-60C-XPI
Start of Test Date: February 28, 2011
End of Test Date: March 24, 2011
Test Duration: 400 Hours
Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

TABLE OF CONTENTS

Section **Page**

LIST OF TABLES

LIST OF FIGURES

Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) is working on a project with the U.S. Army TARDEC on synthetic and alternative fuels. The project goal is to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, JP-8, an FT SPK, manufactured by Syntroleum as S-8, treated with corrosion inhibitor/lubricity improver (CI/LI), and a 1:1 blend of the JP-8 and the synthetic fuels. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Four tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and up to four at 93.3°C (200 °F), for a total of eight tests. The lower temperature ULSD test is considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the Cummins XPI fuel system. This system was developed jointly between Cummins Inc. and Scania. Primarily targeted for Cummins midrange and Scania heavy duty applications, an oil-lubricated fuel pump allows the system to reach rail and injection pressures of up to 30,000 psi. The pump consists of a low pressure gear pump and high pressure piston pump. It is operated at half of the engine angular velocity for a rated condition speed of 1050 rpm. On the high pressure side of the pump, the camshaft drives two plungers which pressurize the fuel entering the rail. Each plunger is driven by three lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure side of the system consists of a gear pump which passes fuel through the final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand specifically configured for the XPI system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Cummins CM2150 engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The fuel pump consisted of a low pressure gear pump to push fuel through a high efficiency filter and send it to the high-pressure cam driven pump. Fuel then flows to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled below its flash point, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each100 hour segment. A schematic of the stand layout is shown in Figure C-1.

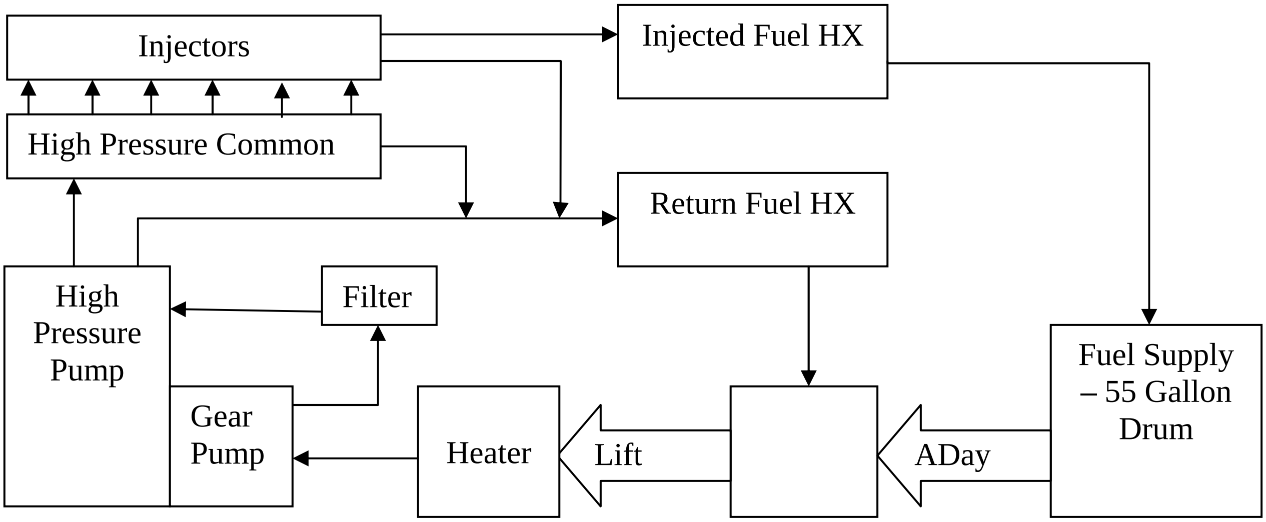


Figure C-1. XPI Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, “load” was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table C-1.

Table C-1. NATO Cycle for XPI Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	400	0	0.5
2	1050	100	2
3	1155	0	0.5
4	788	100	1
5*	400 to 1050	0 to 100	2
6	630	100	0.5
7	400	0	0.5
8	1081	70	0.5
9	650	100	2
10	650	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Cummins ECM for monitoring purposes. The stand did not experience any unusual performance issues related to rail pressure during the course of the test.

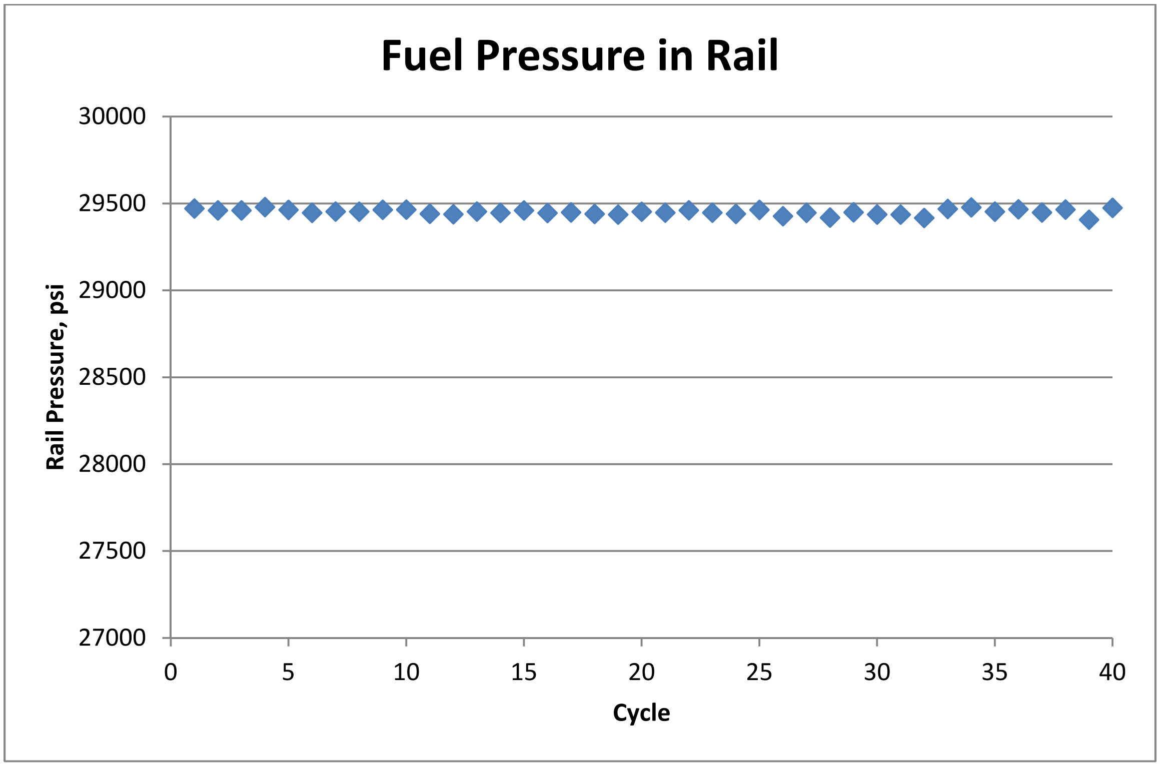


Figure C-2. Fuel Rail Pressure

The reduction in JP-8 flow between cycles 6 and 10 indicates a gradual loss of needle lift, while the steep drop in flow between cycles 10 and 11 indicates complete failure of an injector. During post-test inspection of the injectors, it was found that the solenoid plunger within the #4 injector was seized with debris. The JP-8 (projected) portion of the figure shows what flow rate would be expected, assuming only five of the six injectors were operational for the majority of the test. These projected values show a flow rate similar to that at the start of the test with a slight reduction of flow over time.

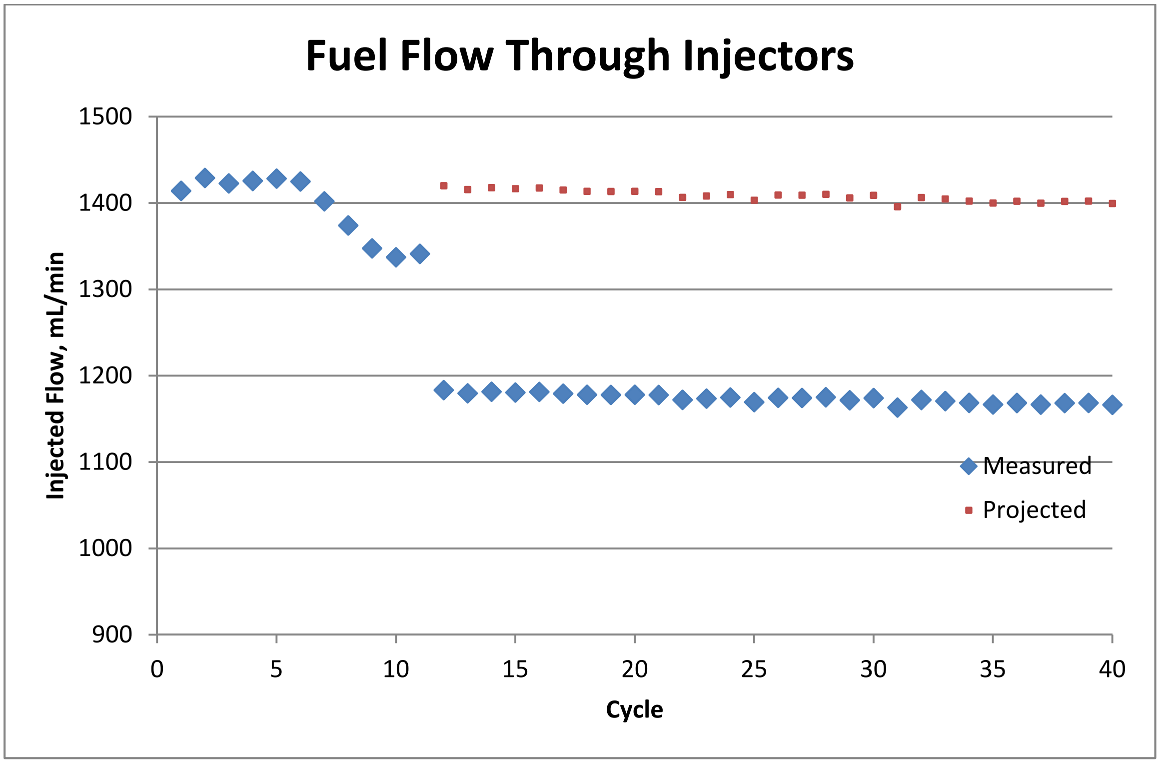


Figure C-3. Injected Fuel Flow

Bypass and return fuel flow is the combined fuel from the high pressure pump relief valve, rail protection check valve, and injectors bypass/cooling flow. The reduction in flow between cycles 6 and 11 is most likely due to the failure of the #4 injector. Since fuel passes through injectors as the needle lifts, degradation of the injectors influences not only the injected flow rate, but the bypass flow rate as well.

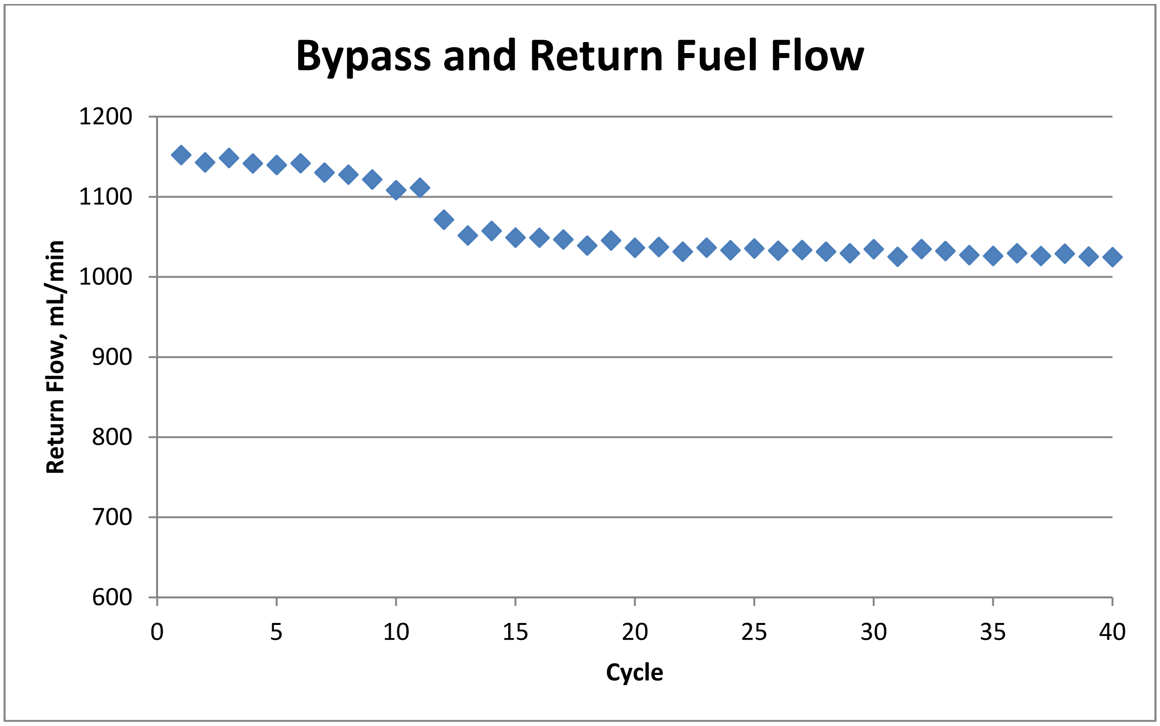


Figure C-4. Return Fuel Flow

Fuel filter inlet pressure is a measure of the pressure being developed by the gear pump portion of the XPI fuel pump. A slight reduction in pressure was seen over the duration of the test.

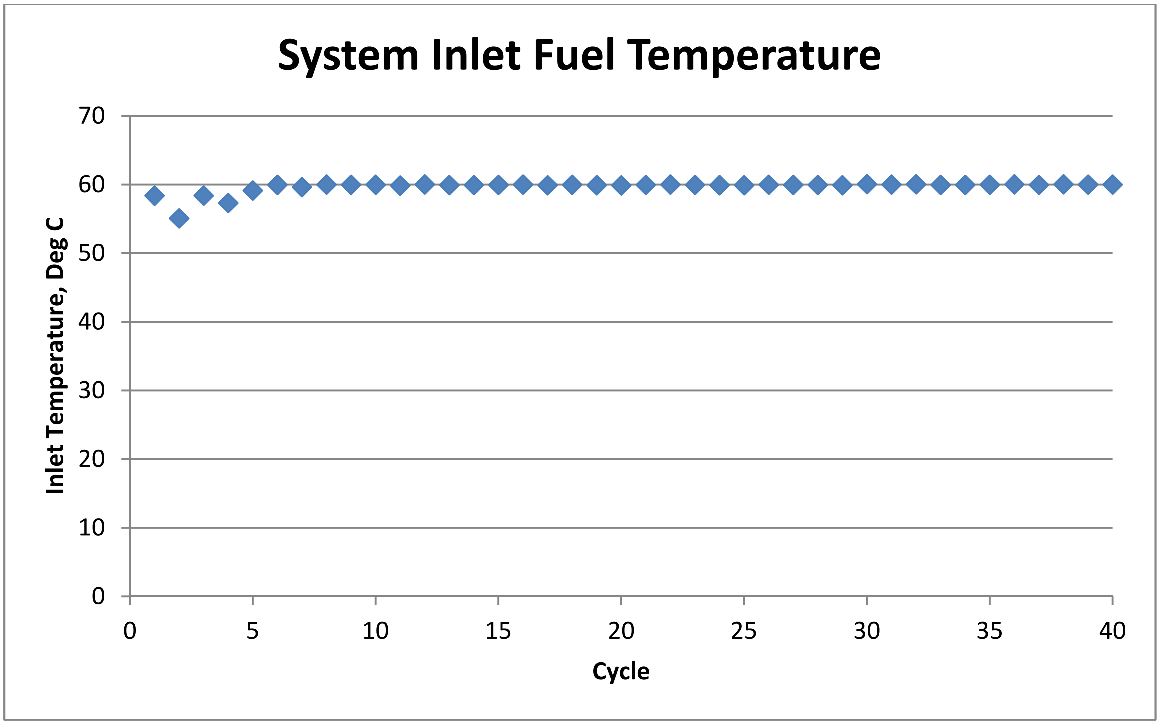


Figure C-5. System Inlet Fuel Temperature

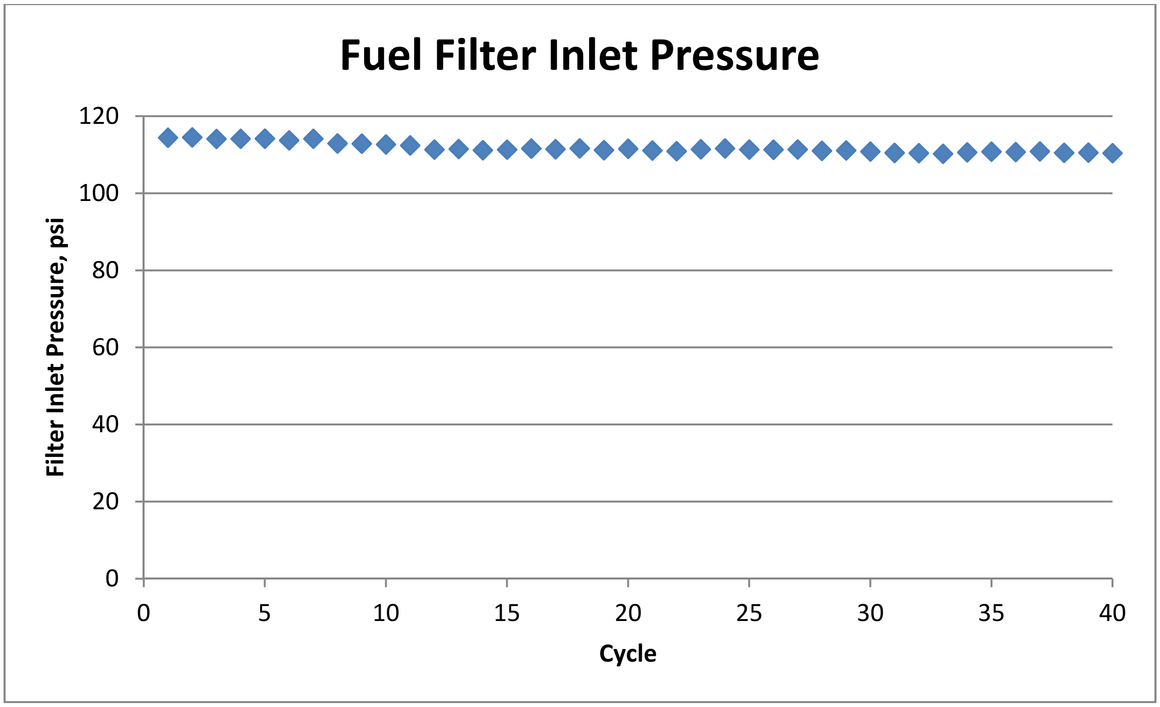


Figure C-6. Fuel Filter Pressure

Table C-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	58.8	2.4	49.9	65.2
Injected Fuel Temperature, deg C	151.8	12.4	4.6	167.2
Rail Pressure, psi	29461	113	28491	29934
Injected Flow Rate, mL/min	1400.6	46.7	1105.8	1499.0
Return Fuel Flow Rate, mL/min	1134.6	25.8	1033.1	1217.8
Fuel Filter Inlet Pressure, psi	113.8	1.3	91.8	118.0
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.3	56.3	63.0
Injected Fuel Temperature, deg C	159.2	6.0	111.8	166.4
Rail Pressure, psi	29446	118	29139	29965
Injected Flow Rate, mL/min	1196.0	53.3	961.8	1413.4
Return Fuel Flow Rate, mL/min	1055.1	29.8	978.2	1157.0
Fuel Filter Inlet Pressure, psi	111.5	0.7	108.5	114.5
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.3	56.2	64.9
Injected Fuel Temperature, deg C	159.0	6.1	112.7	165.6
Rail Pressure, psi	29444	122	29073	29853
Injected Flow Rate, mL/min	1174.0	21.3	882.9	1237.5
Return Fuel Flow Rate, mL/min	1033.1	18.5	966.9	1090.9
Fuel Filter Inlet Pressure, psi	111.2	0.5	109.4	112.6
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.2	56.8	62.5
Injected Fuel Temperature, deg C	159.4	6.0	113.1	165.8
Rail Pressure, psi	29451	131	29068	29966
Injected Flow Rate, mL/min	1168.2	17.0	976.7	1230.7
Return Fuel Flow Rate, mL/min	1027.4	18.2	946.9	1074.4
Fuel Filter Inlet Pressure, psi	110.6	0.5	105.7	114.6

Fuel Analysis

Fuel was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figures C-7 and C-8. Pre and post test fuel analysis did not indicate any unusually large changes in lubricity.

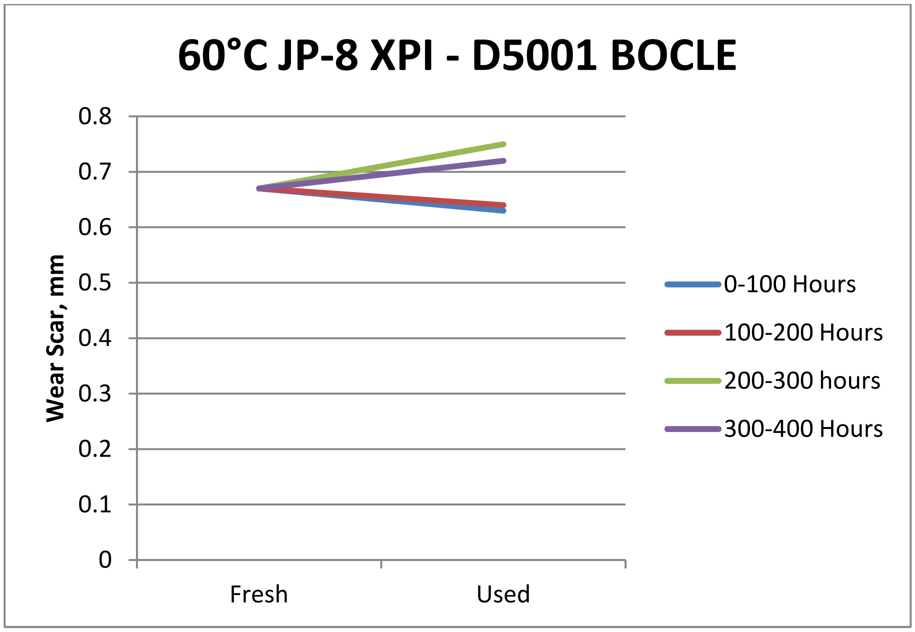


Figure C-7. ASTM D5001 BOCLE

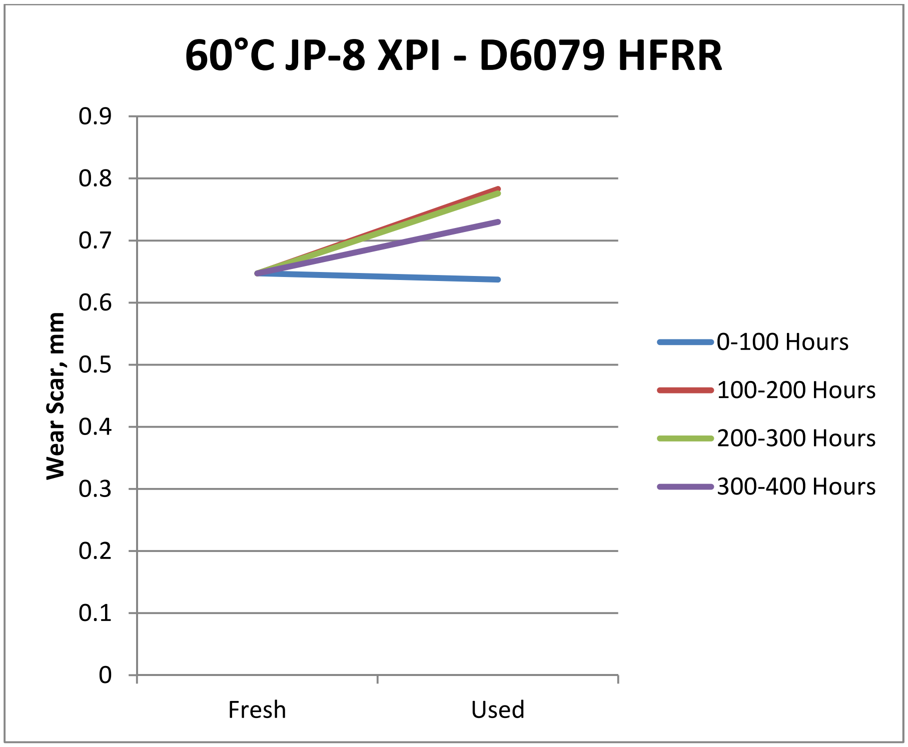


Figure C-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on JP-8. Only fuel wetted components are shown in the figures that follow.

Fuel Pump

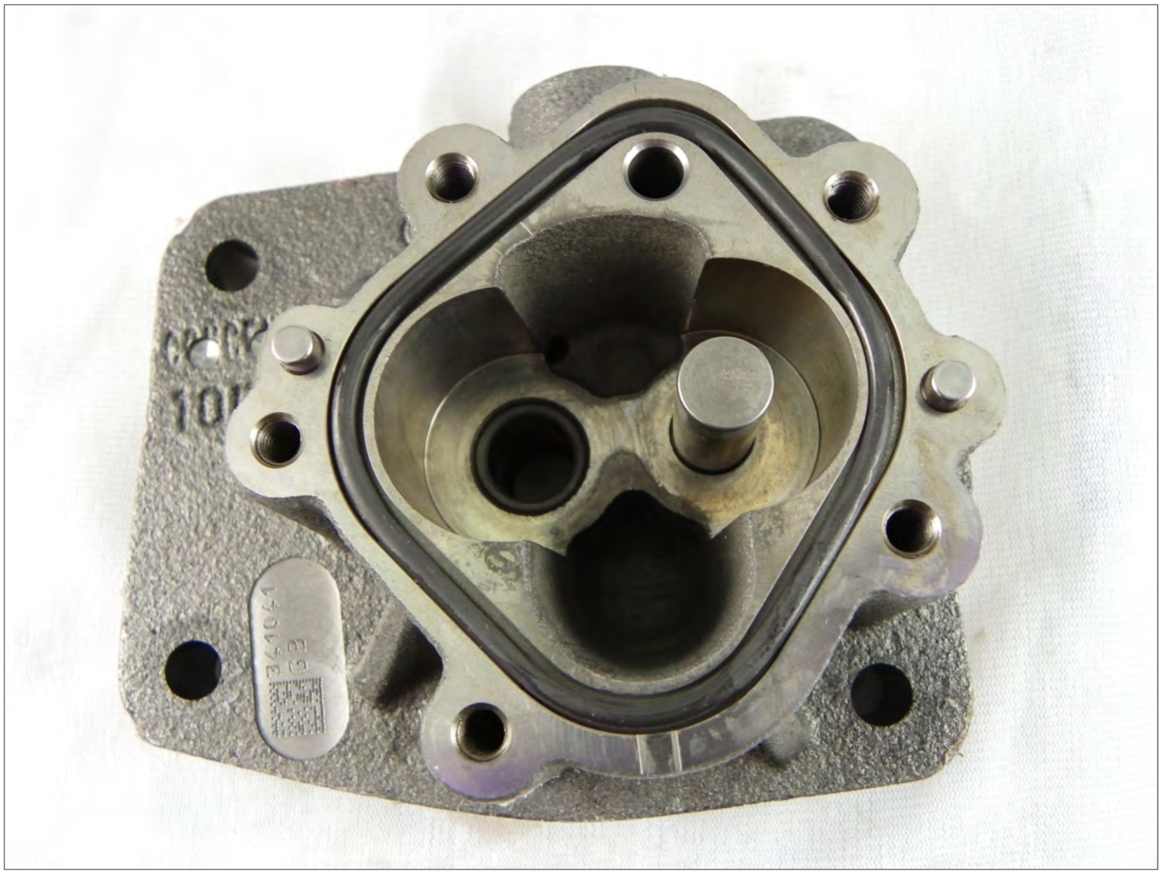


Figure C-9. Low Pressure Gear Pump Housing

Figure C-10. Gear Pump Pressure Relief Valve

Figure C-11. Pump Gears

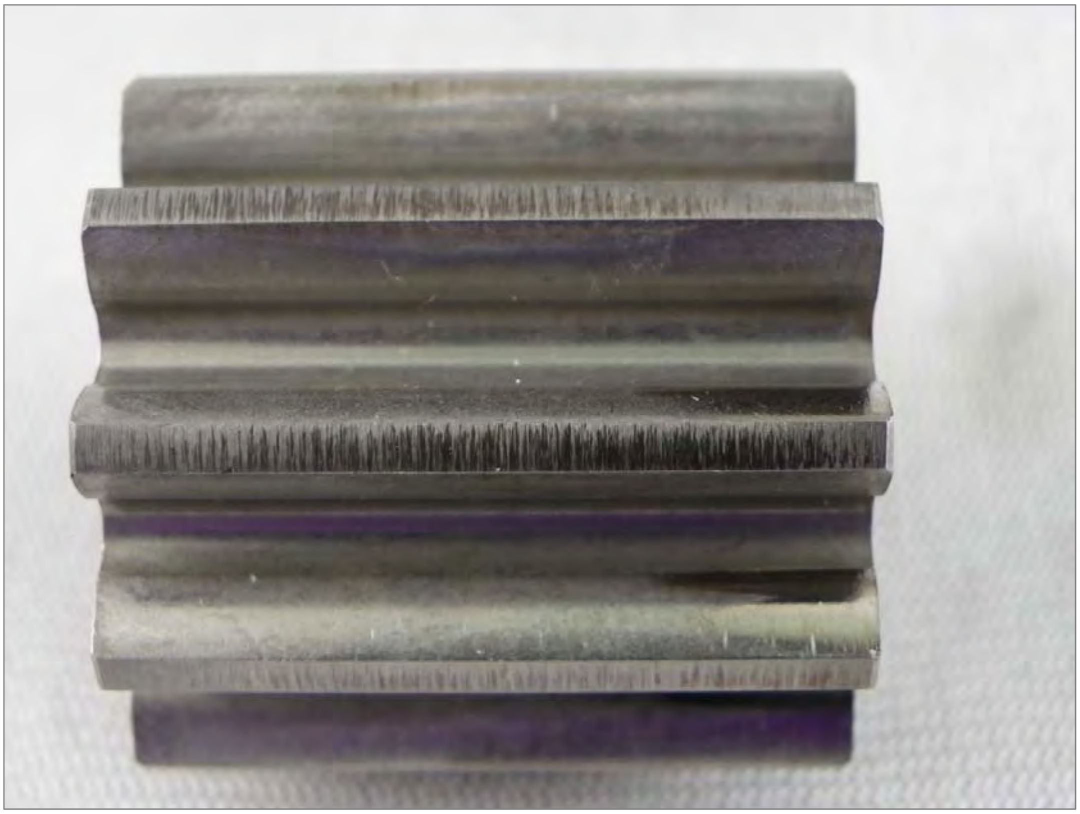


Figure C-12. Gear Tooth Wear

Figure C-13. High Pressure Check Valve

Fuel Injector

It was concluded that injector #4 experienced a failure during the JP-8 test. Photos for this test are shown for both the failed unit one representing a typical condition of the other five injectors. While disassembling the unit, it was found that the solenoid plunger seemed to be seized within its bore. After removal, the plunger would not slide back into the bore as it would in the other injectors. Since no issues of a similar nature were found in the other injectors or the pump, it is assumed this the failure was related to hardware and not the fuel used for testing.

Figure C-14. Upper Injector Components (Typical)

Figure C-15. Upper Injector Components (Failed)

It was observed that the material in the solenoid of the failed injector had a rougher and porous surface appearance compared to that of the typical unit. Additionally, the inside surface of the bore (not shown) had a dull appearance rather than the highly polished surface found in others.

Figure C-16. Solenoid Units, Failed (Left) and Typical (Right)

Upon removal, metallic filings were found on the plunger. It should be noted that the filings are standing out in Figure XX due to the magnetic nature of the piece. While still wet with fuel, the filings were mainly collected between the two wider sections and the top of the plunger. Shown along with plunger from the failed unit is another from the JP-8 test typical of the remaining injectors.

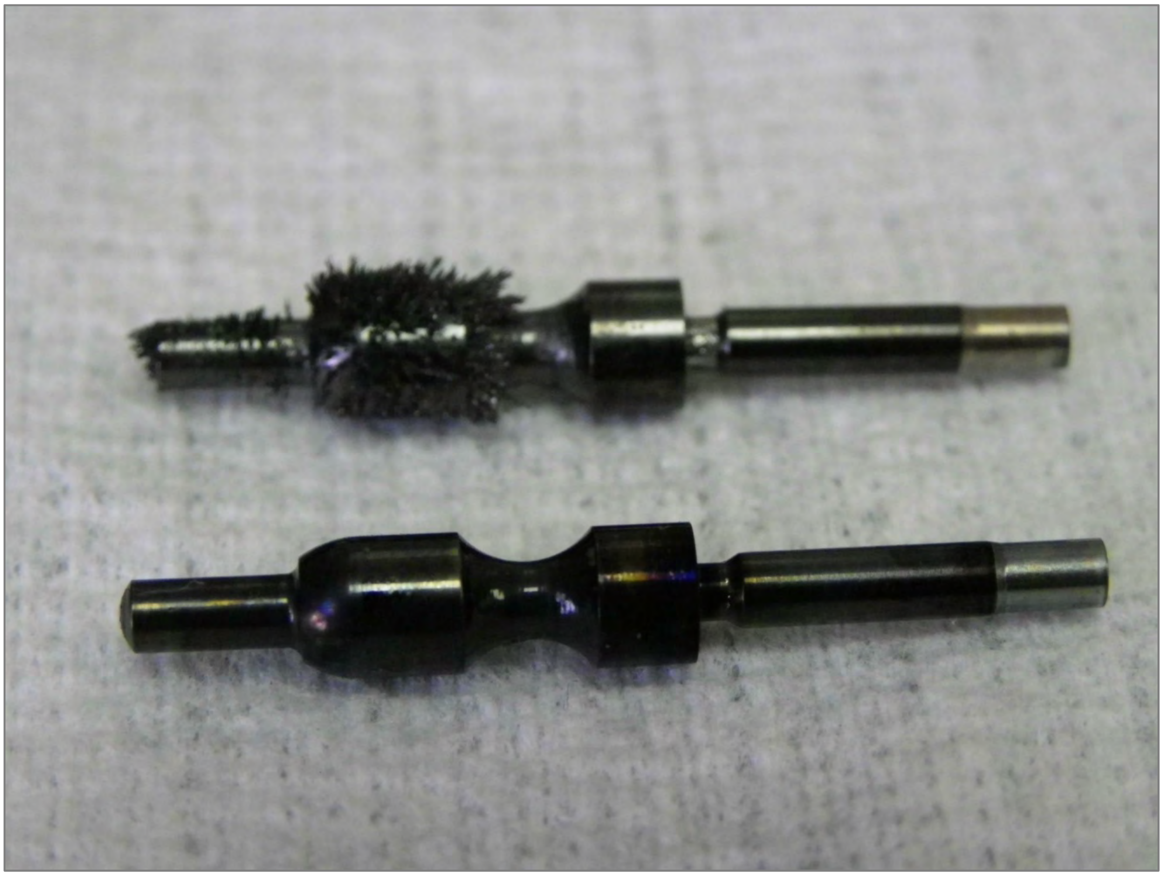


Figure C-17. Solenoid Plungers, Failed on Top, Typical Below

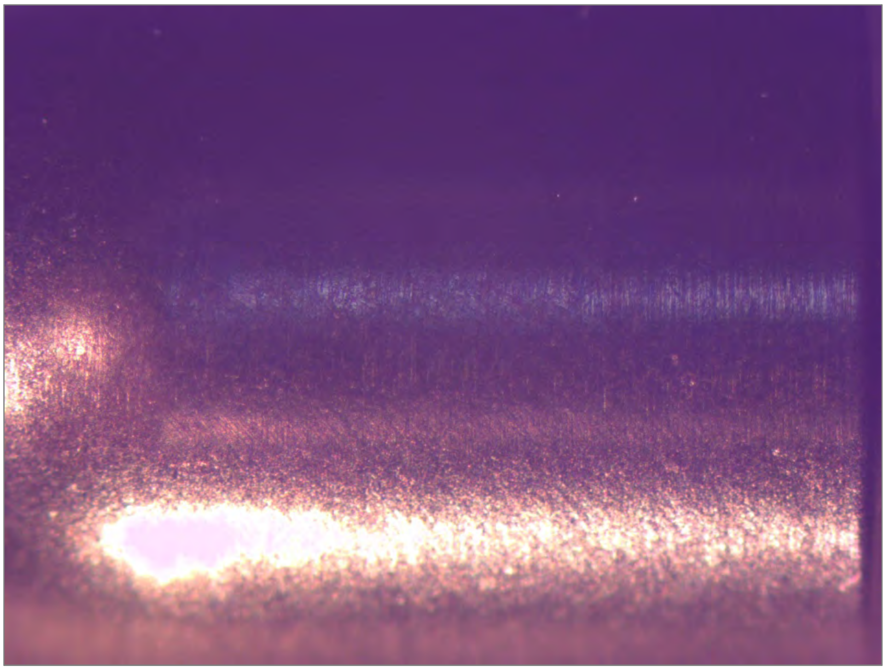


Figure C-18. Solenoid Plunger Close-up (Typical)

It should be noted the gouges visible on the failed injector plunger in Figure C-11. This is likely the source of the metallic shavings.

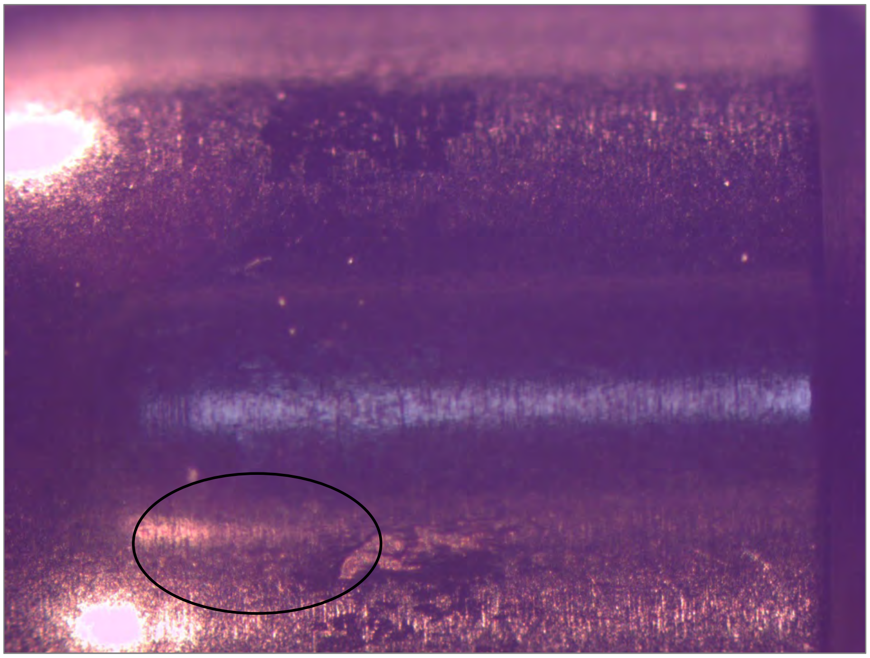


Figure C-19. Solenoid Plunger Close-up (Failed)

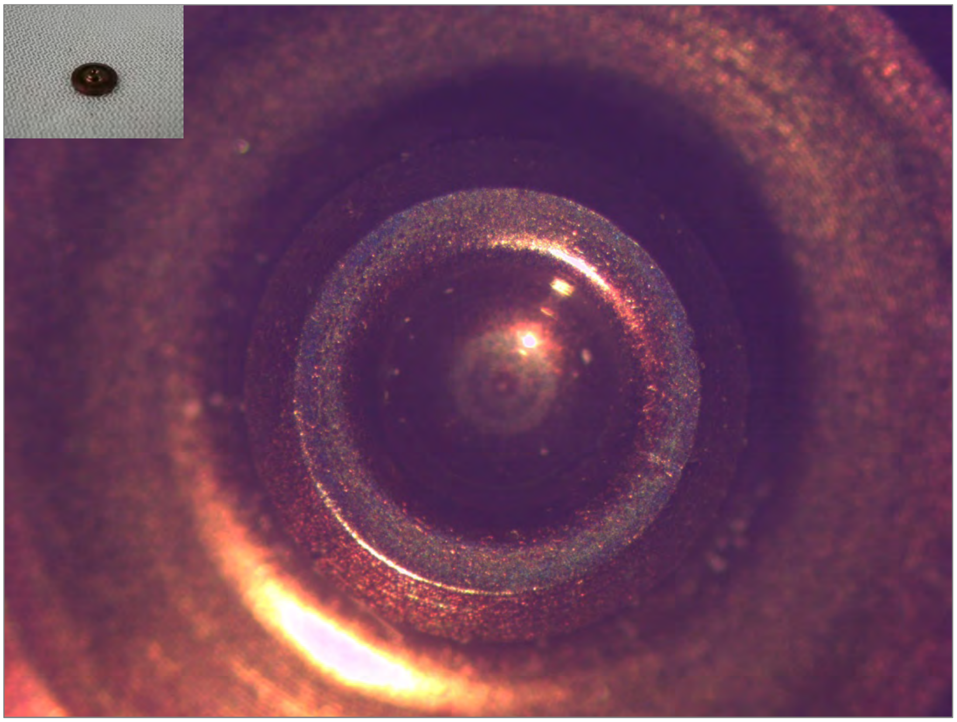


Figure C-20. Upper Ball Seat (Typical)

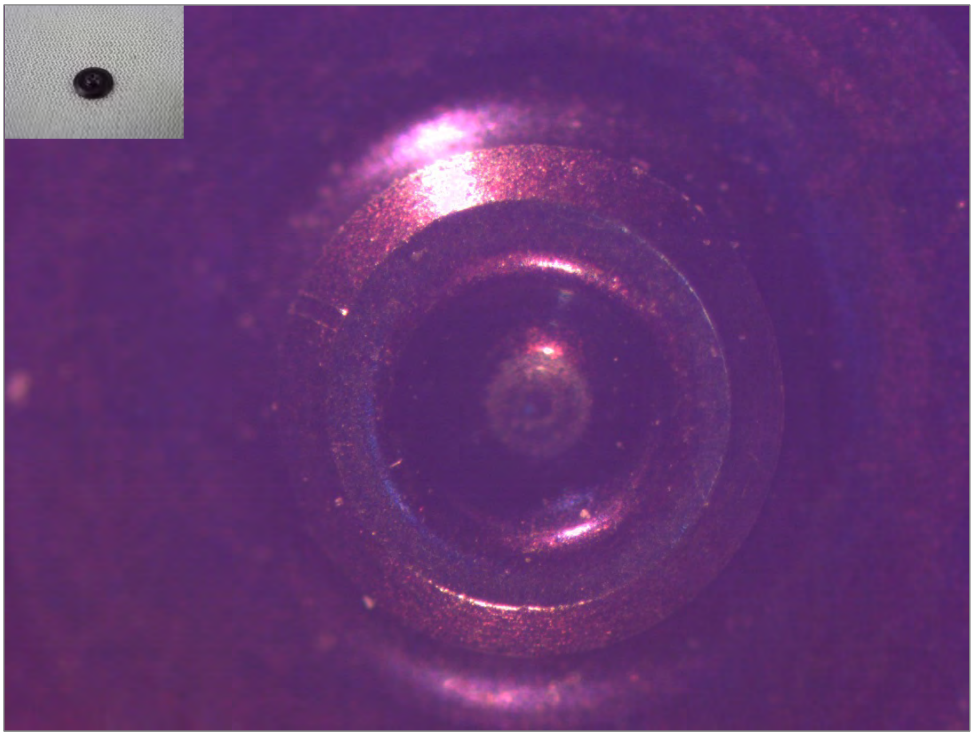


Figure C-21. Upper Ball Seat (Failed)

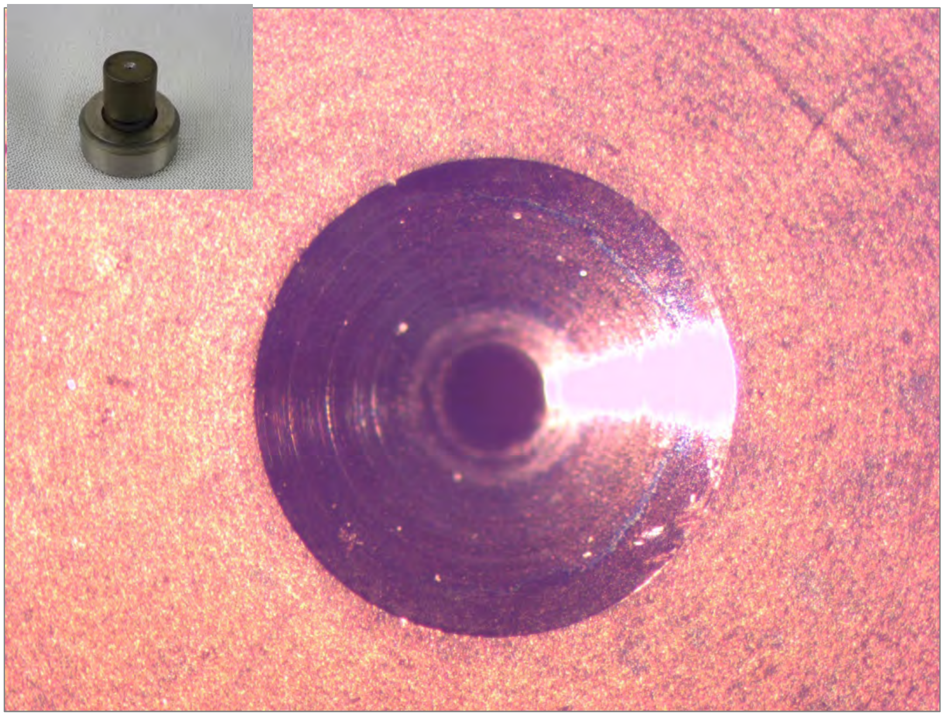


Figure C-22. Lower Ball Seat (Typical)

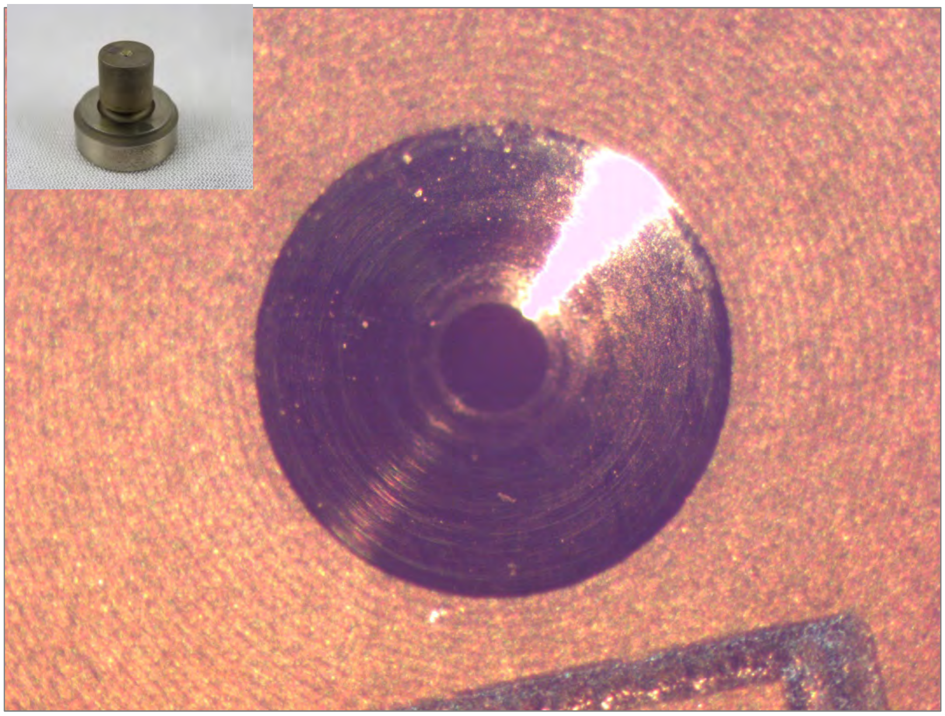


Figure C-23. Lower Ball Seat (Failed)

Figure C-24. Injector Needle (Typical)

Figure C-25. Injector Needle (Failed)

Figure C-26. Injector Needle Scuffing (Typical)

Figure C-27. Injector Needle Scuffing (Failed)

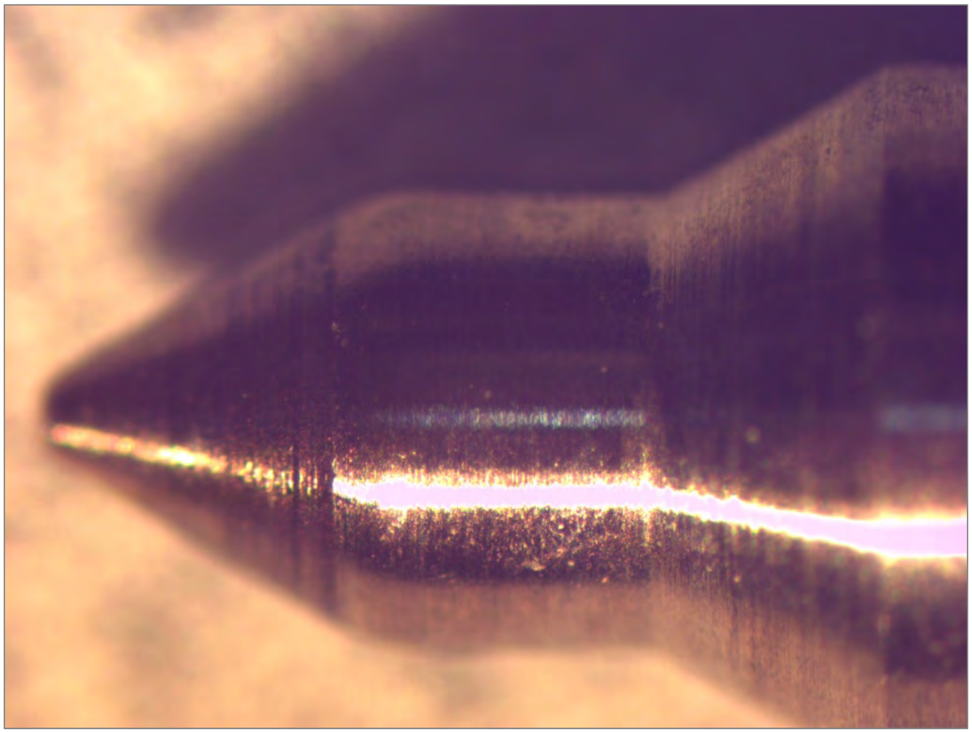


Figure C-28. Injector Needle Tip (Typical)

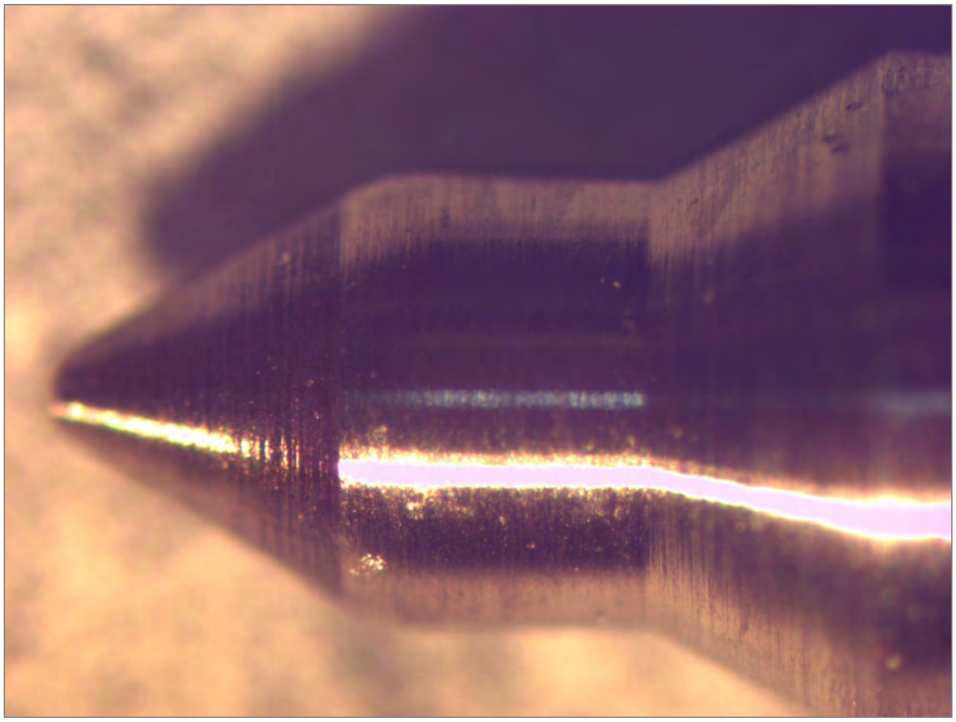


Figure C-29. Injector Needle Tip (Failed)

APPENDIX - D

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: JP-8

Test Number: JP-8-AF7832-93C-XPI

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Cummins XPI Fuel System

Test Fuel: JP-8
Test Number: JP-8-AF7832-93C-XPI
Start of Test Date: August 15, 2011
End of Test Date: September 9, 2011
Test Duration: 400 Hours
Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

TABLE OF CONTENTS

Section **Page**

LIST OF TABLES

LIST OF FIGURES

Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) is working on a project with the U.S. Army TARDEC on synthetic and alternative fuels. The project goal is to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, JP-8, an FT SPK, manufactured by Syntroleum as S-8, treated with corrosion inhibitor/lubricity improver (CI/LI), and a 1:1 blend of the JP-8 and the synthetic fuels. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Four tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and up to four at 93.3°C (200 °F), for a total of eight tests. The lower temperature ULSD test is considered a baseline for comparison of other tests. As the project progressed, it was determined that the 93.3°C ULSD and full synthetic tests would be replaced with 60°C evaluations of Jet-A and the synthetic fuel without any lubricity improver.

Test System

Test fuel was evaluated in the Cummins XPI fuel system. This system was developed jointly between Cummins Inc. and Scania. Primarily targeted for Cummins midrange and Scania heavy duty applications, an oil-lubricated fuel pump allows the system to reach rail and injection pressures of up to 30,000 psi. The pump consists of a low pressure gear pump and high pressure piston pump. It is operated at half of the engine angular velocity for a rated condition speed of 1050 rpm. On the high pressure side of the pump, the camshaft drives two plungers which pressurize the fuel entering the rail. Each plunger is driven by three lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure side of the system consists of a gear pump which passes fuel through the final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand specifically configured for the XPI system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Cummins CM2150 engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The fuel pump consisted of a low pressure gear pump to push fuel through a high efficiency filter and send it to the high-pressure cam driven pump. Fuel then flows to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled below its flash point, and returned to the remote drum.

Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each 100 hour segment. A schematic of the stand layout is shown in Figure D-1.

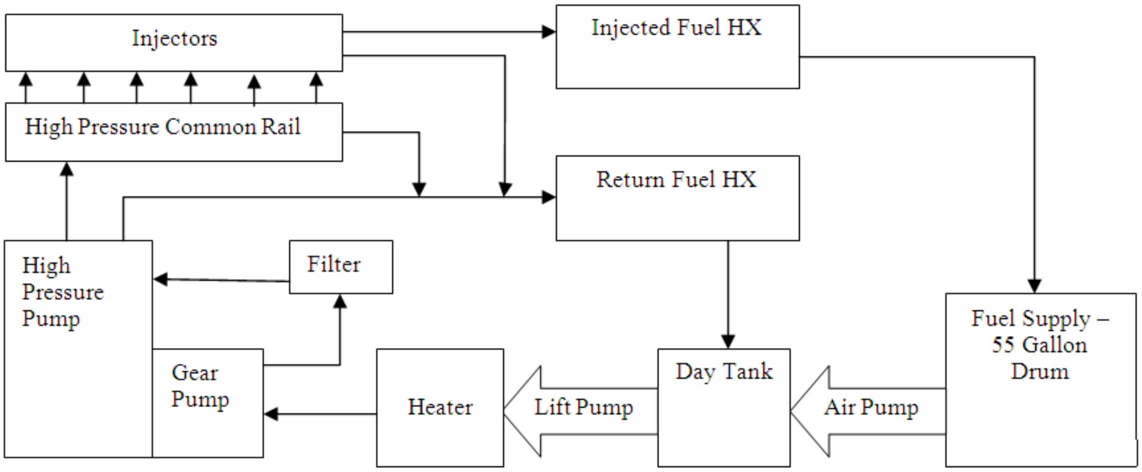


Figure D-1. XPI Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, “load” was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table D-1.

Table D-1. NATO Cycle for XPI Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	400	0	0.5
2	1050	100	2
3	1155	0	0.5
4	788	100	1
5*	400 to 1050	0 to 100	2
6	630	100	0.5
7	400	0	0.5
8	1081	70	0.5
9	650	100	2
10	650	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Cummins ECM for monitoring purposes. The stand did not experience any unusual performance issues related to rail pressure during the course of the test.

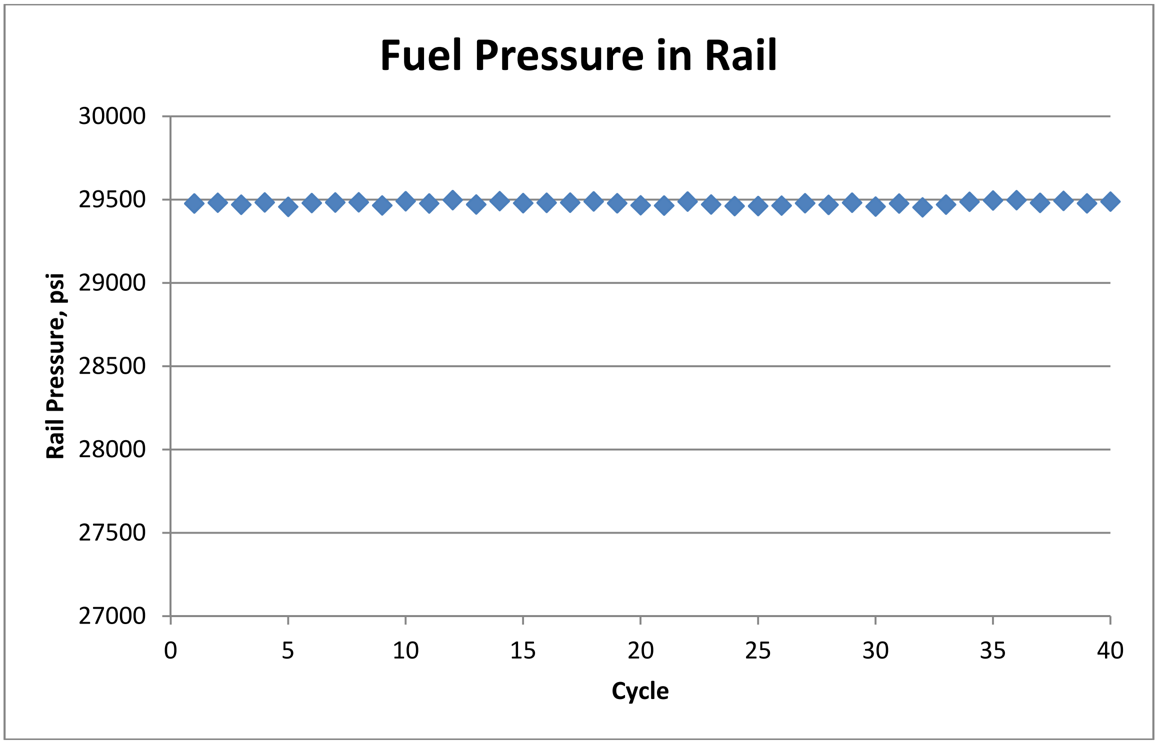


Figure D-2. Fuel Rail Pressure

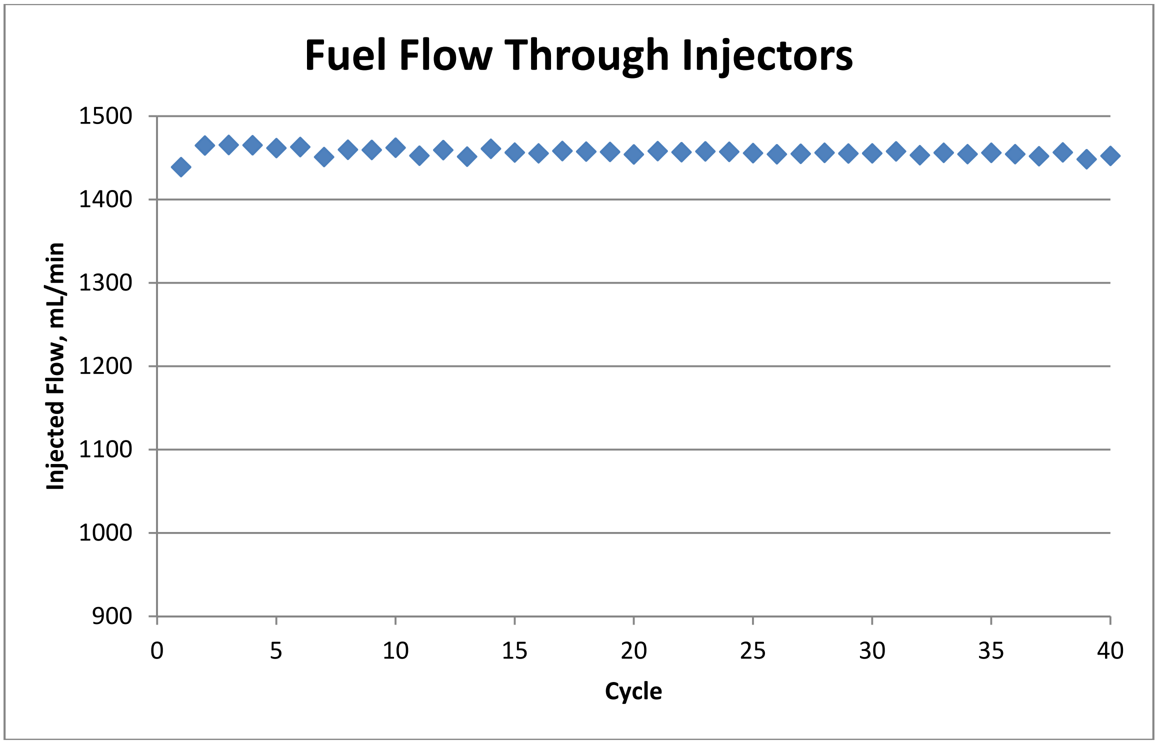


Figure D-3. Injected Fuel Flow

Both injected and bypass flow rates were consistent throughout the evaluation.

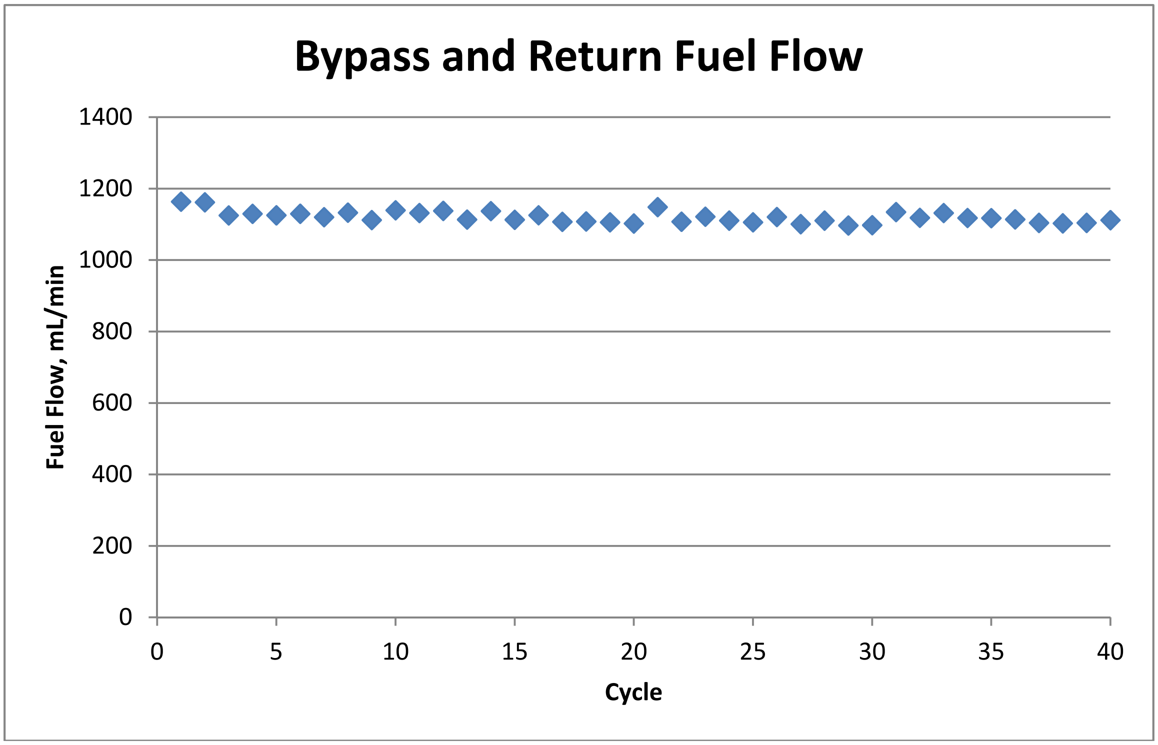


Figure D-4. Return Fuel Flow

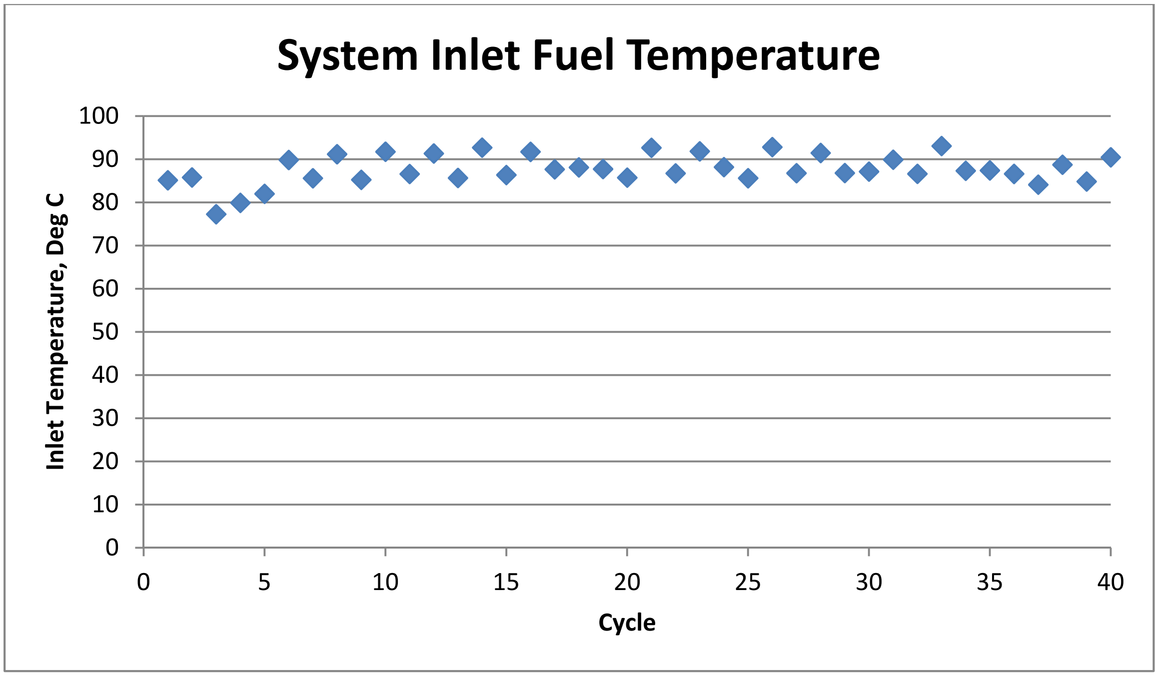


Figure D-5. System Inlet Fuel Temperature

At the flow rate experienced at rated conditions, the test stand heater maintains a temperature below the 93.3° C set point.

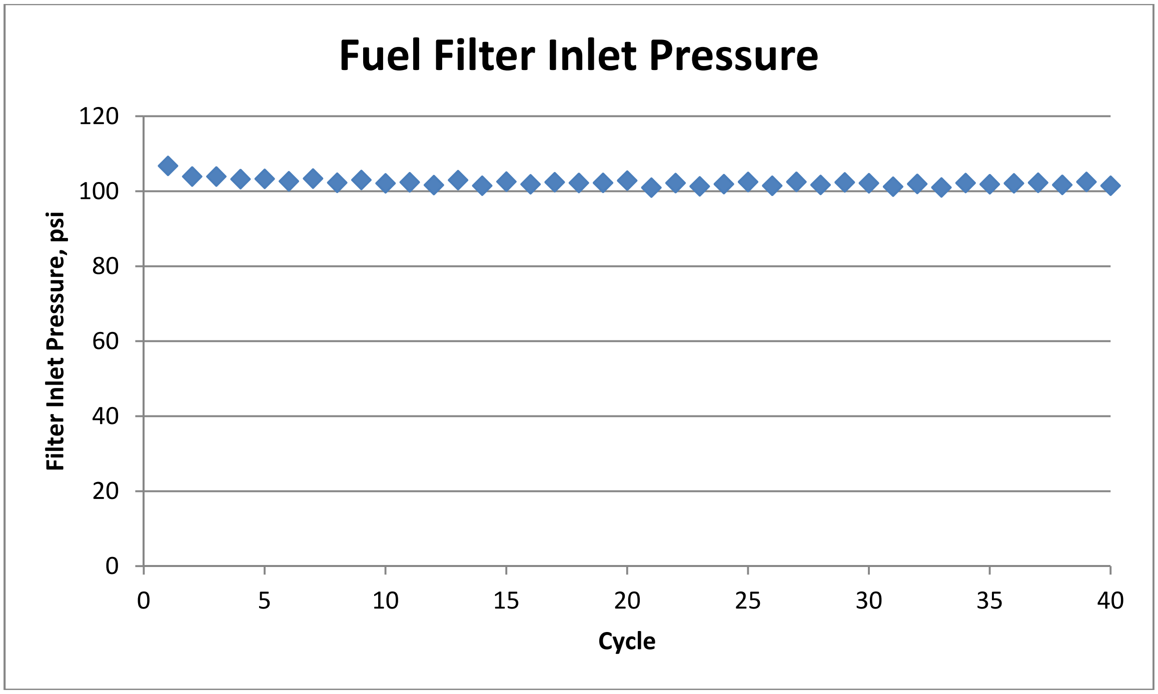


Figure D-6. Fuel Filter Pressure

Fuel filter inlet pressure is a measure of the pressure being developed by the gear pump portion of the XPI fuel pump.

Table D-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	85.4	4.7	74.7	94.5
Injected Fuel Temperature, deg C	181.5	7.2	130.6	192.8
Rail Pressure, psi	29476	96.1	28932.4	29872.2
Injected Flow Rate, mL/min	1458.9	23.6	1185.9	1503.7
Return Fuel Flow Rate, mL/min	1133.2	21.5	1016.5	1196.0
Fuel Filter Inlet Pressure, psi	103.5	1.4	101.0	109.1
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	88.4	2.8	78.8	94.2
Injected Fuel Temperature, deg C	183.5	7.1	119.8	192.8
Rail Pressure, psi	29481	101.5	29074.4	29801.6
Injected Flow Rate, mL/min	1456.1	18.7	1280.7	1496.3
Return Fuel Flow Rate, mL/min	1117.5	18.6	1014.8	1158.8
Fuel Filter Inlet Pressure, psi	102.3	0.7	100.6	106.1
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	89.0	2.9	84.2	93.8
Injected Fuel Temperature, deg C	184.4	6.0	148.7	192.7
Rail Pressure, psi	29471	120.3	29066.6	29878.4
Injected Flow Rate, mL/min	1456.0	17.5	1365.2	1531.7
Return Fuel Flow Rate, mL/min	1111.2	18.9	1032.5	1174.1
Fuel Filter Inlet Pressure, psi	102.0	0.7	99.9	104.1
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	87.9	2.8	81.9	93.8
Injected Fuel Temperature, deg C	183.9	5.8	148.3	193.1
Rail Pressure, psi	29481	117.7	29105.0	29874.5
Injected Flow Rate, mL/min	1454.0	17.3	1377.1	1513.1
Return Fuel Flow Rate, mL/min	1115.1	16.1	1047.2	1153.5
Fuel Filter Inlet Pressure, psi	101.9	0.7	100.0	104.0

Fuel Analysis

Fuel was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figures D-7 and D-8. Pre and post test fuel analysis did not indicate any unusually large changes in lubricity.

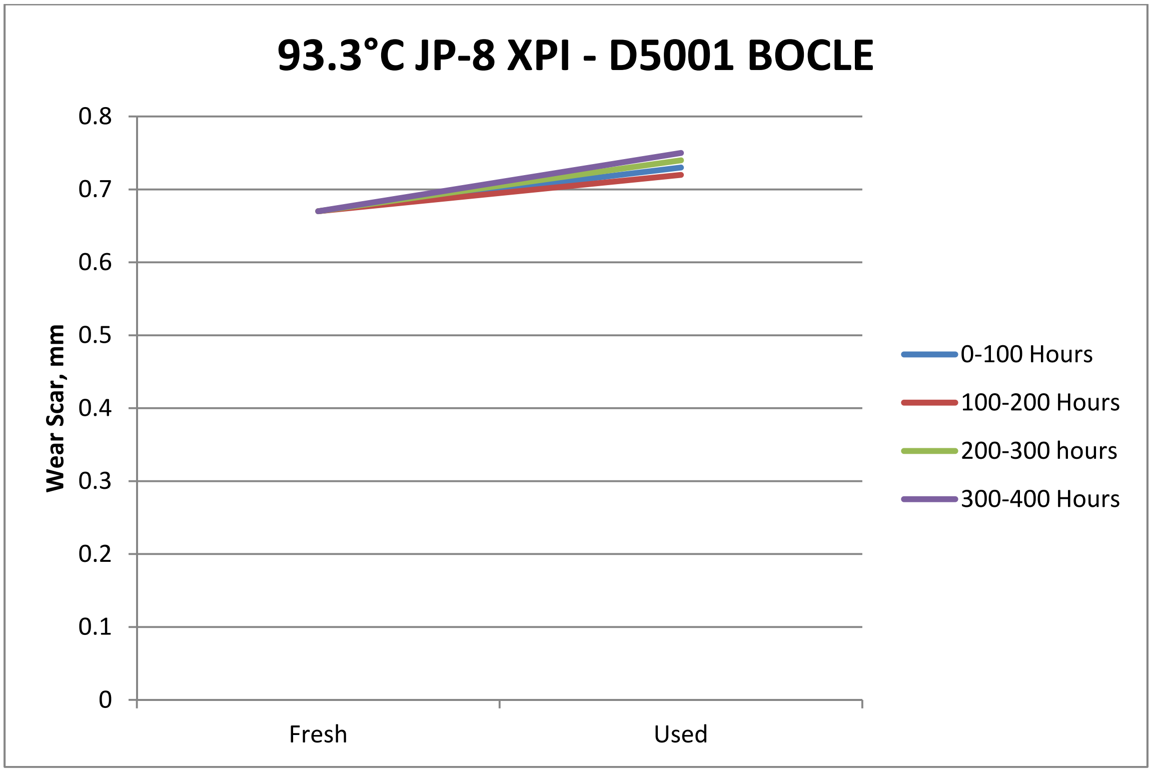


Figure D-7. ASTM D5001 BOCLE

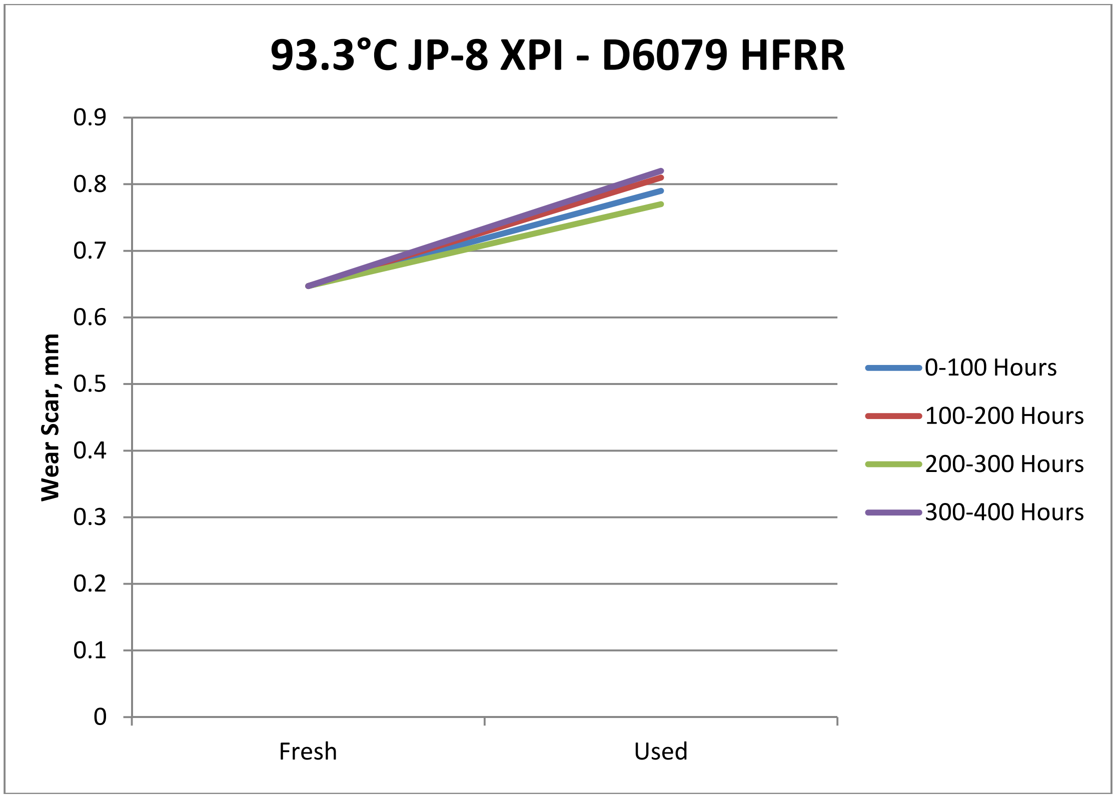


Figure D-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on JP-8. Only fuel wetted components are shown in the figures that follow.

Fuel Pump

Figure D-9. Low Pressure Gear Pump Housing

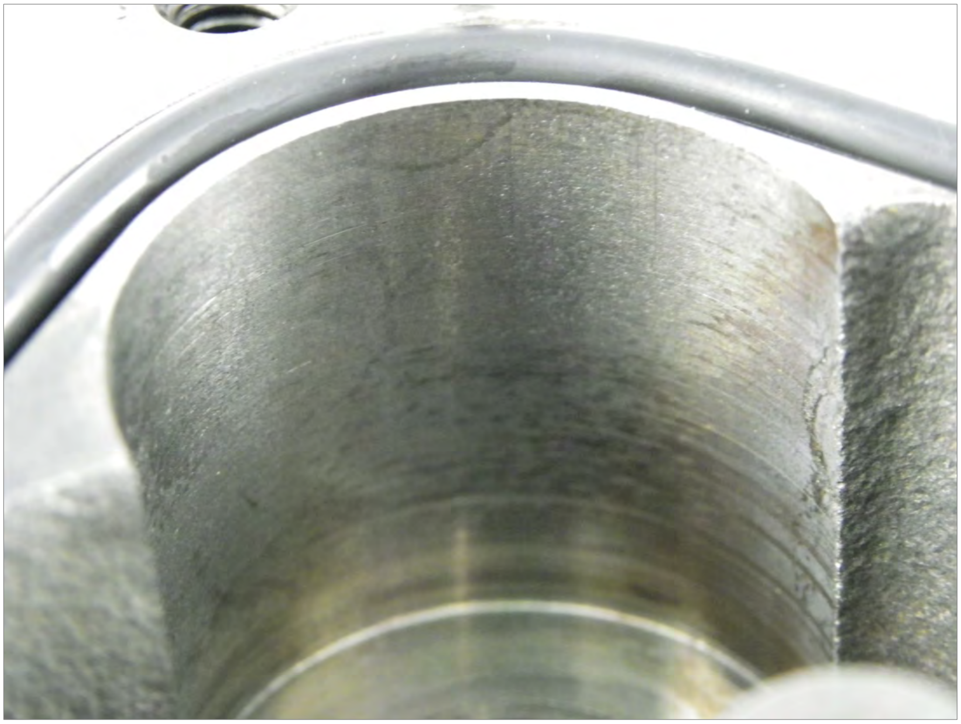


Figure D-10. Gear Pump Side Wall

Figure D-11. Gear Pump Pressure Relief Valve

Figure D-12. Pump Gears

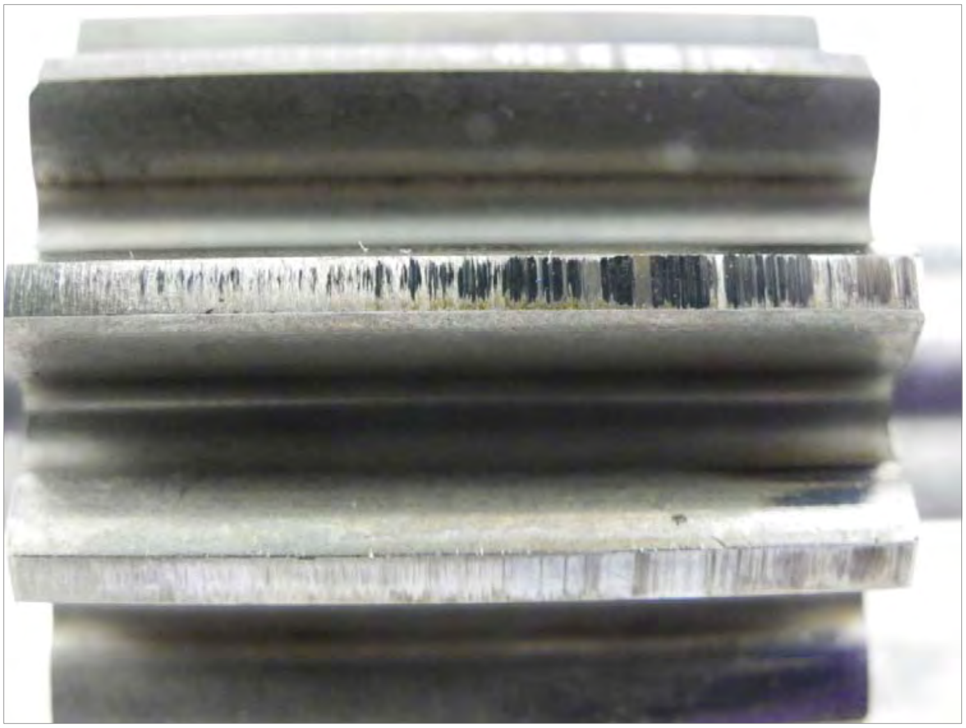


Figure D-13. Gear Tooth Wear

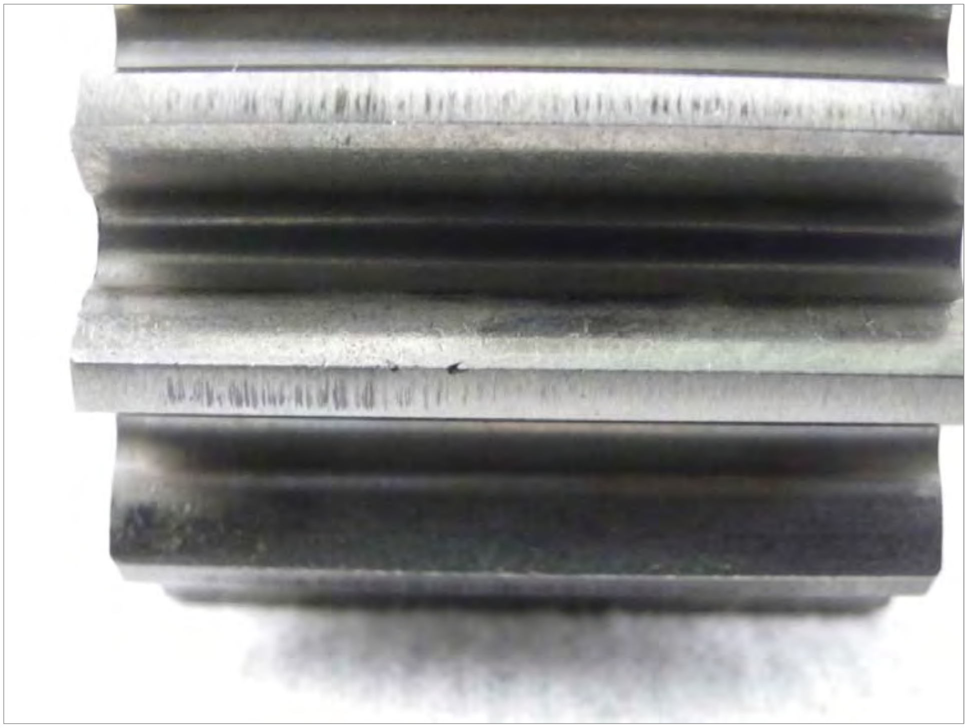


Figure D-14. Gear Tooth Chipping

Fuel Injector

Figure D-15. Upper Injector Components

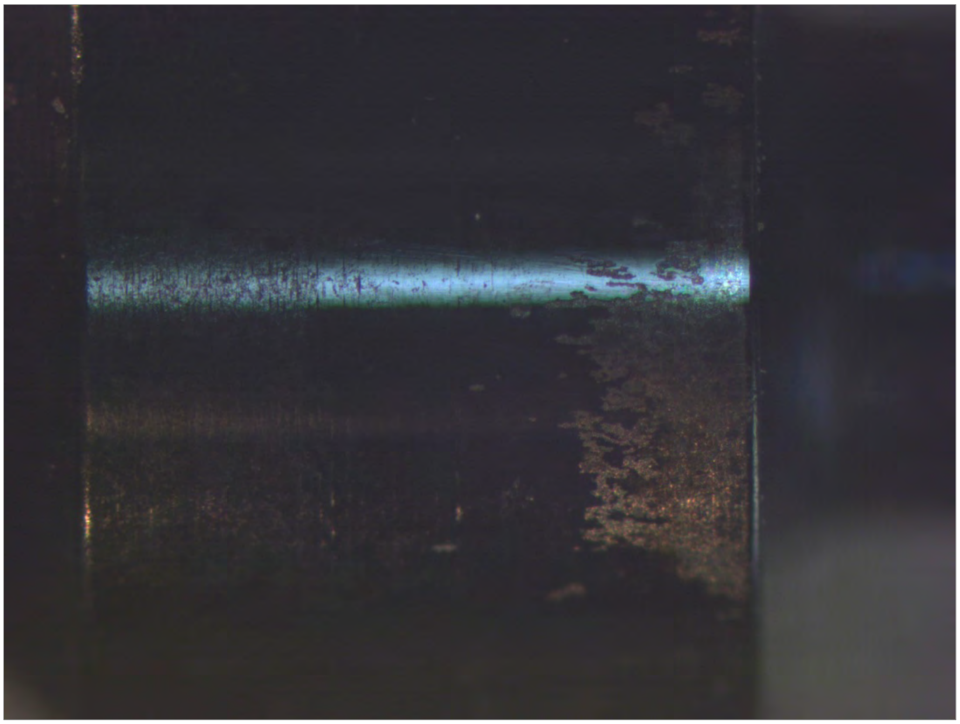


Figure D-16. Solenoid Plunger Close-Up

Figure D-17. Upper Ball Seat

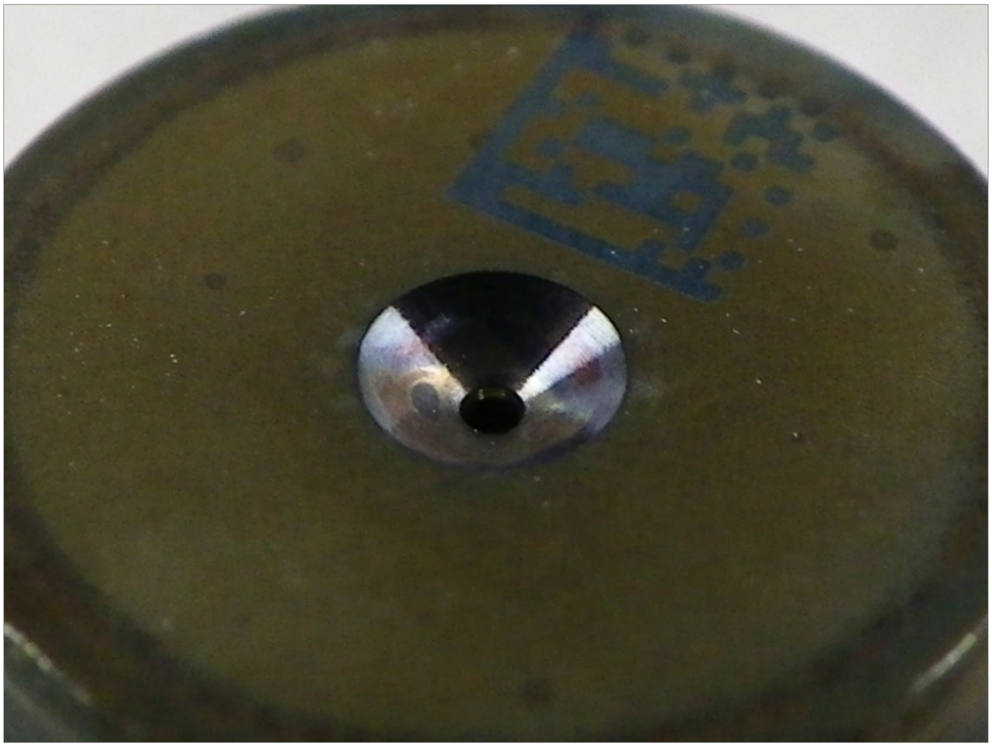


Figure D-18. Lower Ball Seat

Figure D-19. Injector Needle

Figure D-20. Injector Needle Scuffing

Figure D-21. Injector Needle Tip

APPENDIX - E

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: SPK with 22.5 ppm DCI-4A
Test Number: ULSD-AF7469-60C-XPI

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Cummins XPI Fuel System

Test Fuel: SPK with 22.5 ppm DCI-4A
Test Number: SPK-AF7876-60C-XPI
Start of Test Date: March 28, 2011
End of Test Date: April 26, 2011
Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) is working on a project with the U.S. Army TARDEC on synthetic and alternative fuels. The project goal is to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, JP-8, an FT SPK, manufactured by Syntroleum as S-8, treated with corrosion inhibitor/lubricity improver (CI/LI), and a 1:1 blend of the JP-8 and the synthetic fuels. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Four tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and four at 93.3°C (200 °F), for a total of eight tests. The lower temperature ULSD test is considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the Cummins XPI fuel system. This system was developed jointly between Cummins Inc. and Scania. Primarily targeted for Cummins midrange and Scania heavy duty applications, an oil-lubricated fuel pump allows the system to reach rail and injection pressures of up to 30,000 psi. The pump consists of a low pressure gear pump and high pressure piston pump. It is operated at half of the engine angular velocity for a rated condition speed of 1050 rpm. On the high pressure side of the pump, the camshaft drives two plungers which pressurize the fuel entering the rail. Each plunger is driven by three lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure side of the system consists of a gear pump which passes fuel through the final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand specifically configured for the XPI system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Cummins CM2150 engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The fuel pump consisted of a low pressure gear pump to push fuel through a high efficiency filter and send it to the high-pressure cam driven pump. Fuel then flows to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled below its flash point, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each 100 hour segment. A schematic of the stand layout is shown in Figure E-1.

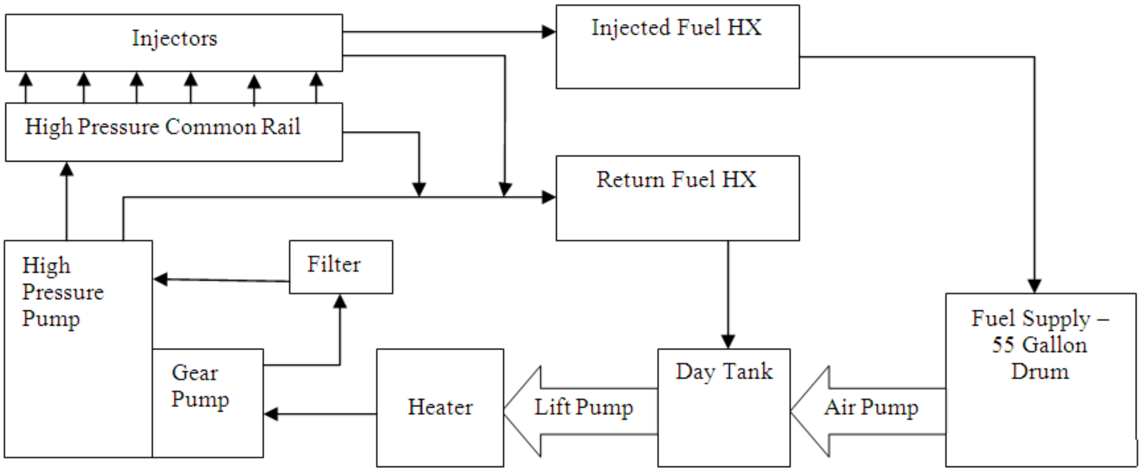


Figure E-1. XPI Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table E-1.

Table E-1. NATO Cycle for XPI Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	400	0	0.5
2	1050	100	2
3	1155	0	0.5
4	788	100	1
5*	400 to 1050	0 to 100	2
6	630	100	0.5
7	400	0	0.5
8	1081	70	0.5
9	650	100	2
10	650	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Cummins ECM for monitoring purposes. The stand did not experience any performance issues related to rail pressure during the course of the test.

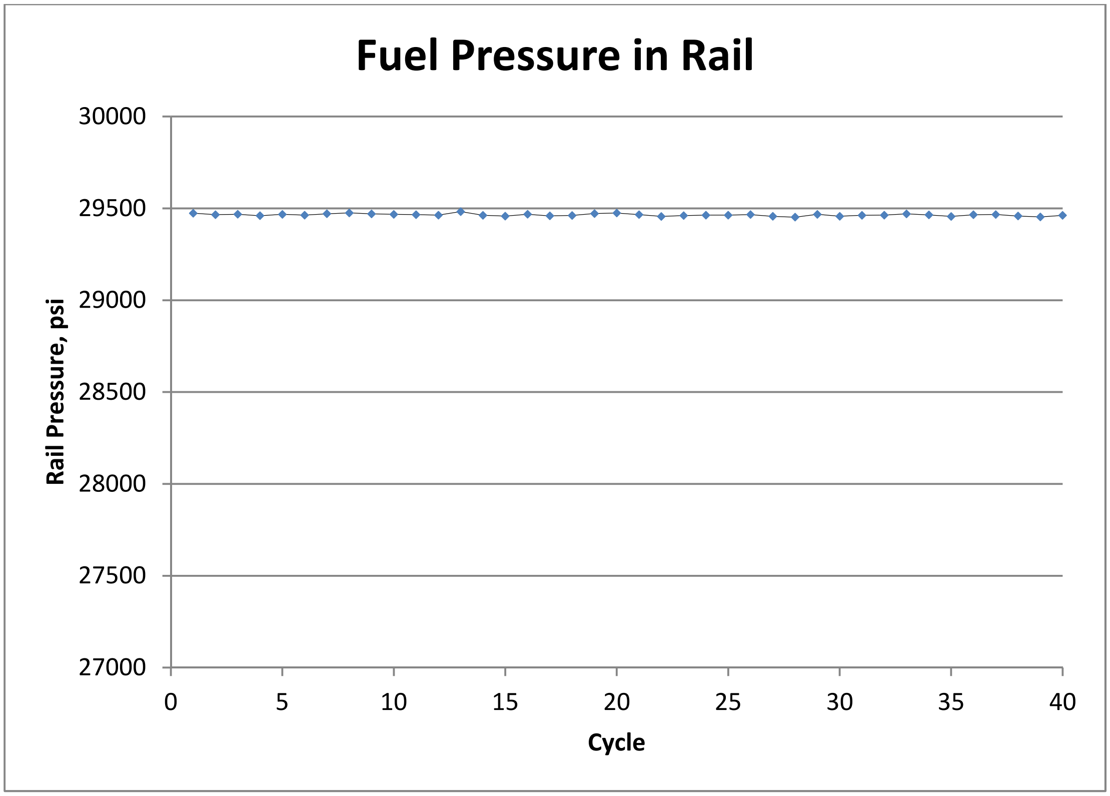


Figure E-2. Fuel Rail Pressure

Bypass and return fuel flow is the combined fuel from the high pressure pump relief valve, rail protection check valve, and injectors bypass/cooling flow. There is a reduction in flow over the test, possibly due to wear in the low pressure gear pump.

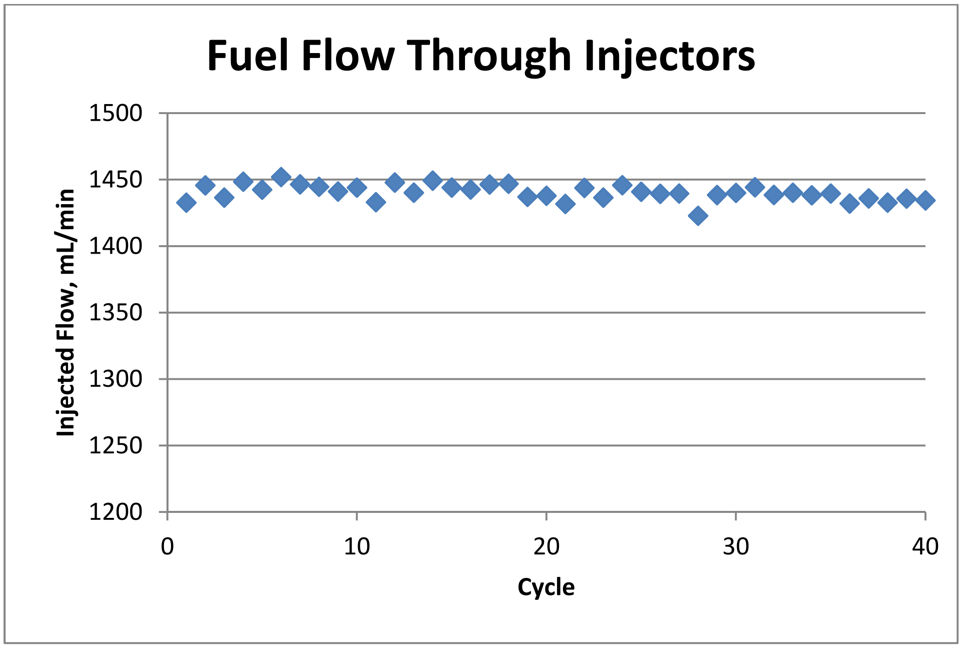


Figure E-3. Injected Fuel Flow

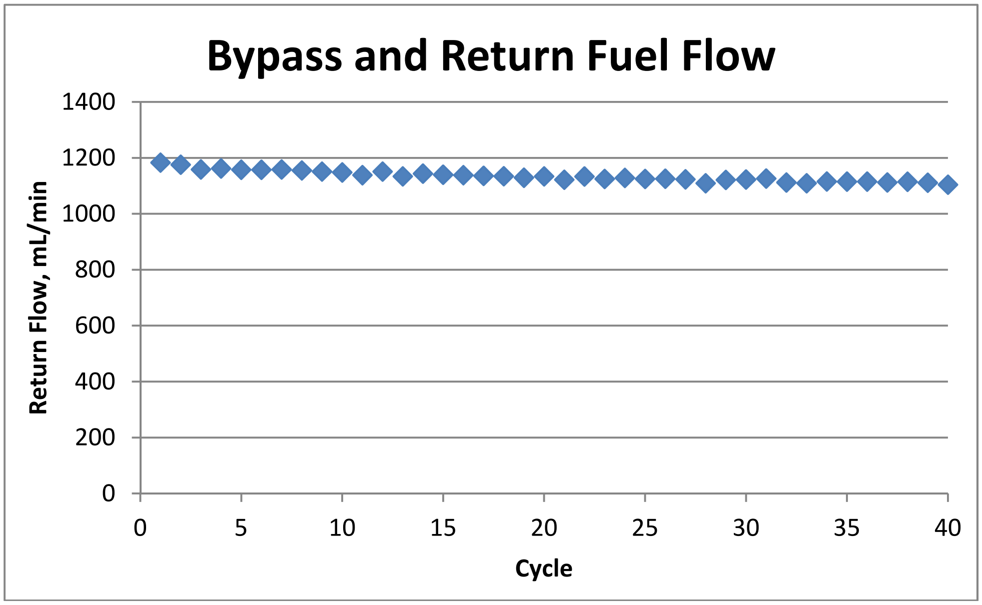


Figure E-4. Return Fuel Flow

Fuel filter inlet pressure is a measure of the pressure being developed by the gear pump portion of the XPI fuel pump. An internal bypass valve prevents undesired pressure building.

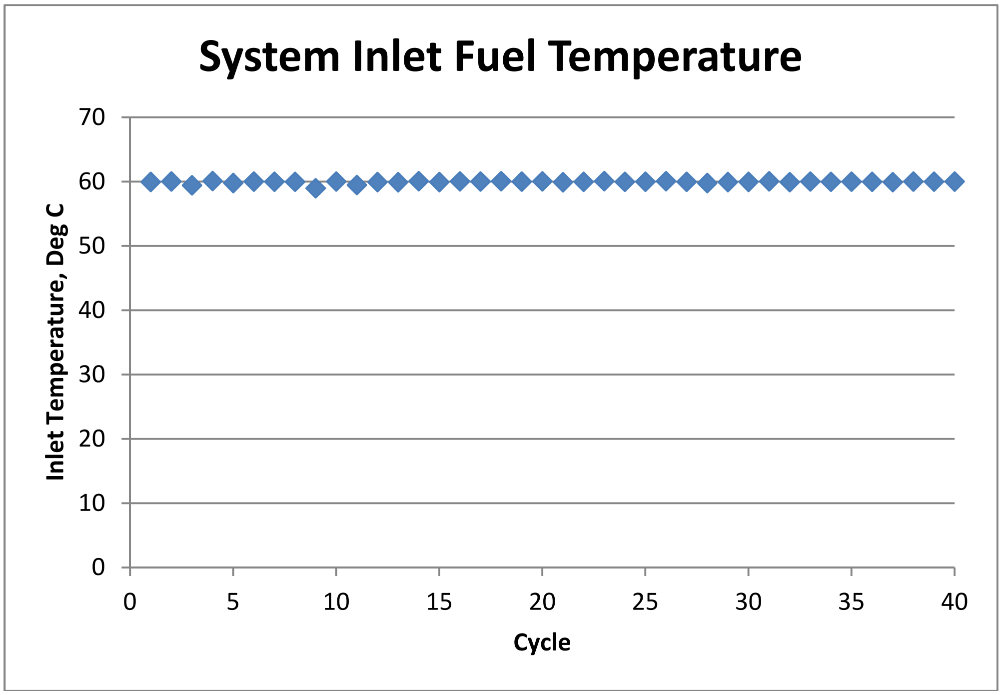


Figure E-5. System Inlet Fuel Temperature

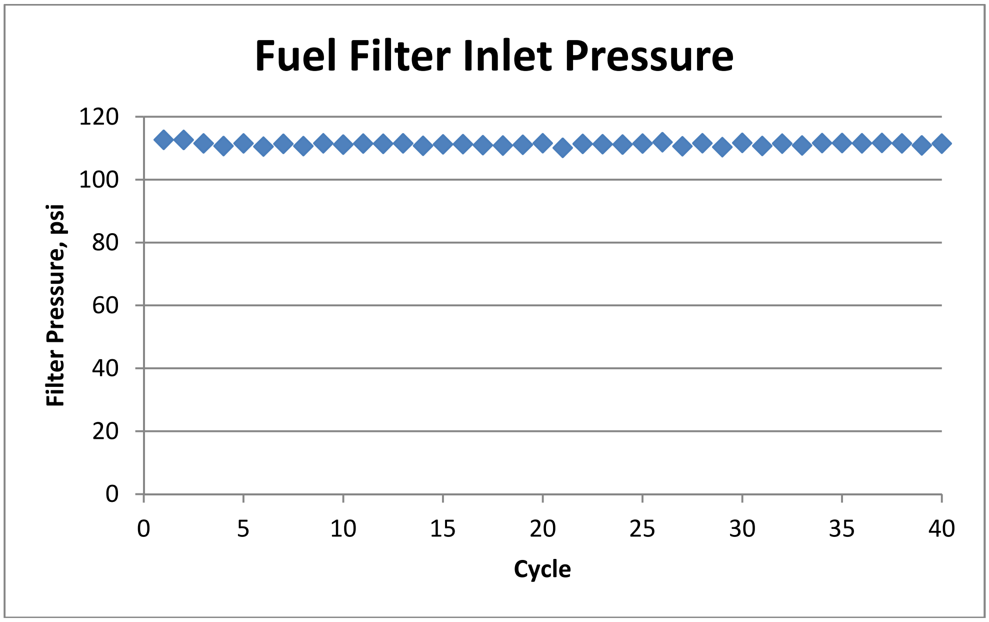


Figure E-6. Fuel Filter Pressure

Table E-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	59.8	1.5	55.4	63.4
Injected Fuel Temperature, deg C	161.7	5.5	129.2	168.2
Rail Pressure, psi	29468	69	29266	29666
Injected Flow Rate, mL/min	1443.3	23.3	1238.0	1517.9
Return Fuel Flow Rate, mL/min	1160.0	24.2	1063.2	1231.4
Fuel Filter Inlet Pressure, psi	111.5	1.2	107.8	114.7
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.4	56.8	63.8
Injected Fuel Temperature, deg C	161.6	5.3	132.6	167.1
Rail Pressure, psi	29466	72	29260	29698
Injected Flow Rate, mL/min	1442.4	31.1	1108.3	1544.9
Return Fuel Flow Rate, mL/min	1137.3	22.1	1056.1	1200.1
Fuel Filter Inlet Pressure, psi	111.3	1.2	107.3	115.7
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.4	48.3	62.9
Injected Fuel Temperature, deg C	160.8	6.2	97.9	167.0
Rail Pressure, psi	29461	71	29187	29693
Injected Flow Rate, mL/min	1437.9	29.0	1171.3	1556.2
Return Fuel Flow Rate, mL/min	1123.2	21.2	987.0	1177.1
Fuel Filter Inlet Pressure, psi	111.2	1.3	106.0	119.5
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.1	57.2	62.8
Injected Fuel Temperature, deg C	162.0	4.8	133.8	166.9
Rail Pressure, psi	29462	73	29271	29728
Injected Flow Rate, mL/min	1437.1	28.6	1157.1	1519.2
Return Fuel Flow Rate, mL/min	1113.1	18.3	1044.9	1161.2
Fuel Filter Inlet Pressure, psi	111.4	1.1	106.3	118.9

Fuel Analysis

Fuel was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figures E-7 and E-8.

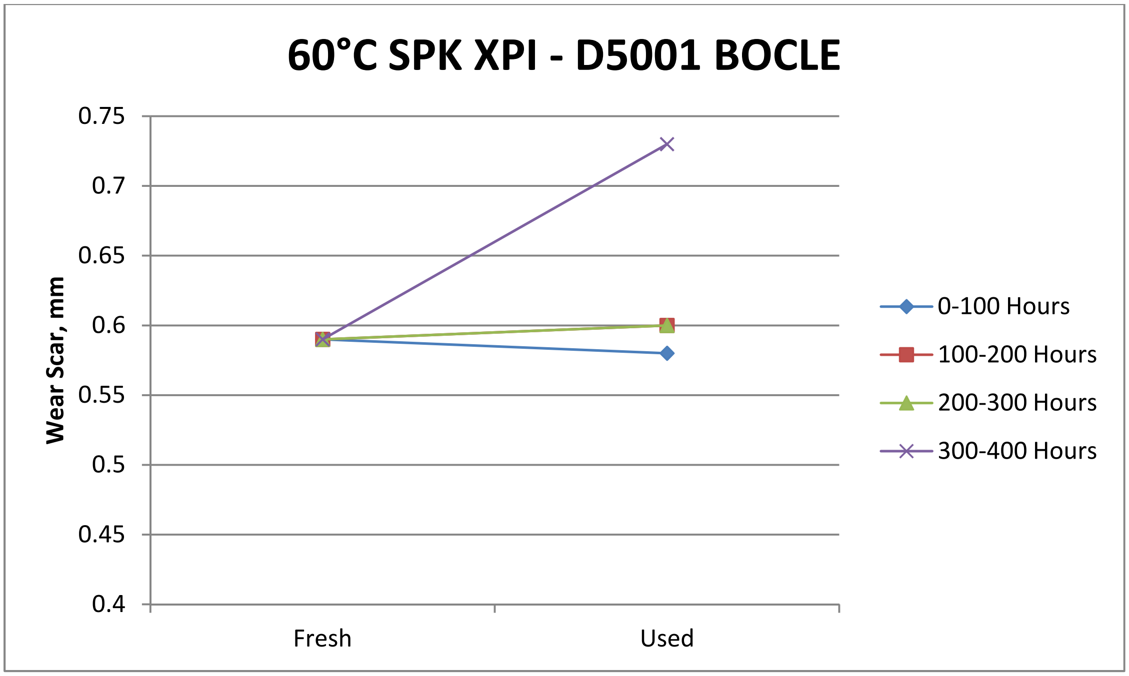


Figure E-7. ASTM D5001 BOCLE

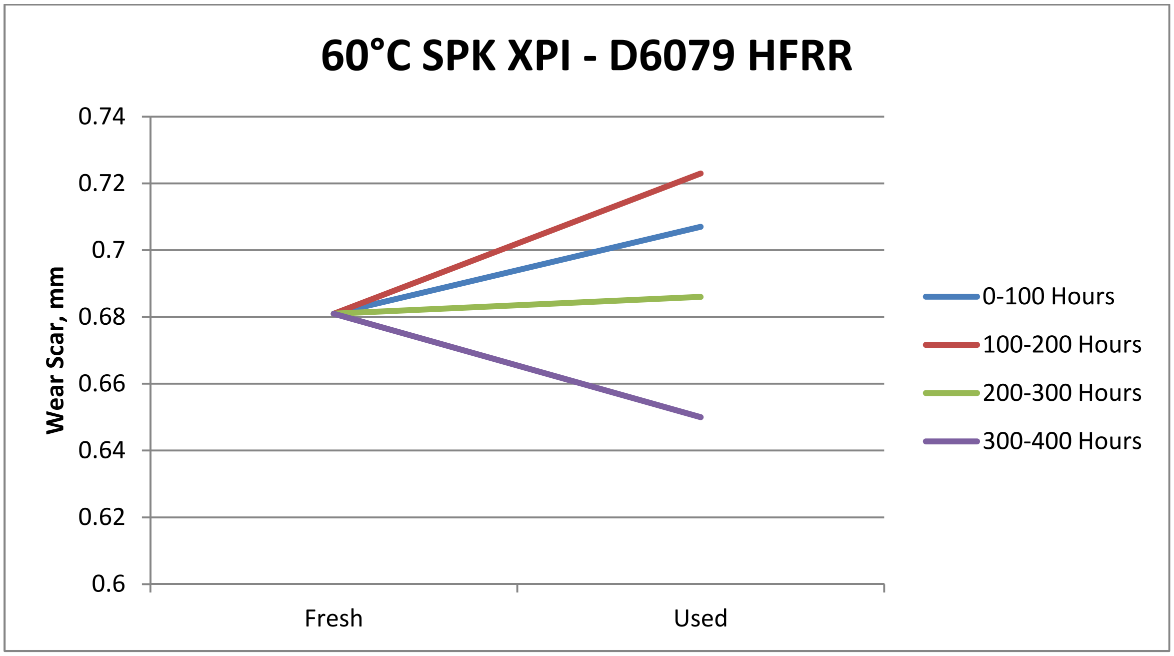


Figure E-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on SPK. Only fuel wetted components are shown in the figures that follow.

Fuel Pump

Figure E-9. Low Pressure Gear Pump Housing

Figure E-10. Gear Pump Housing Wear

Figure E-11. Gear Pump Pressure Relief Valve

Figure E-12. Pump Gears

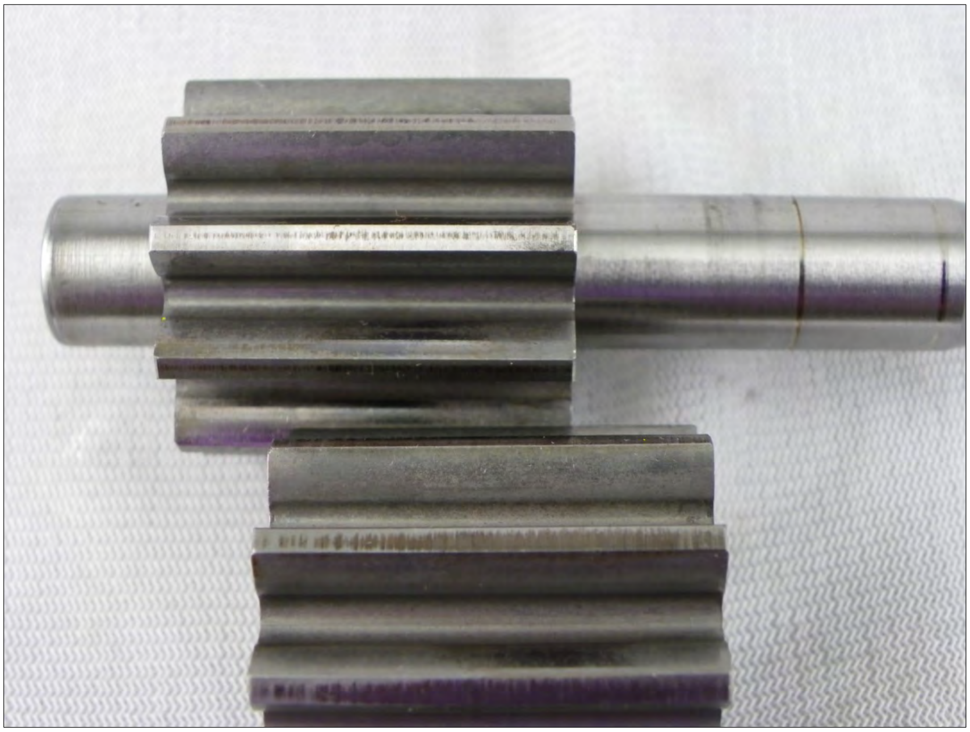


Figure E-13. Gear Tooth Wear

Fuel Injector

Figure E-14. Upper Injector Components

Figure E-15. Solenoid Plunger

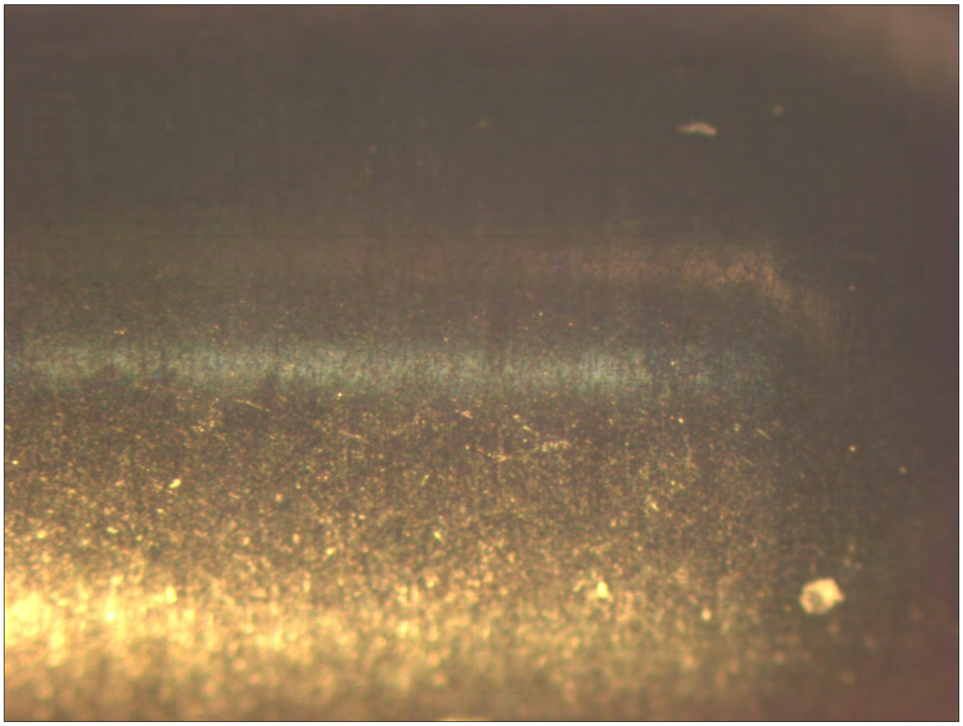


Figure E-16. Solenoid Plunger Close-Up

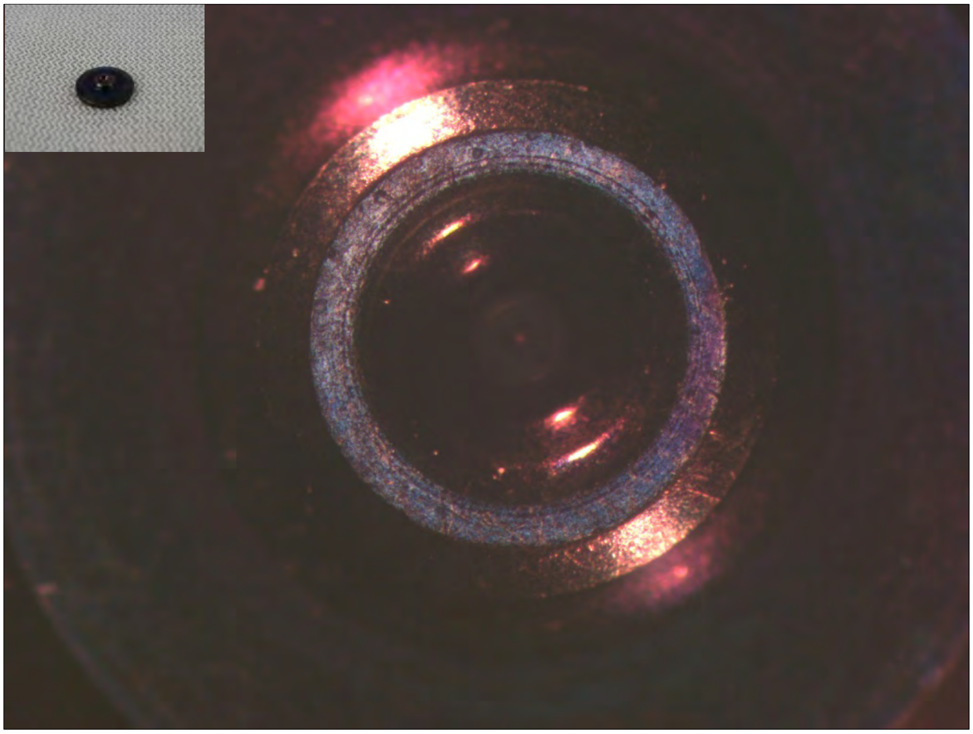


Figure E-17. Upper Ball Seat

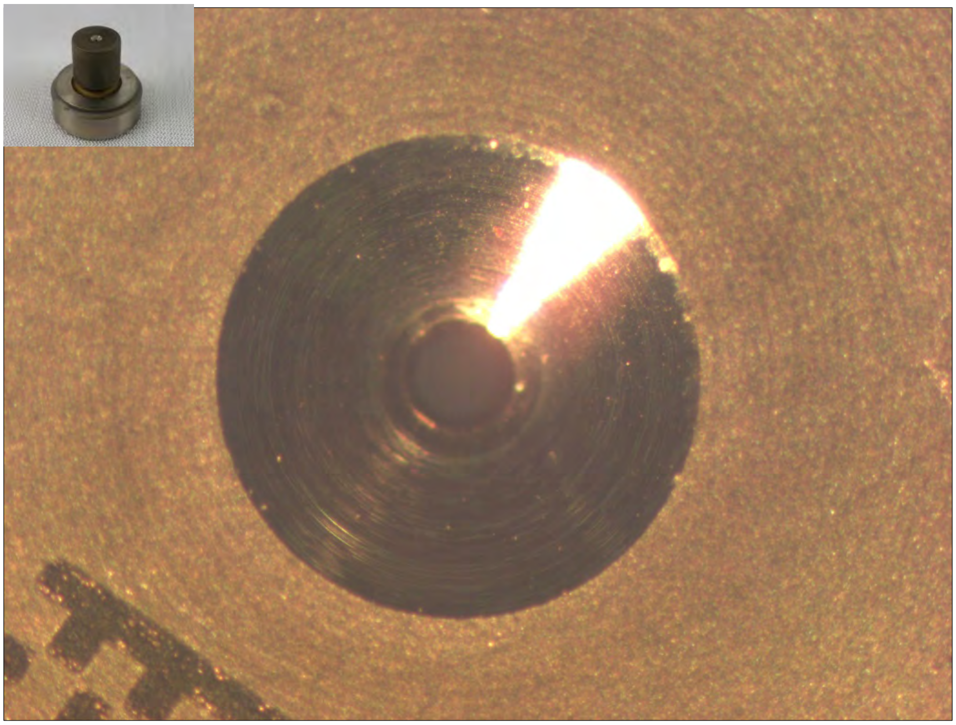


Figure E-18. Lower Ball Seat

Figure E-19. Injector Needle

Figure E-20. Injector Needle Scuffing

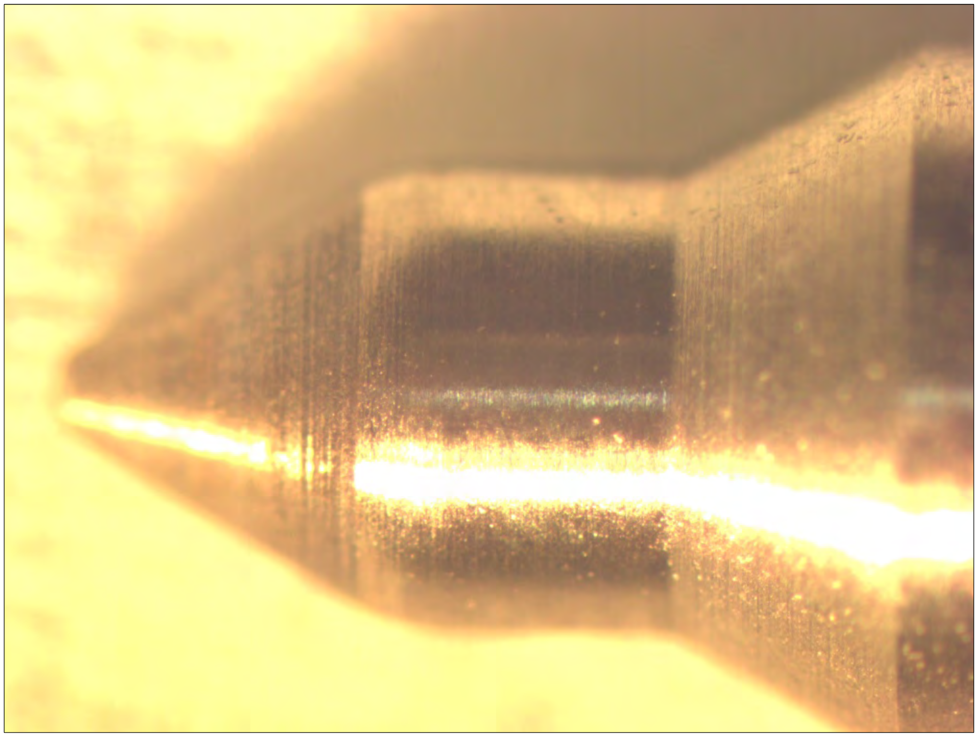


Figure E-21. Injector Needle Tip

APPENDIX - F

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: SPK/JP-8 Blend

Test Number: Blend-AF7879-60C-XPI

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Cummins XPI Fuel System

Test Fuel: SPK/JP-8 Blend
Test Number: Blend-AF7879-60C-XPI
Start of Test Date: May 3, 2011
End of Test Date: June 17, 2011
Test Duration: 400 Hours
Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

TABLE OF CONTENTS

Section **Page**

LIST OF TABLES

LIST OF FIGURES

Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) is working on a project with the US Army TARDEC on synthetic and alternative fuels. The project goal is to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, JP-8, an FT SPK, manufactured by Syntroleum as S-8, treated with corrosion inhibitor/lubricity improver (CI/LI), and a 1:1 blend of the JP-8 and the synthetic fuels. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Four tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and four at 93.3°C (200 °F), for a total of eight tests. The lower temperature ULSD test is considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the Cummins XPI fuel system. This system was developed jointly between Cummins Inc. and Scania. Primarily targeted for Cummins midrange and Scania heavy duty applications, an oil-lubricated fuel pump allows the system to reach rail and injection pressures of up to 30,000 psi. The pump consists of a low pressure gear pump and high pressure piston pump. It is operated at half of the engine angular velocity for a rated condition speed of 1050 rpm. On the high pressure side of the pump, the camshaft drives two plungers which pressurize the fuel entering the rail. Each plunger is driven by three lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure side of the system consists of a gear pump which passes fuel through the final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand specifically configured for the XPI system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Cummins CM2150 engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The fuel pump consisted of a low pressure gear pump to push fuel through a high efficiency filter and send it to the high-pressure cam driven pump. Fuel then flows to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled below its flash point, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each 100 hour segment. A schematic of the stand layout is shown in Figure F-1.

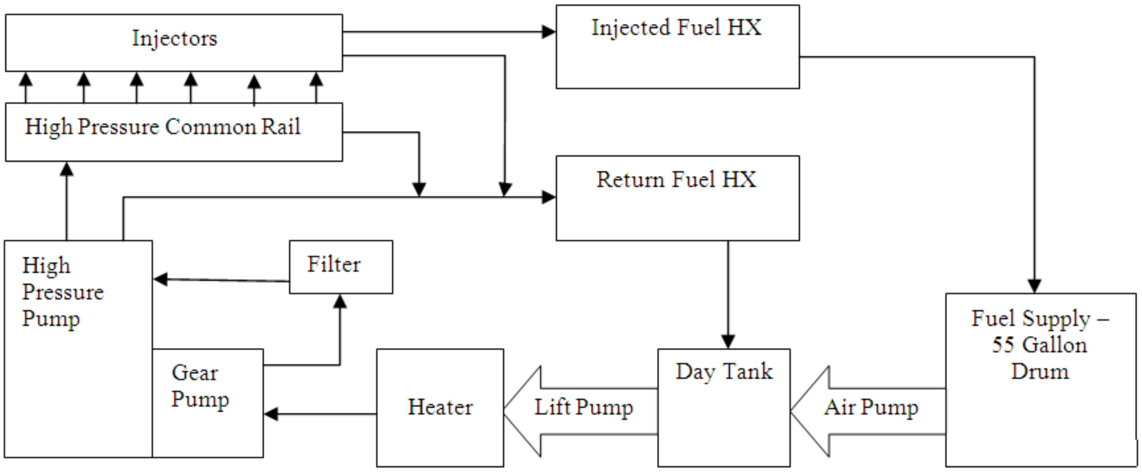


Figure F-1. XPI Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table F-1.

Table F-1. NATO Cycle for XPI Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	400	0	0.5
2	1050	100	2
3	1155	0	0.5
4	788	100	1
5*	400 to 1050	0 to 100	2
6	630	100	0.5
7	400	0	0.5
8	1081	70	0.5
9	650	100	2
10	650	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Cummins ECM for monitoring purposes. The stand did not experience any performance issues related to rail pressure during the course of the test.

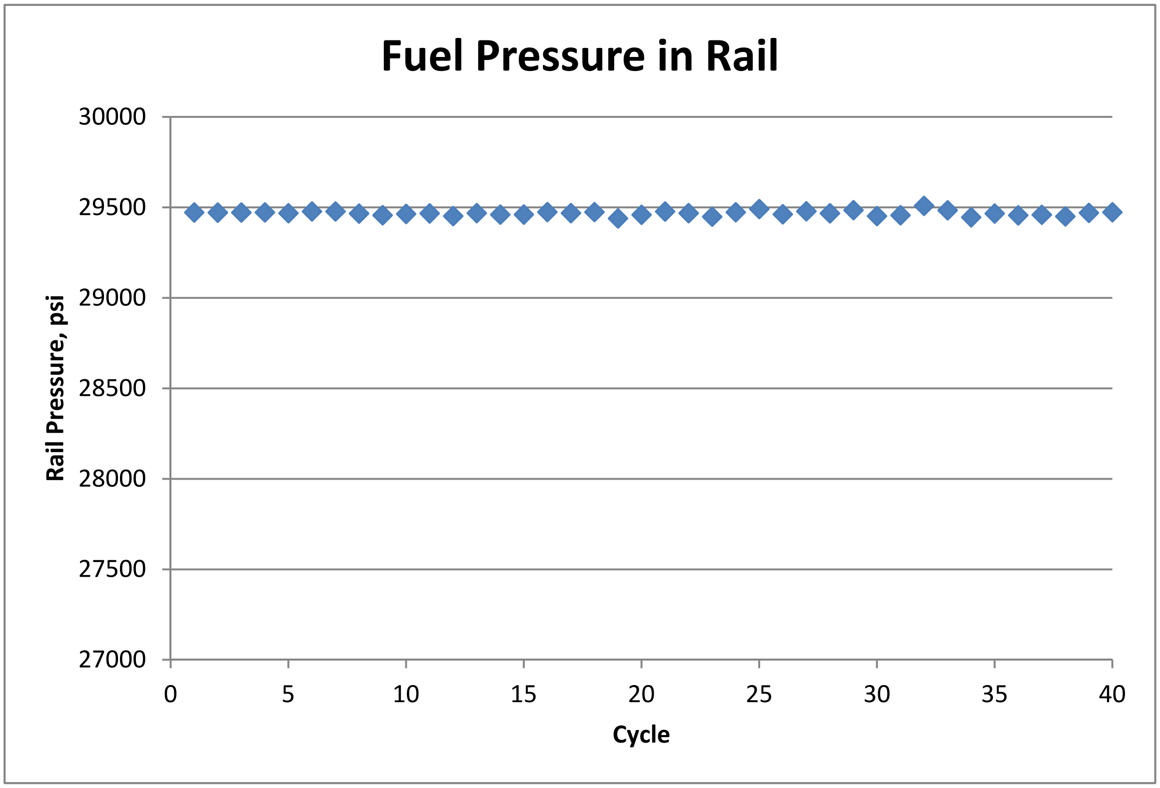


Figure F-2. Fuel Rail Pressure

Bypass and return fuel flow is the combined fuel from the high pressure pump relief valve, rail protection check valve, and injector's bypass/cooling flow.

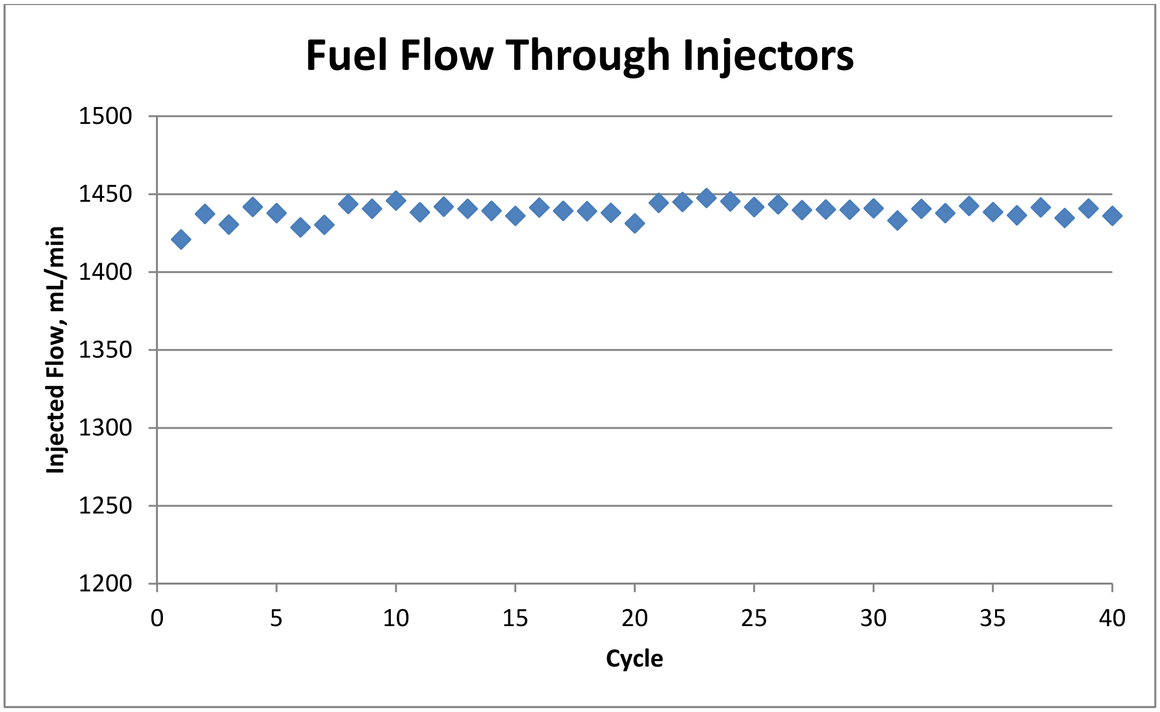


Figure F-3. Injected Fuel Flow

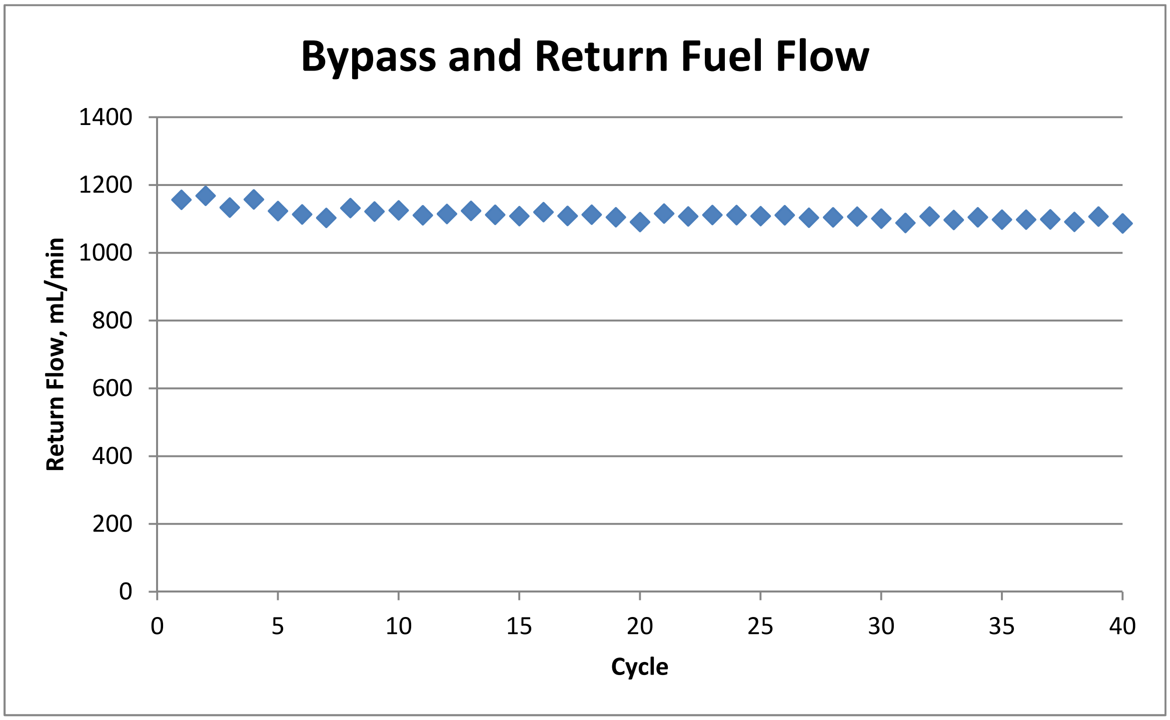


Figure F-4. Return Fuel Flow

Fuel filter inlet pressure is a measure of the pressure being developed by the gear pump portion of the XPI fuel pump. An internal bypass valve prevents undesired pressure building.

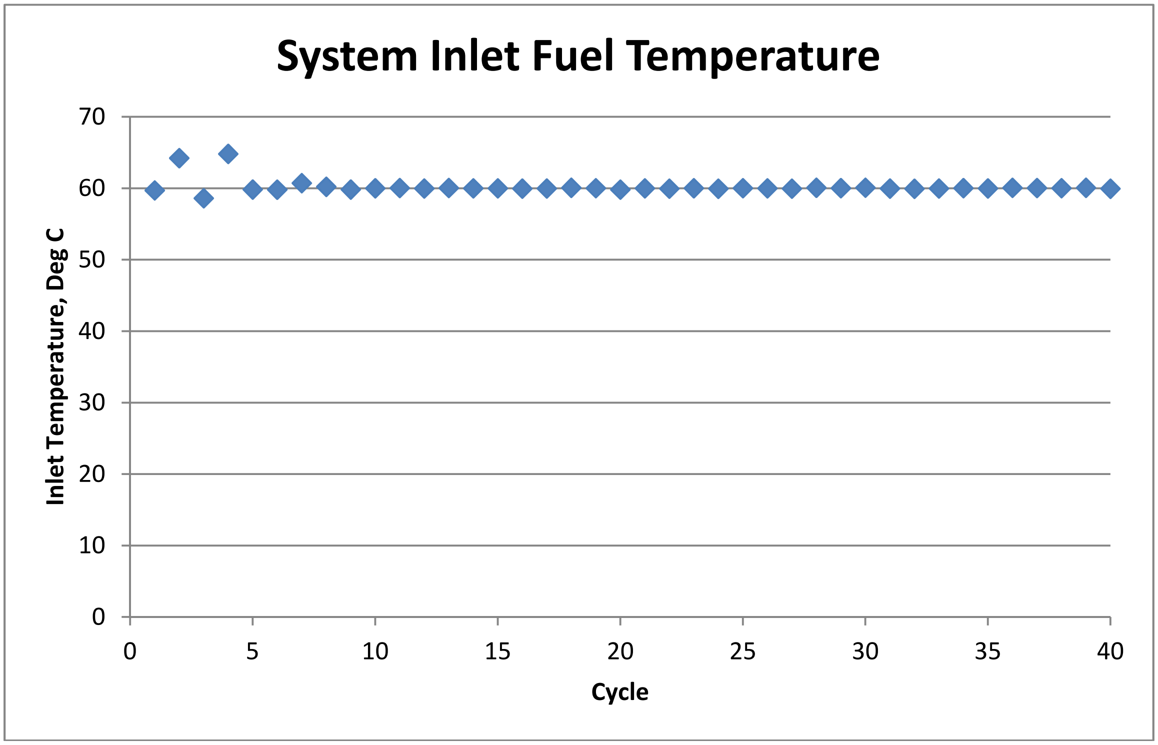


Figure F-5. System Inlet Fuel Temperature

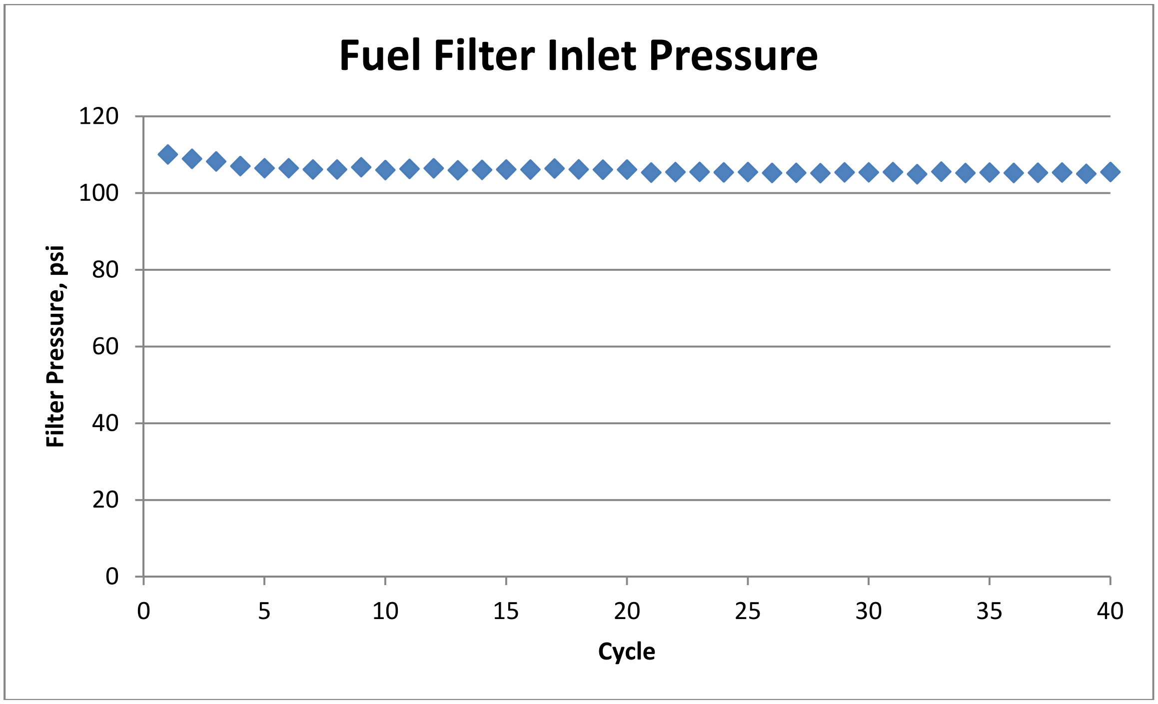


Figure F-6. Fuel Filter Pressure

Table F-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.8	3.7	23.7	82.6
Injected Fuel Temperature, deg C	160.3	9.2	87.1	170.2
Rail Pressure, psi	29470	125	28356	30719
Injected Flow Rate, mL/min	1435.7	33.8	1120.0	1528.7
Return Fuel Flow Rate, mL/min	1132.8	37.7	968.7	1254.4
Fuel Filter Inlet Pressure, psi	107.2	2.4	64.7	113.7
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.2	50.9	63.7
Injected Fuel Temperature, deg C	161.3	6.1	99.7	167.2
Rail Pressure, psi	29462	121	28765	30188
Injected Flow Rate, mL/min	1438.5	21.9	1272.3	1517.7
Return Fuel Flow Rate, mL/min	1110.2	28.3	977.0	1250.3
Fuel Filter Inlet Pressure, psi	106.2	0.7	94.1	108.4
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.0	56.7	63.6
Injected Fuel Temperature, deg C	163.5	4.8	135.6	168.5
Rail Pressure, psi	29470	167	26168	30024
Injected Flow Rate, mL/min	1442.8	15.7	1360.5	1518.6
Return Fuel Flow Rate, mL/min	1107.6	23.4	1020.1	1234.4
Fuel Filter Inlet Pressure, psi	105.4	1.3	72.3	111.6
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	0.9	57.2	63.2
Injected Fuel Temperature, deg C	162.9	5.3	134.6	168.8
Rail Pressure, psi	29467	141	28830	30560
Injected Flow Rate, mL/min	1438.2	13.3	1368.9	1502.4
Return Fuel Flow Rate, mL/min	1097.3	24.3	1024.2	1204.3
Fuel Filter Inlet Pressure, psi	105.3	1.1	80.9	108.2

Fuel Analysis

Fuel was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figures F-7 and F-8. It should be noted that a number of results overlap each other.

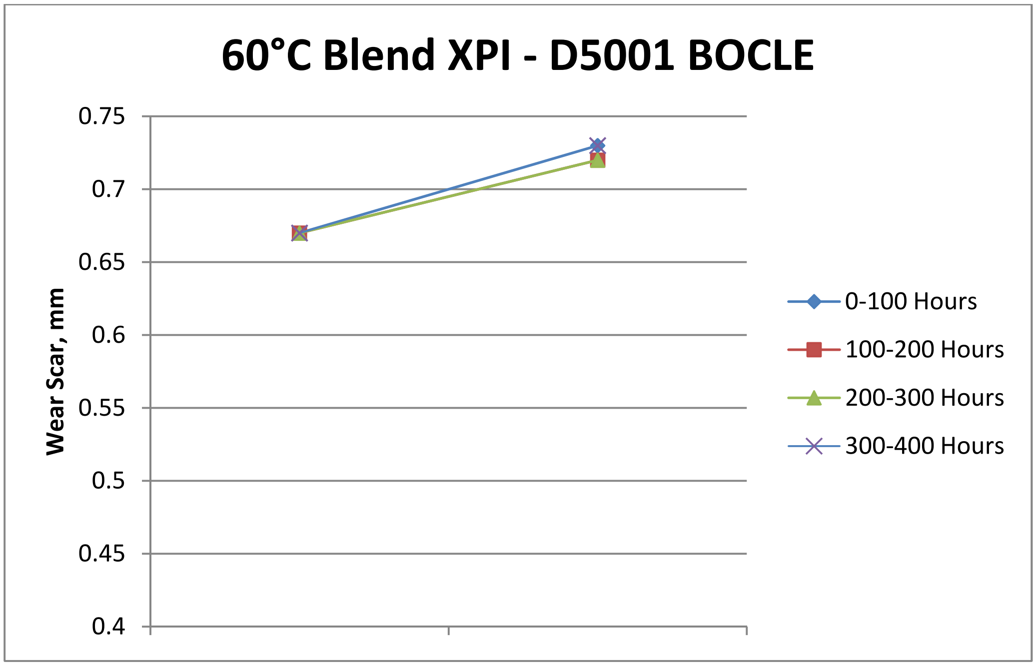


Figure F-7. ASTM D5001 BOCLE

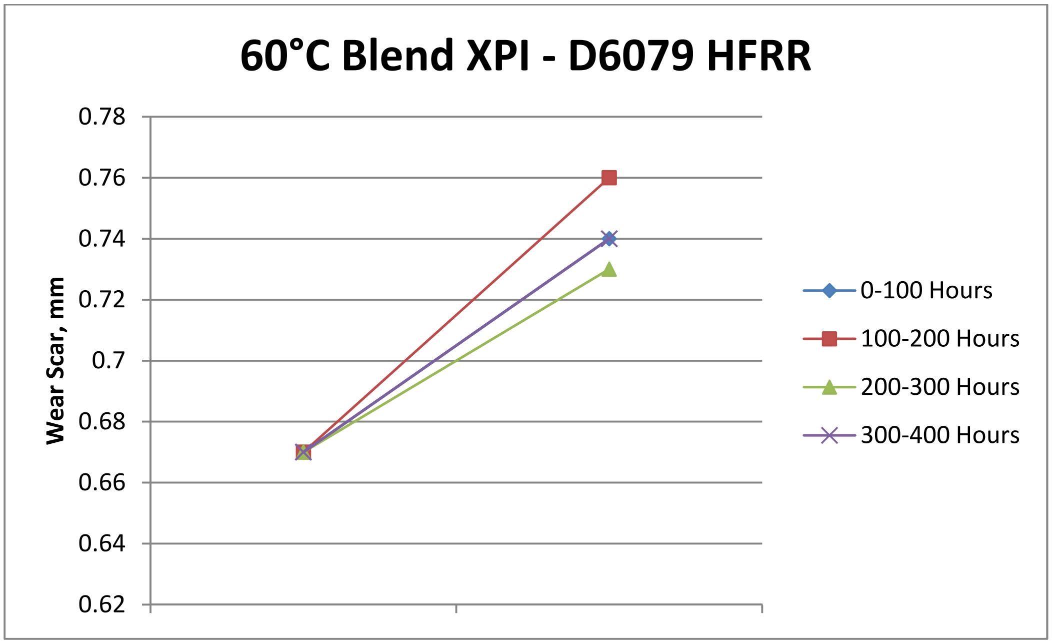


Figure F-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on the blend of synthetic and JP-8 fuels. Only fuel wetted components are shown in the figures that follow.

Fuel Pump

Figure F-9. Low Pressure Gear Pump Housing

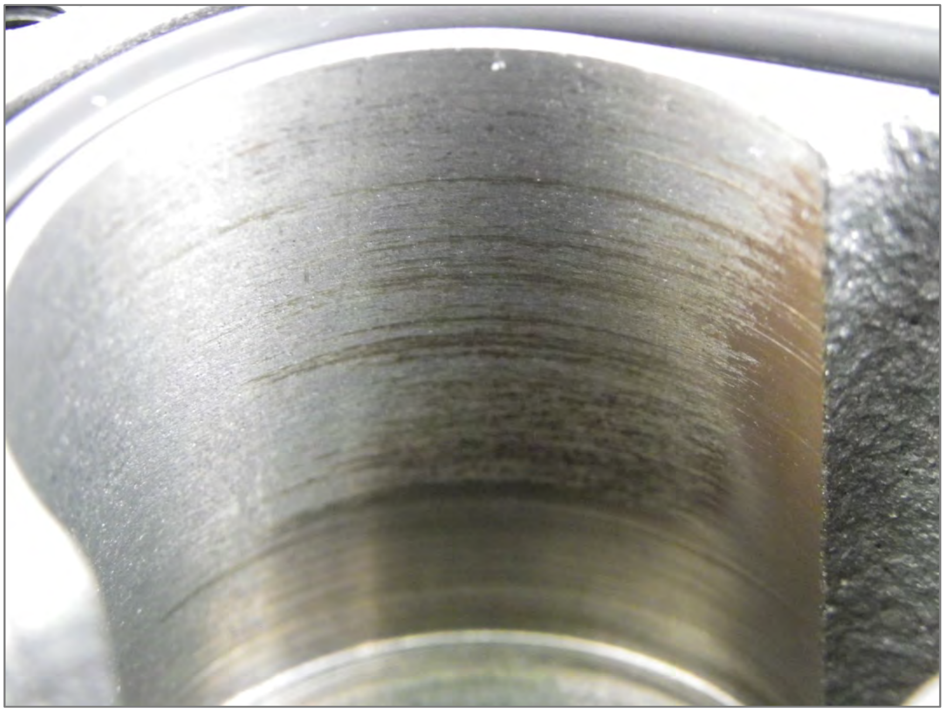


Figure F-10. Gear Pump Housing Wall

Figure F-11. Gear Pump Pressure Relief Valve

Figure F-12. Pump Gears

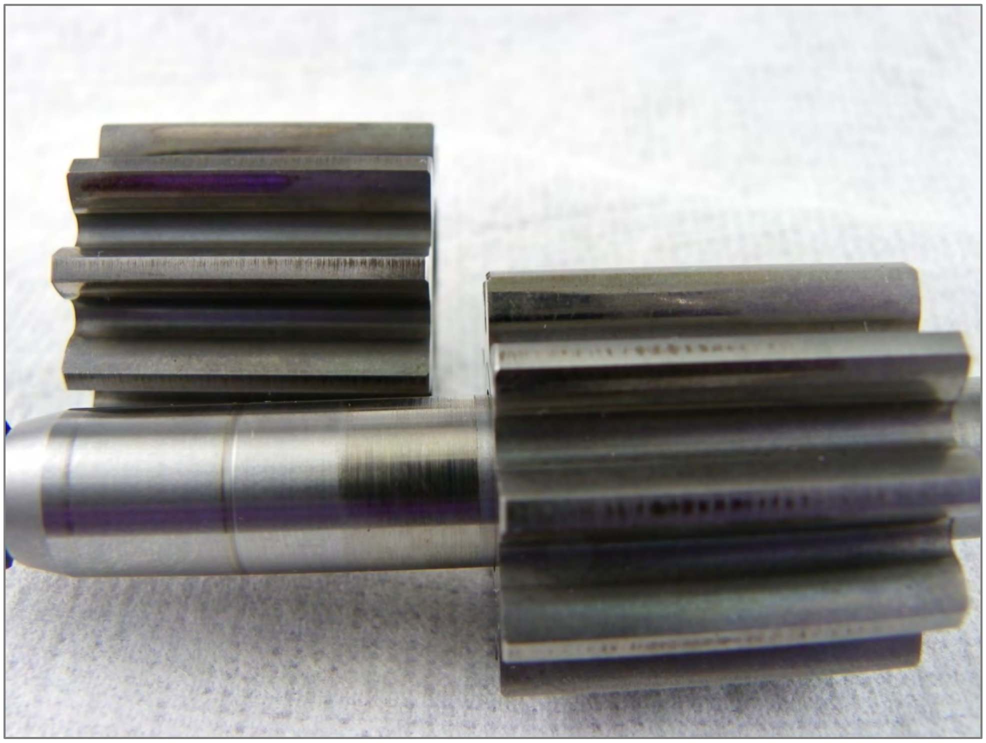


Figure F-13. Gear Tooth Wear

Fuel Injector

Figure F-14. Upper Injector Components

Figure F-15. Solenoid Plunger

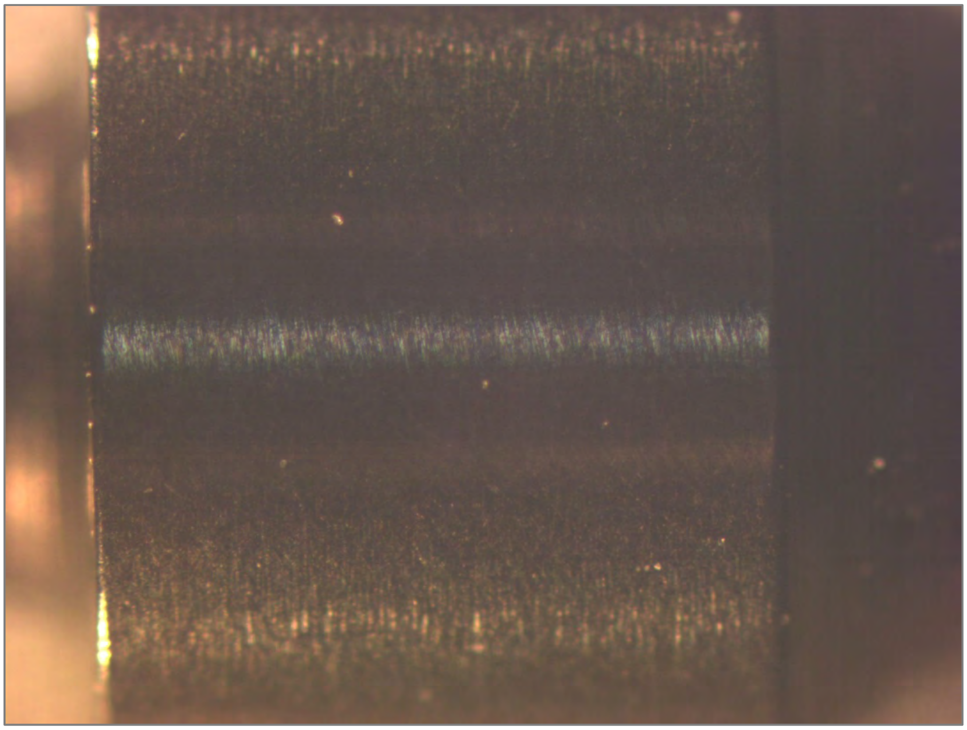


Figure F-16. Solenoid Plunger Close-Up

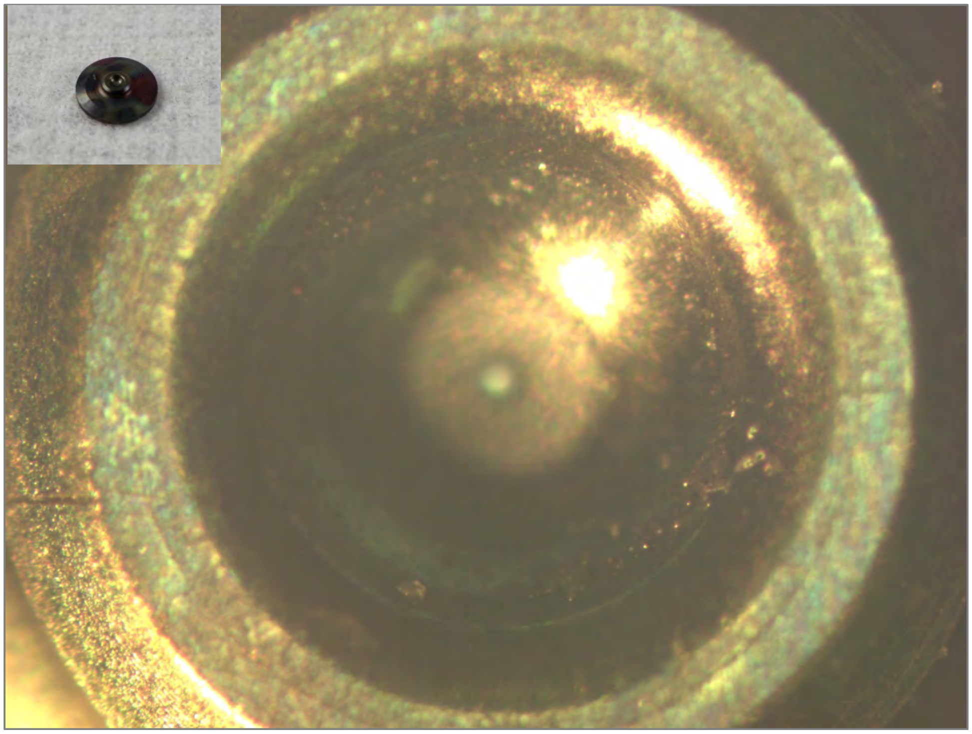


Figure F-17. Upper Ball Seat

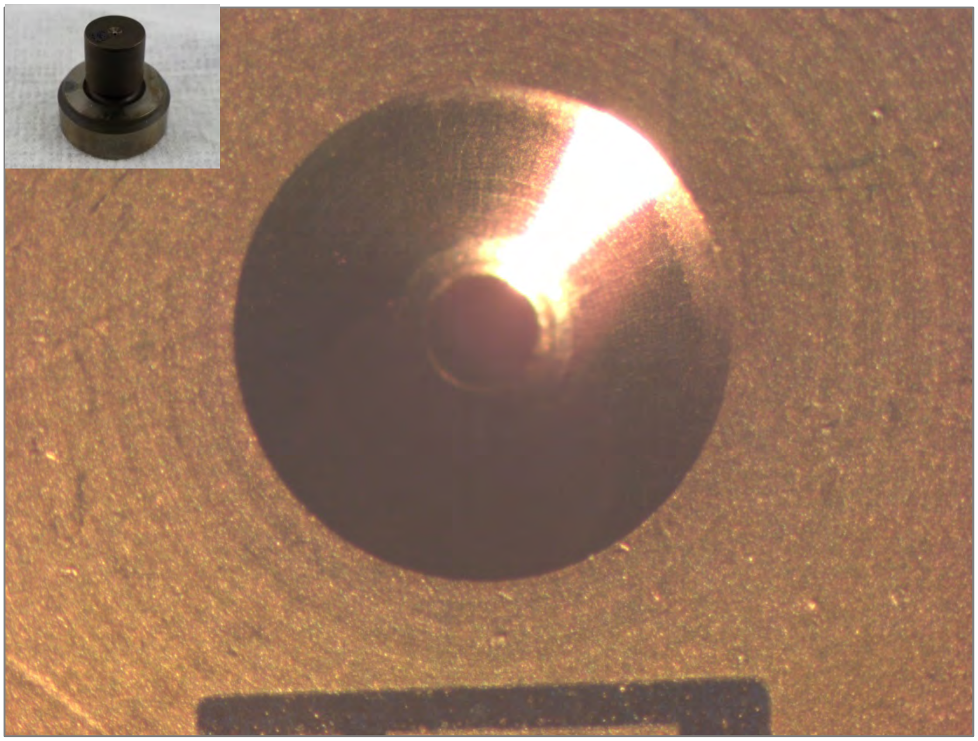


Figure F-18. Lower Ball Seat

Figure F-19. Injector Needle

Figure F-20. Injector Needle Scuffing

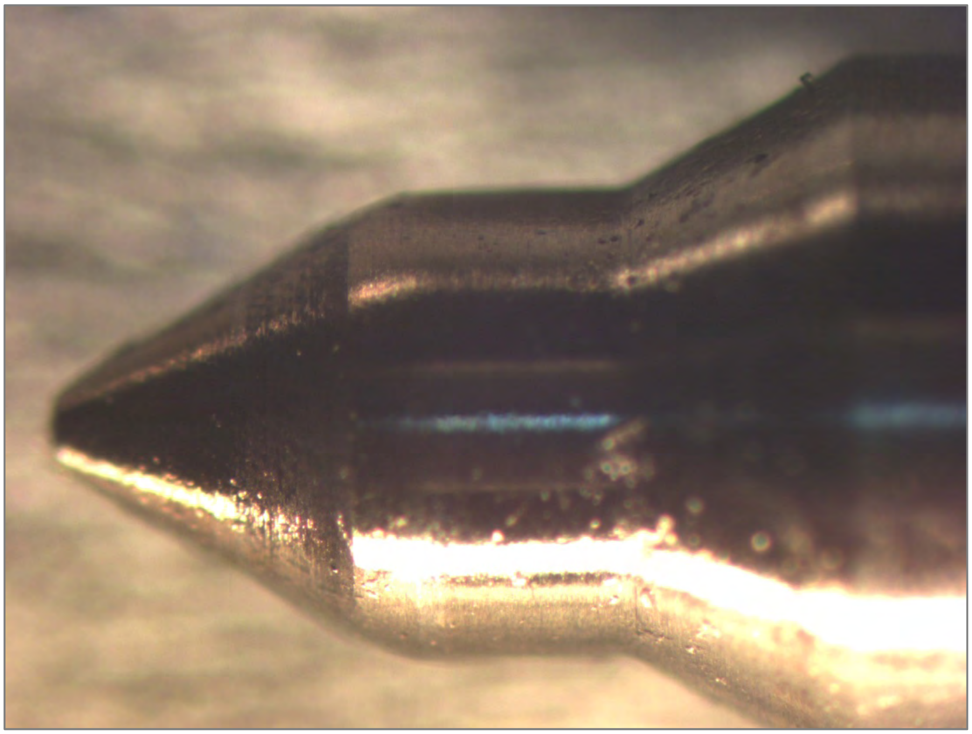


Figure F-21. Injector Needle Tip

APPENDIX - G

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: SPK/JP-8 Blend

Test Number: Blend-AF7879-93C-XPI

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Cummins XPI Fuel System

Test Fuel: SPK/JP-8 Blend
Test Number: Blend-AF7879-93C-XPI
Start of Test Date: June 24, 2011
End of Test Date: July 25, 2011
Test Duration: 400 Hours
Test Procedure:
Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

TABLE OF CONTENTS

Section **Page**

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

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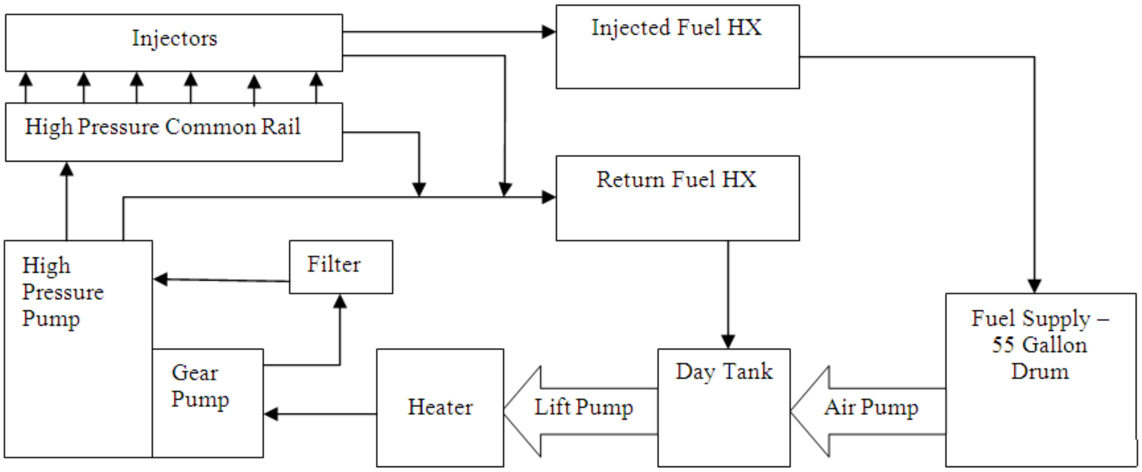

Figure G-1. XPI Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table 1

Table G-1. NATO Cycle for XPI Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	400	0	0.5
2	1050	100	2
3	1155	0	0.5
4	788	100	1
5*	400 to 1050	0 to 100	2
6	630	100	0.5
7	400	0	0.5
8	1081	70	0.5
9	650	100	2
10	650	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Cummins ECM for monitoring purposes. The stand did not experience any performance issues related to rail pressure during the course of the test.

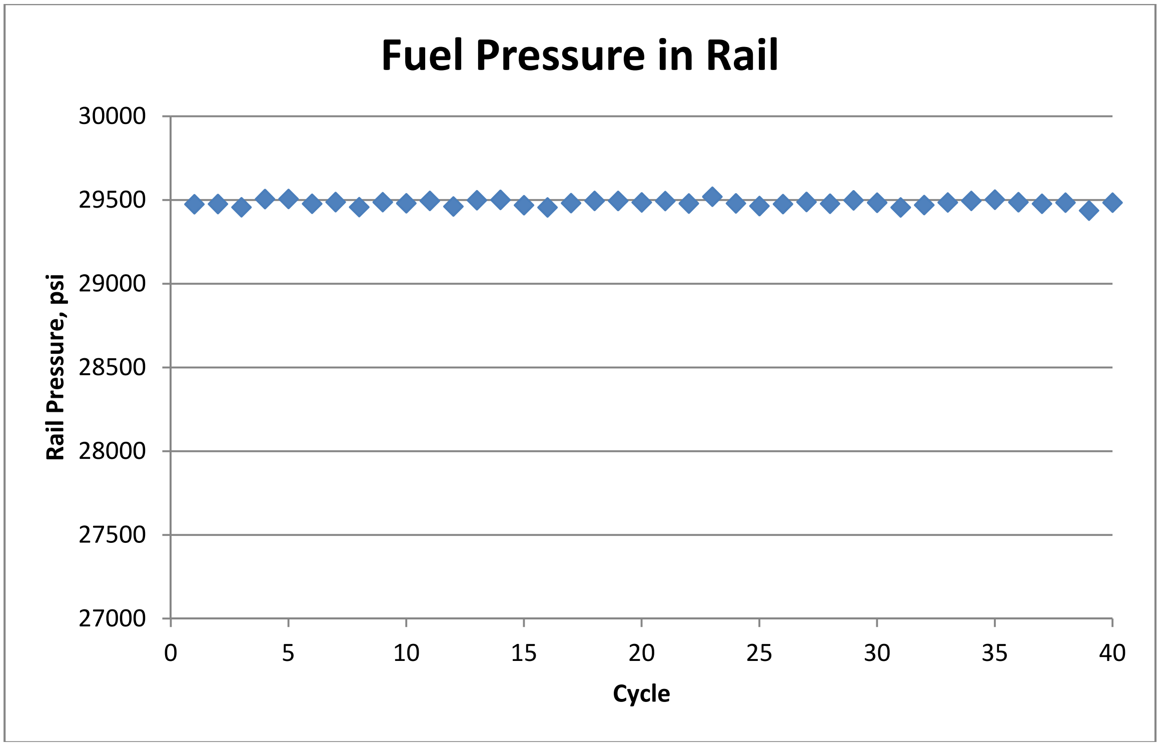

Figure G-2. Fuel Rail Pressure

Bypass and return fuel flow is the combined fuel from the high pressure pump relief valve, rail protection check valve, and injector's bypass/cooling flow.

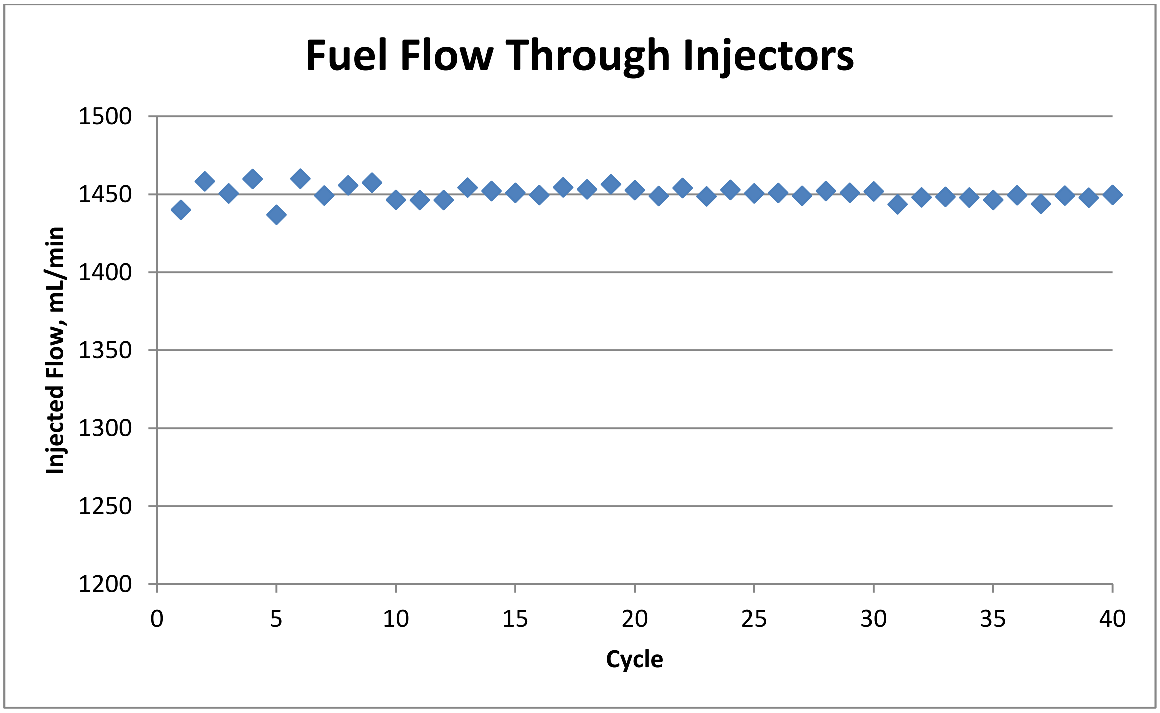

Figure G-3. Injected Fuel Flow

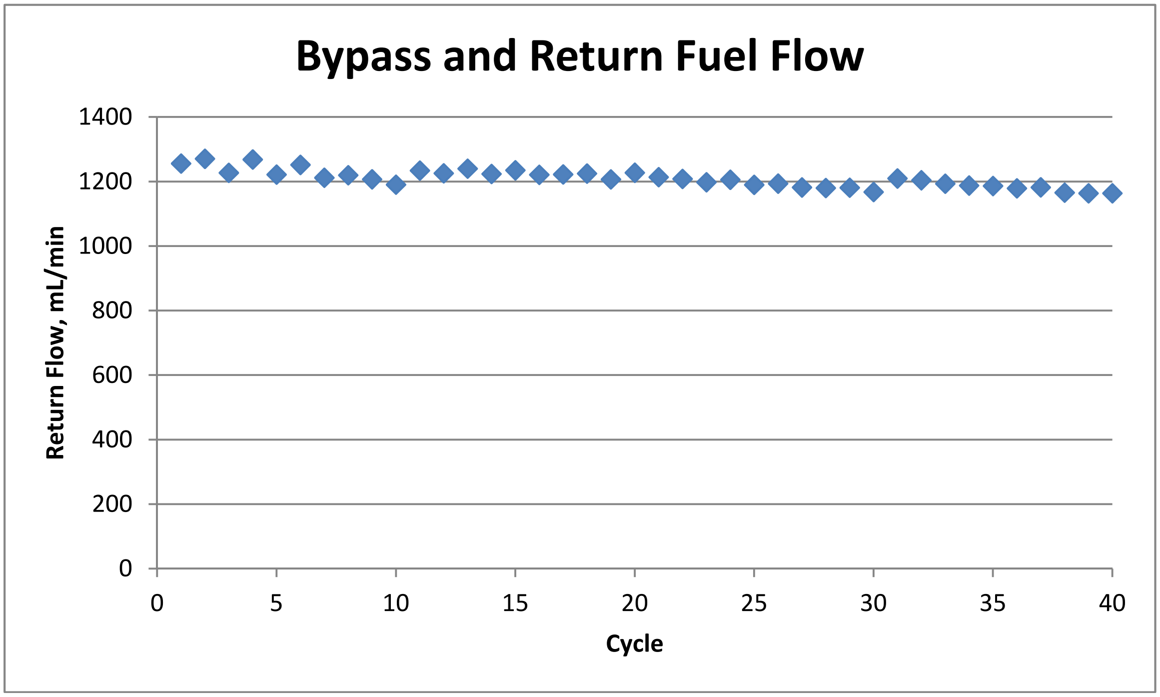

Figure G-4. Return Fuel Flow

Fuel filter inlet pressure is a measure of the pressure being developed by the gear pump portion of the XPI fuel pump. An internal bypass valve prevents undesired pressure building.

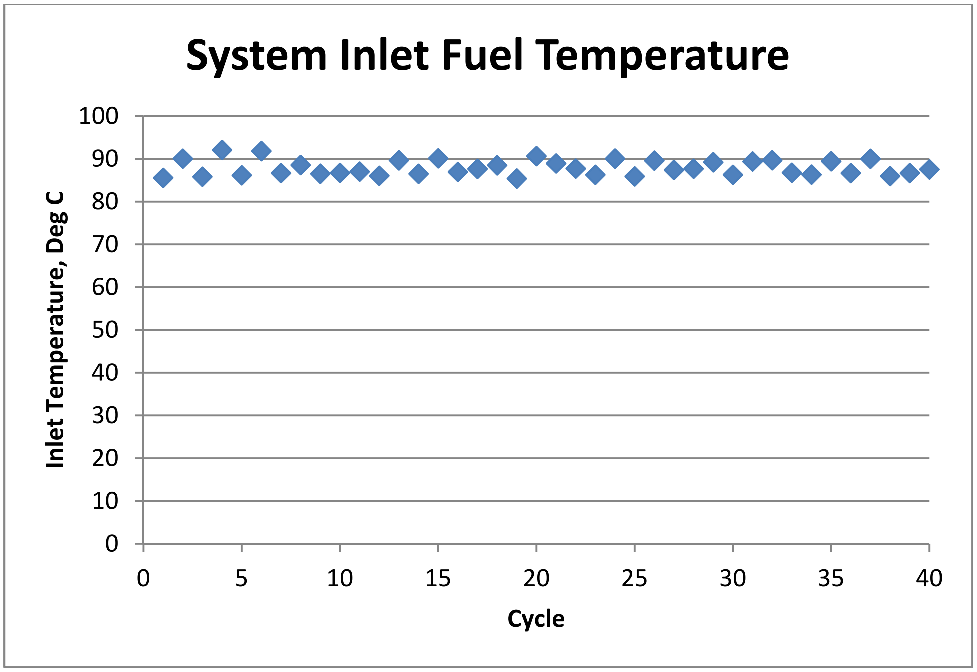

Figure G-5. System Inlet Fuel Temperature

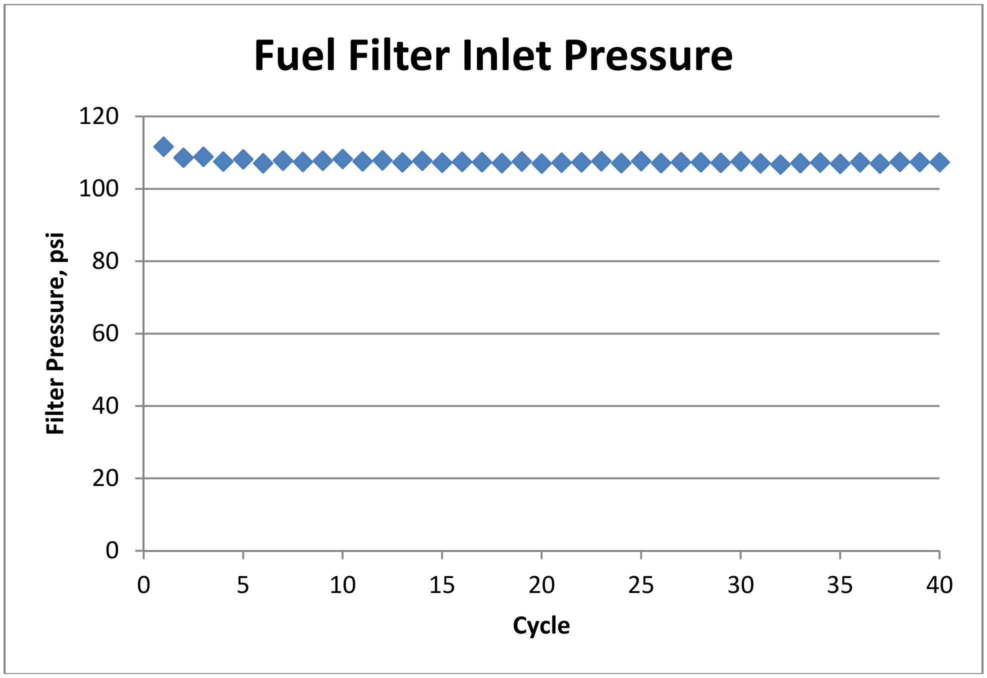

Figure G-6. Fuel Filter Pressure

Table G-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	88.0	2.9	79.6	95.9
Injected Fuel Temperature, deg C	183.4	7.6	121.9	192.9
Rail Pressure, psi	29482	201	28952	30137
Injected Flow Rate, mL/min	1451.3	20.3	1266.7	1501.9
Return Fuel Flow Rate, mL/min	1231.2	35.8	1018.3	1306.4
Fuel Filter Inlet Pressure, psi	108.3	1.4	106.1	114.5
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	87.8	2.6	76.0	96.2
Injected Fuel Temperature, deg C	183.3	6.7	123.7	190.7
Rail Pressure, psi	29484	190	28994	30126
Injected Flow Rate, mL/min	1451.5	24.0	1249.4	1545.8
Return Fuel Flow Rate, mL/min	1224.8	24.5	1113.3	1286.3
Fuel Filter Inlet Pressure, psi	107.4	0.6	105.9	109.9
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	87.9	2.3	83.2	96.4
Injected Fuel Temperature, deg C	183.2	5.5	148.7	189.2
Rail Pressure, psi	29486	174	29041	30166
Injected Flow Rate, mL/min	1451.0	22.5	1283.9	1509.4
Return Fuel Flow Rate, mL/min	1191.1	20.3	1098.6	1259.7
Fuel Filter Inlet Pressure, psi	107.4	0.5	106.0	109.2
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	87.8	2.4	82.4	96.2
Injected Fuel Temperature, deg C	182.5	5.8	145.6	189.9
Rail Pressure, psi	29478	165	29058	30091
Injected Flow Rate, mL/min	1447.5	22.3	1249.1	1497.6
Return Fuel Flow Rate, mL/min	1182.7	21.7	1063.8	1254.4
Fuel Filter Inlet Pressure, psi	107.2	0.5	105.7	108.8

Fuel Analysis

Fuel was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figures G-7 and G-8.

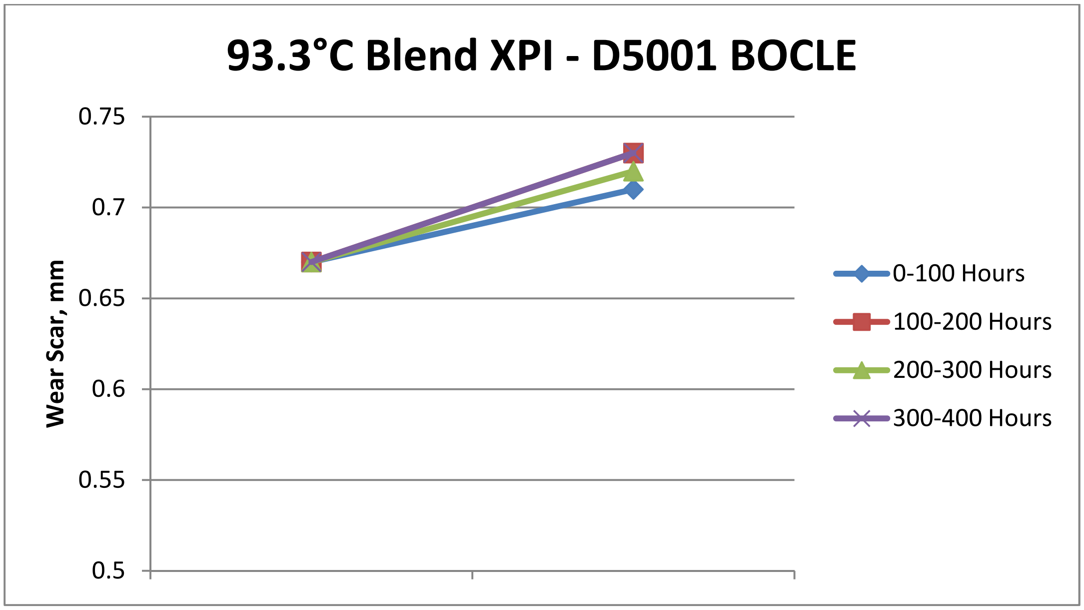

Figure G-7. ASTM D5001 BOCLE

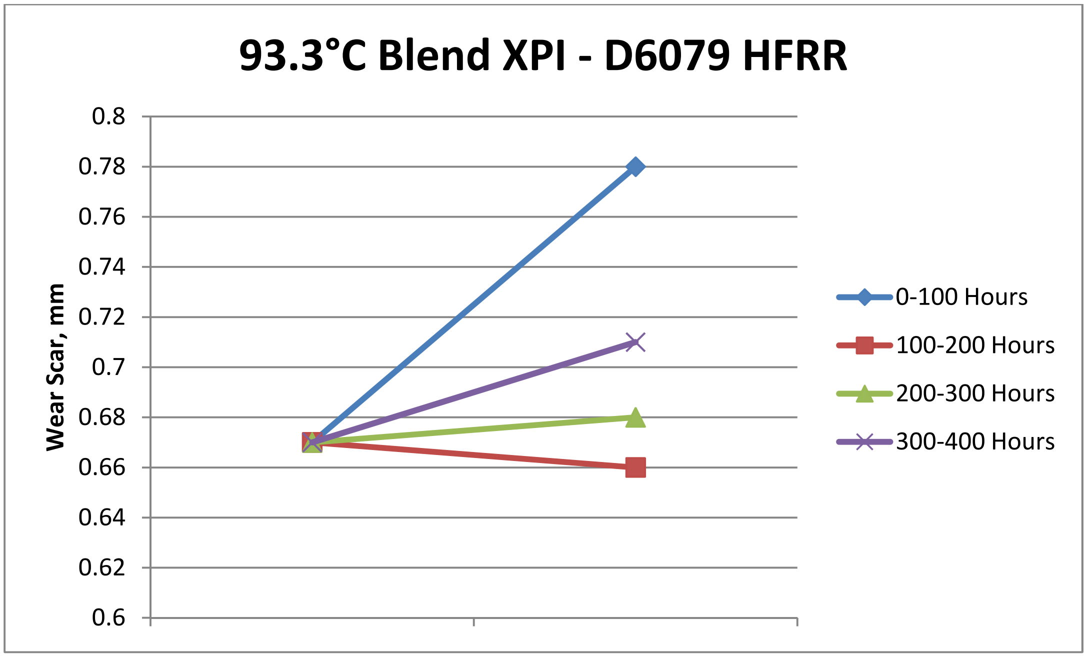

Figure G-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on the blend of synthetic and JP-8 fuels. Only fuel wetted components are shown in the figures that follow.

Fuel Pump

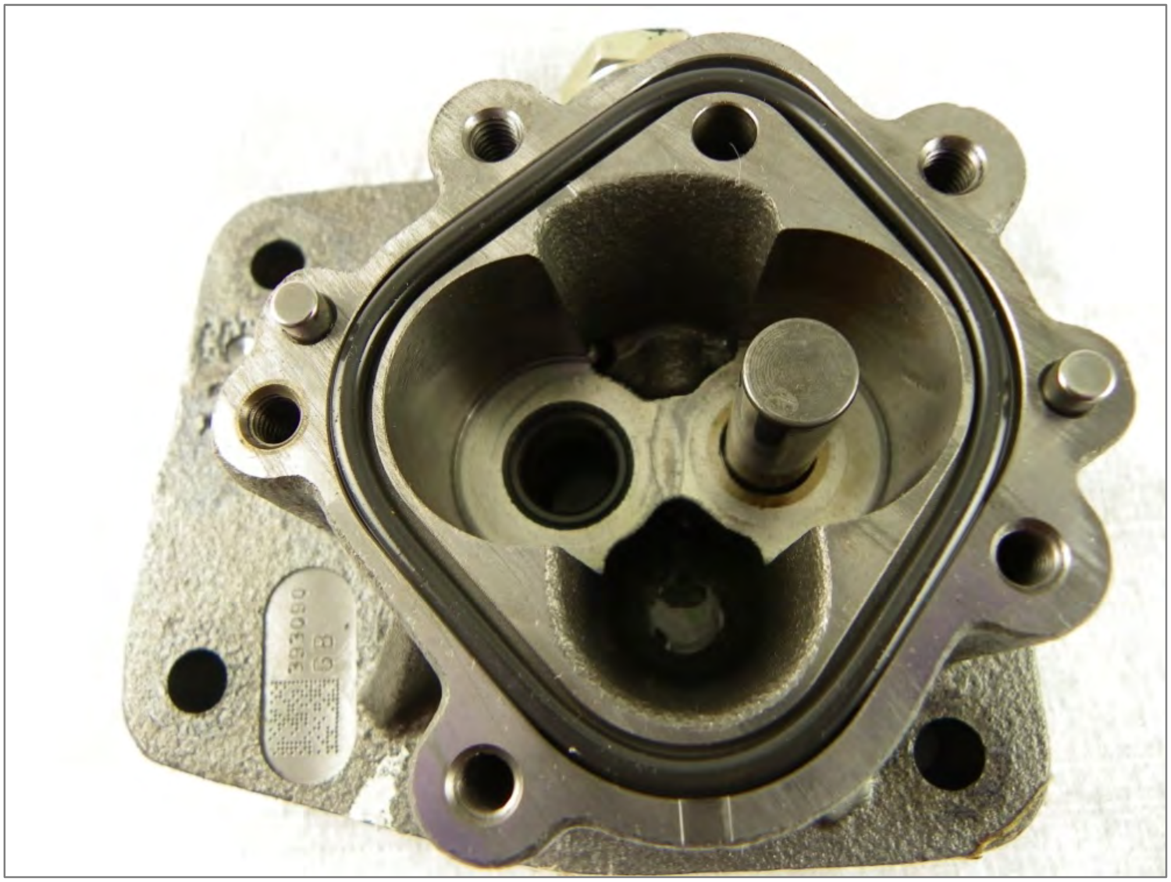

Figure G-9. Low Pressure Gear Pump Housing

Figure G-10. Gear Pump Side

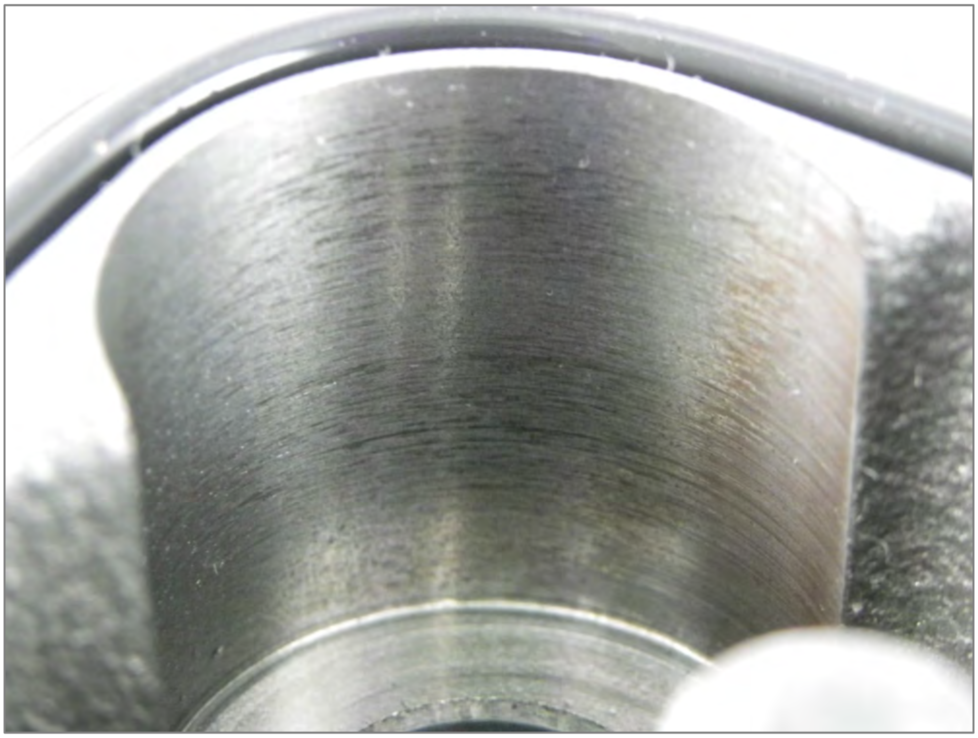

Figure G-11. Gear Pump Housing Wall

Figure G-12. Gear Pump Pressure Relief Valve

Figure G-13. Pump Gears

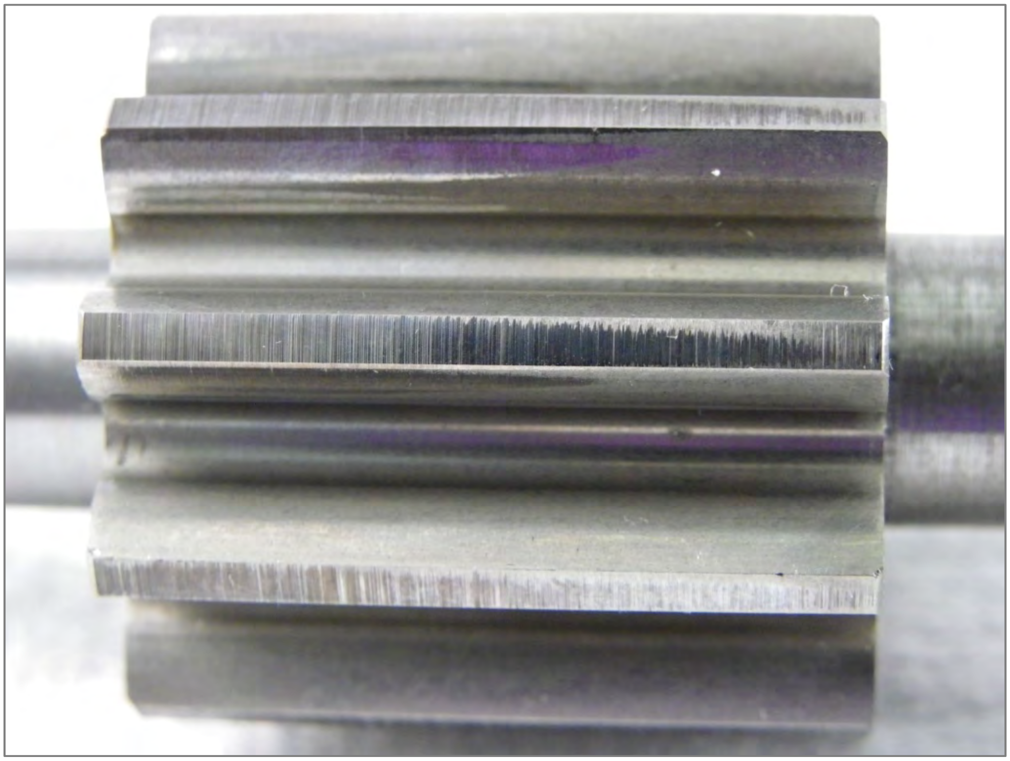

Figure G-14. Gear Tooth Wear

Fuel Injector

Figure G-15. Upper Injector Components

Figure G-16. Solenoid Plungers

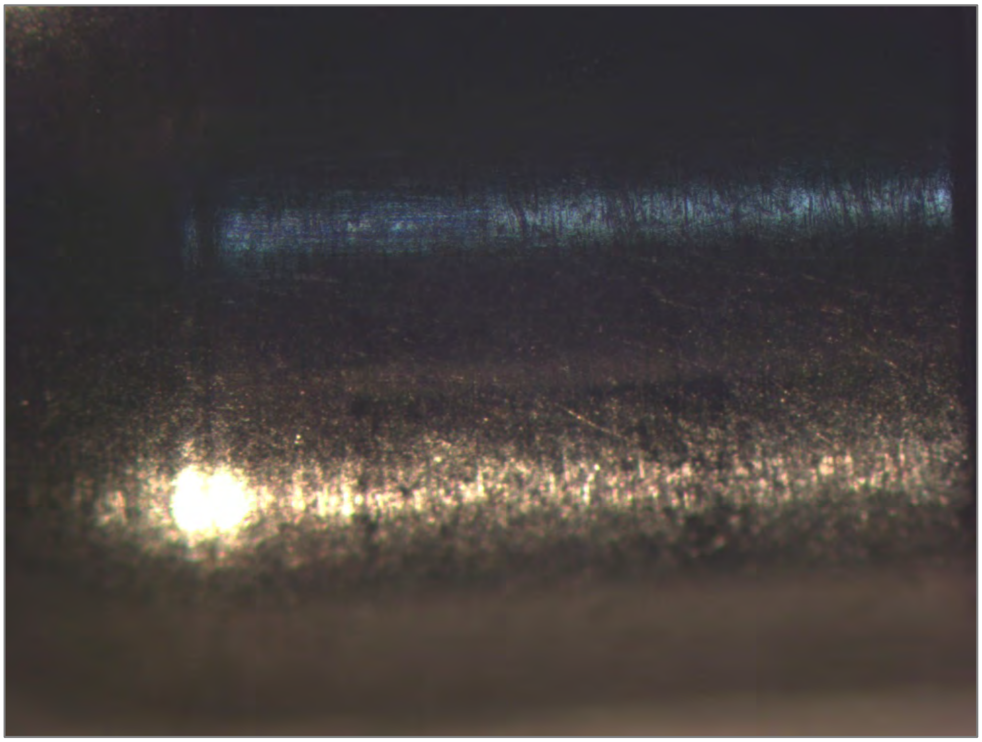

Figure G-17. Solenoid Plunger Close-Up

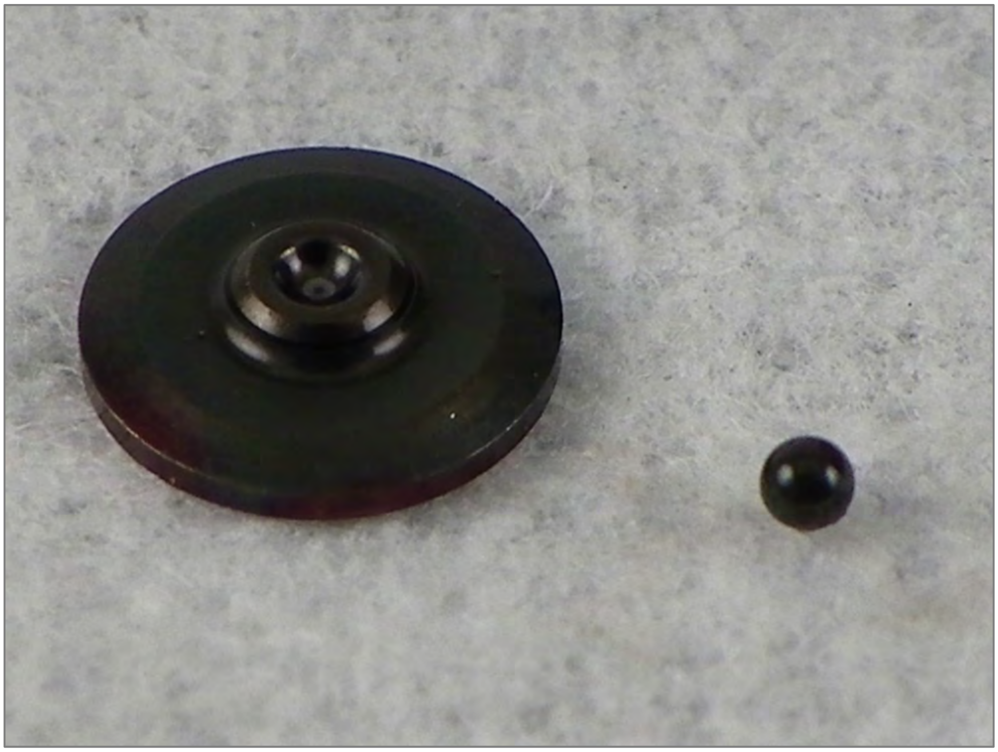

Figure G-18. Upper Ball Seat

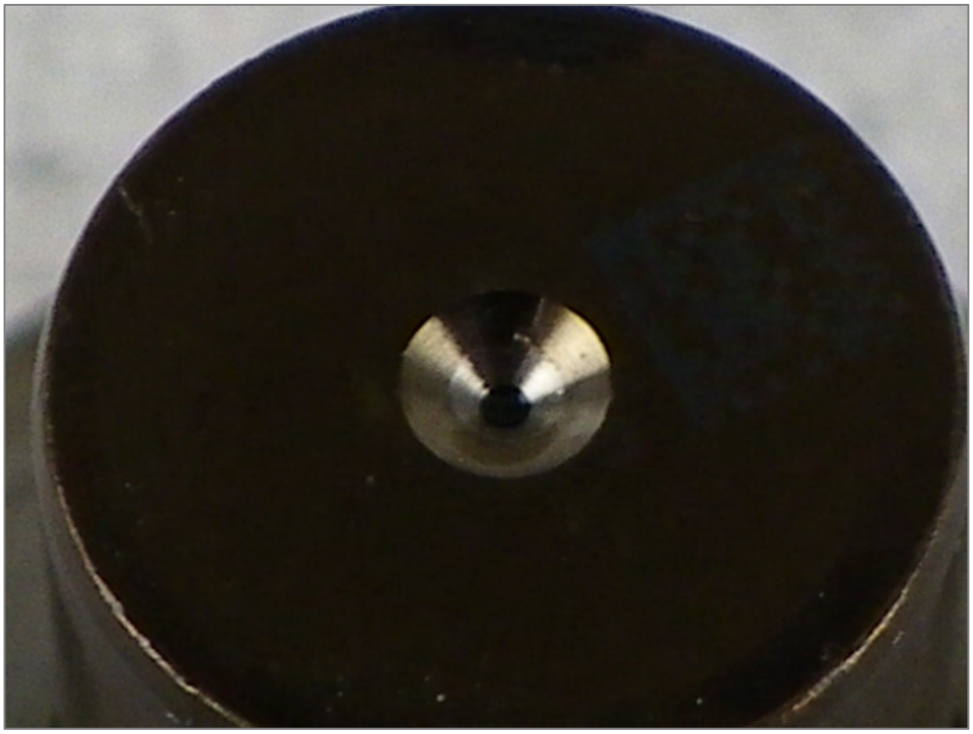

Figure G-19. Lower Ball Seat

Figure G-20. Injector Needle

Figure G-21. Injector Needle Scuffing

Figure G-22. Injector Needle Tip

APPENDIX - H

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: Jet-A
Test Number: Jet-A-AF7090-60C-XPI

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Cummins XPI Fuel System

Test Fuel: Jet-A
Test Number: Jet-A-AF7090-60C-XPI
Start of Test Date: September 20, 2011
End of Test Date: October 18, 2011
Test Duration: 400 Hours
Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) is working on a project with the U.S. Army TARDEC on synthetic and alternative fuels. The project goal is to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, JP-8, an FT SPK, manufactured by Syntroleum as S-8, treated with corrosion inhibitor/lubricity improver (CI/LI), and a 1:1 blend of the JP-8 and the synthetic fuels. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Four tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and up to four at 93.3°C (200 °F), for a total of eight tests. The lower temperature ULSD test is considered a baseline for comparison of other tests. As the project progressed, it was determined that the 93.3°C ULSD and full synthetic tests would be replaced with 60°C evaluations of Jet-A and the synthetic fuel without any lubricity improver.

Test System

Test fuel was evaluated in the Cummins XPI fuel system. This system was developed jointly between Cummins Inc. and Scania. Primarily targeted for Cummins midrange and Scania heavy duty applications, an oil-lubricated fuel pump allows the system to reach rail and injection pressures of up to 30,000 psi. The pump consists of a low pressure gear pump and high pressure piston pump. It is operated at half of the engine angular velocity for a rated condition speed of 1050 rpm. On the high pressure side of the pump, the camshaft drives two plungers which pressurize the fuel entering the rail. Each plunger is driven by three lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure side of the system consists of a gear pump which passes fuel through the final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand specifically configured for the XPI system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Cummins CM2150 engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The fuel pump consisted of a low pressure gear pump to push fuel through a high efficiency filter and send it to the high-pressure cam driven pump. Fuel then flows to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled below its flash point, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each 100 hour segment. A schematic of the stand layout is shown in Figure H-1.

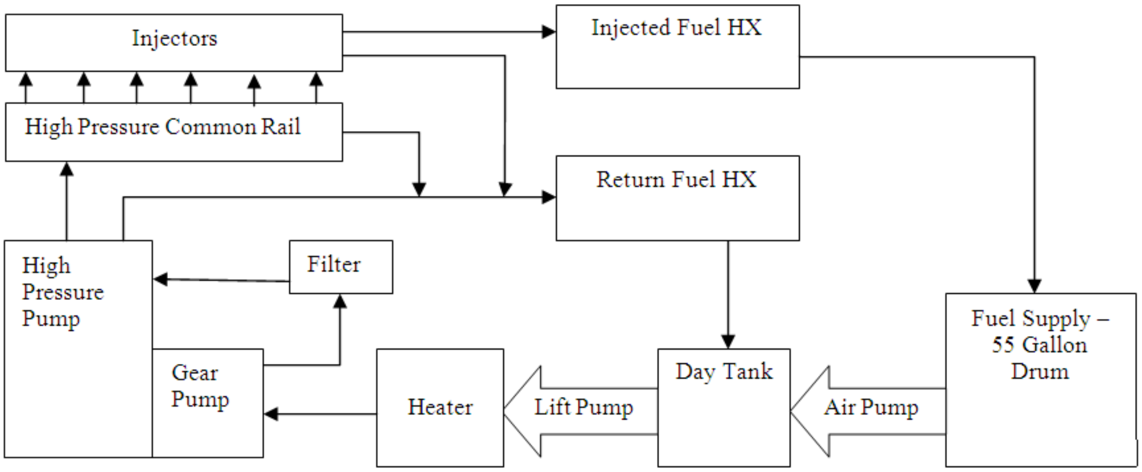

Figure H-1. XPI Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, "load" was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table H-1.

Table H-1. NATO Cycle for XPI Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	400	0	0.5
2	1050	100	2
3	1155	0	0.5
4	788	100	1
5*	400 to 1050	0 to 100	2
6	630	100	0.5
7	400	0	0.5
8	1081	70	0.5
9	650	100	2
10	650	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Cummins ECM for monitoring purposes. At the start of the test, the high pressure rail and supply line from the pump were replaced. Between Cycles 26 and 27 it was found that a small shard of metal from the fabrication process of the high pressure line was blocking the inlet port to the rail and increasing the required output from the pump. Once the shard was removed, the rail pressure returned to the value experience during all other testing. It should be noted that the shift in pressure was around 450psi, or 1.5% of the total rail pressure.

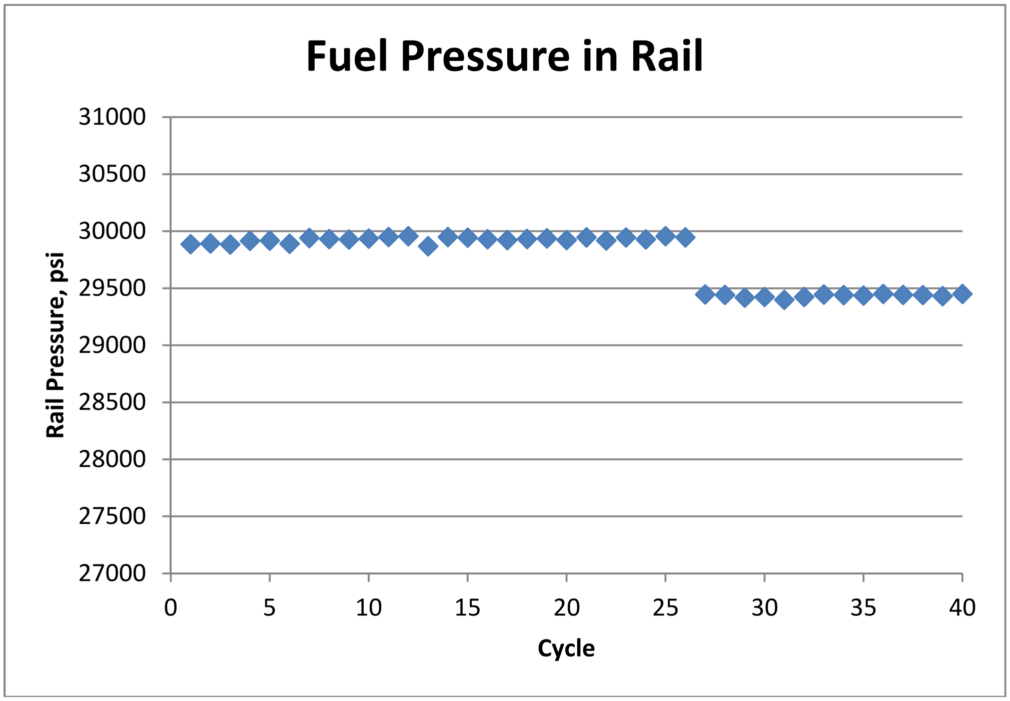

Figure H-2. Fuel Rail Pressure

The impact of the shard in the high pressure rail can be seen in the return flow. Likely, the elevated rail pressure caused additional leakage and bypass around the injectors as they fired.

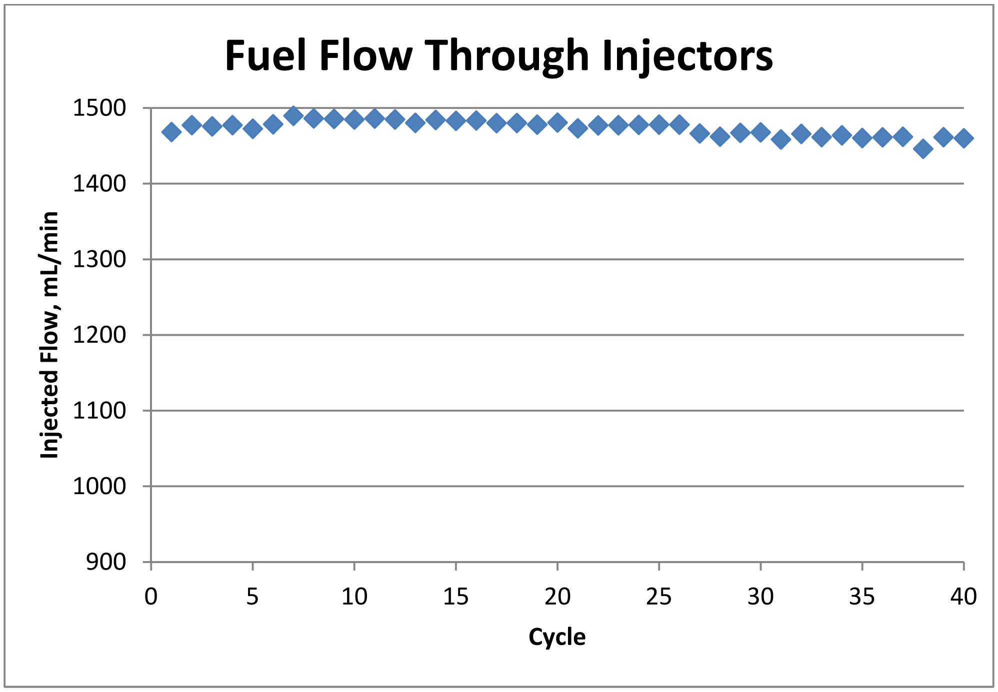

Figure H-3. Injected Fuel Flow

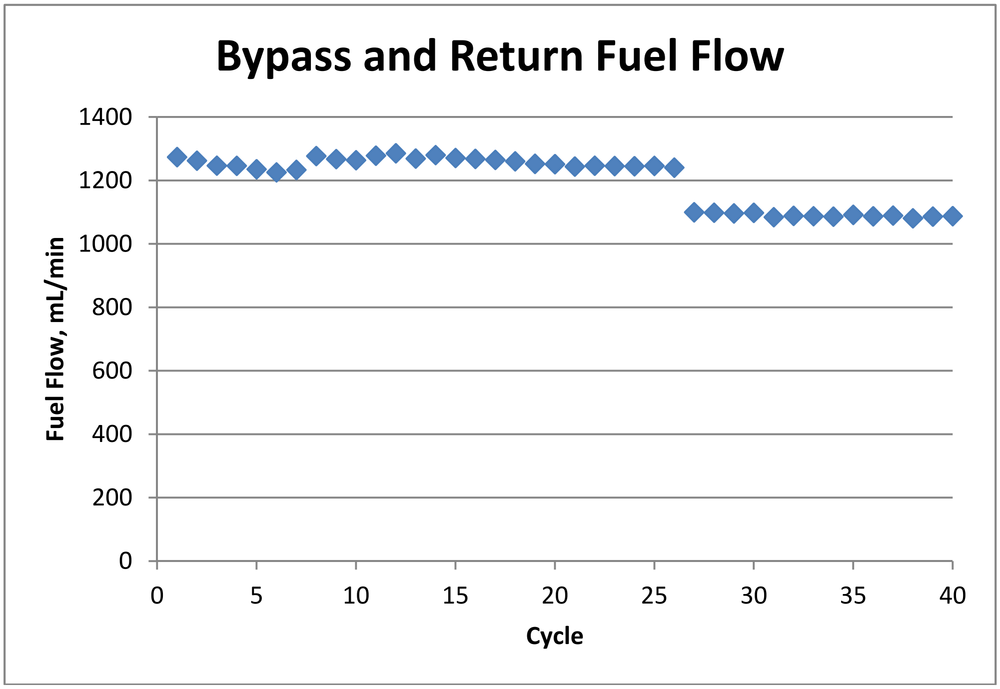

Figure H-4. Return Fuel Flow

Fuel filter inlet pressure is a measure of the pressure being developed by the gear pump portion of the XPI fuel pump.

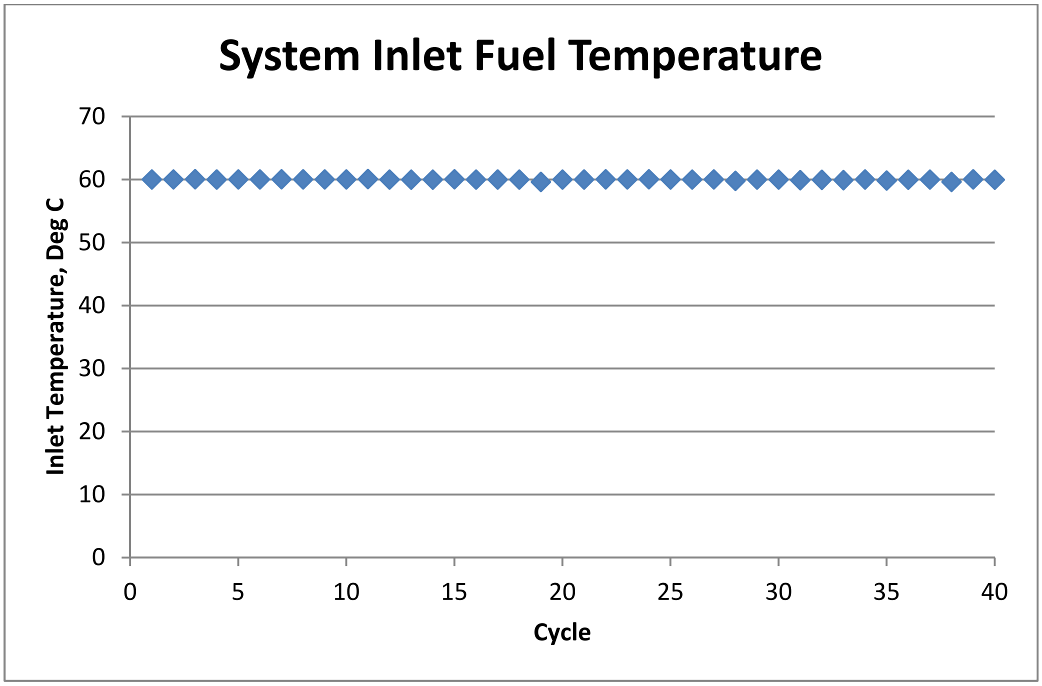

Figure H-5. System Inlet Fuel Temperature

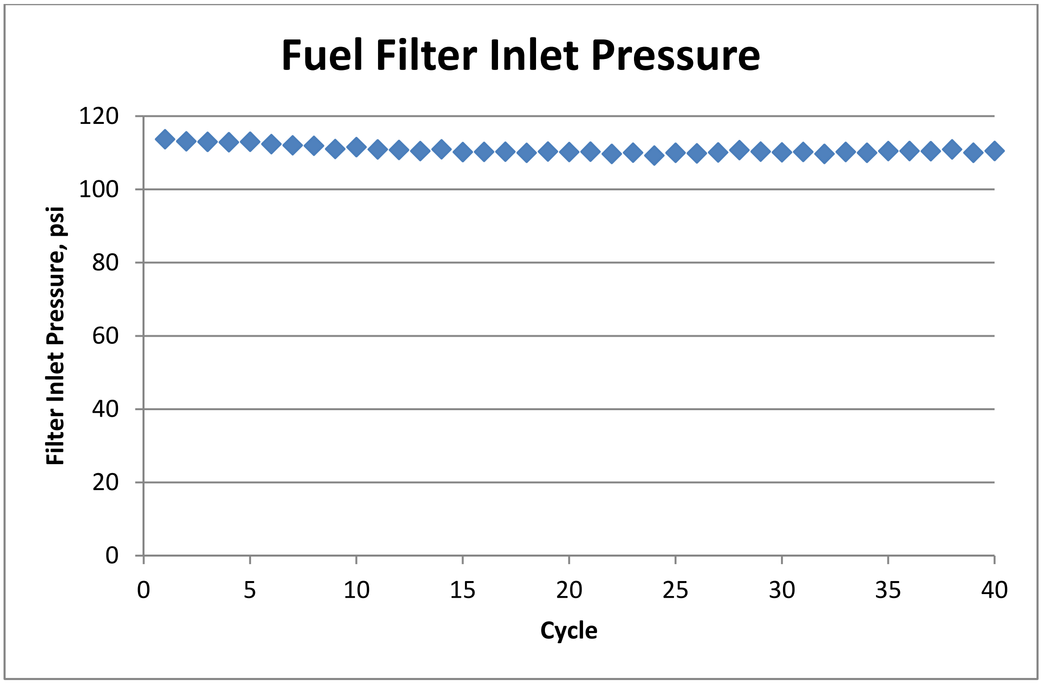

Figure H-6. Fuel Filter Pressure

Table H-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	0.7	57.4	62.8
Injected Fuel Temperature, deg C	173.5	6.0	139.4	180.2
Rail Pressure, psi	29911.8	117.8	29431.8	30259.3
Injected Flow Rate, mL/min	1479.8	21.6	1304.6	1510.5
Return Fuel Flow Rate, mL/min	1252.1	24.2	1133.3	1307.1
Fuel Filter Inlet Pressure, psi	112.5	0.9	109.7	115.7
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	0.9	56.1	63.4
Injected Fuel Temperature, deg C	174.7	6.5	117.9	180.5
Rail Pressure, psi	29931.5	221.2	23579.4	30215.3
Injected Flow Rate, mL/min	1482.3	14.5	1393.7	1522.2
Return Fuel Flow Rate, mL/min	1267.1	25.9	912.5	1338.8
Fuel Filter Inlet Pressure, psi	110.5	1.5	68.9	112.9
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.0	57.5	64.0
Injected Fuel Temperature, deg C	170.4	7.2	133.4	179.2
Rail Pressure, psi	29735.5	277.0	29078.1	30464.0
Injected Flow Rate, mL/min	1472.5	14.5	1395.4	1506.5
Return Fuel Flow Rate, mL/min	1185.2	74.1	1031.7	1297.7
Fuel Filter Inlet Pressure, psi	110.1	0.9	104.0	115.6
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.0	55.7	64.0
Injected Fuel Temperature, deg C	164.1	6.3	96.0	170.4
Rail Pressure, psi	29434.6	128.8	28970.7	29837.3
Injected Flow Rate, mL/min	1460.0	16.2	1362.5	1497.3
Return Fuel Flow Rate, mL/min	1086.4	18.9	991.8	1135.1
Fuel Filter Inlet Pressure, psi	110.4	0.7	103.2	114.4

Fuel Analysis

Fuel was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figures H-7 and H-8. Pre and post test fuel analysis did not indicate any unusually large changes in lubricity.

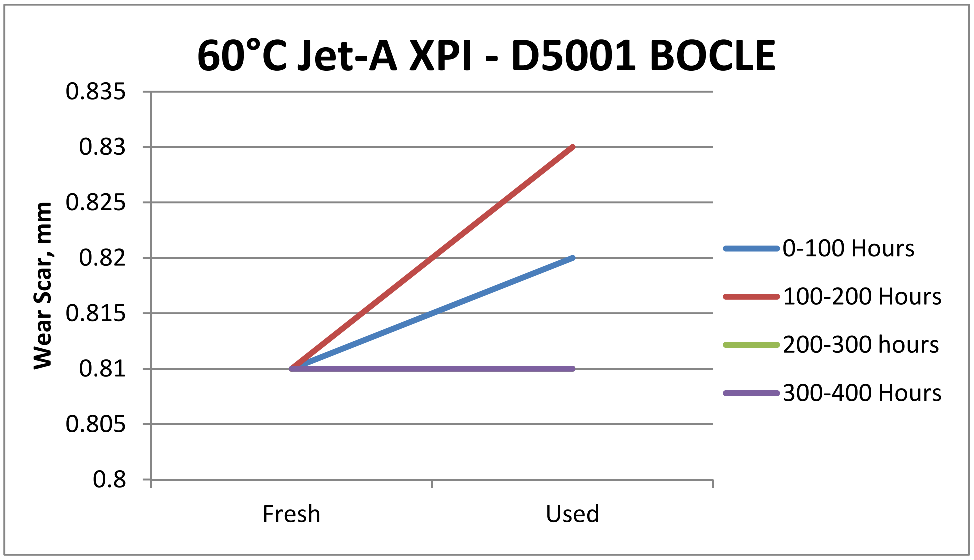

Figure H-7. ASTM D5001 BOCLE

The results from the last 200 hours of the Jet-A test were identical, resulting in the overlay of the lines in the figure above. This is also true for the first 200 hours of HFRR results shown below.

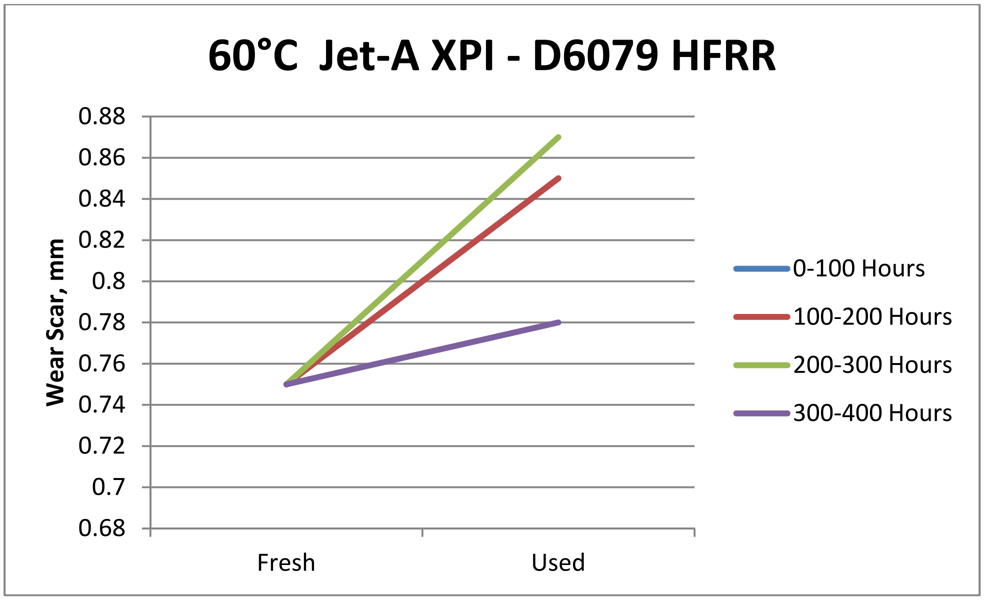

Figure H-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on Jet-A. Only fuel wetted components are shown in the figures that follow.

Fuel Pump

Figure H-9. Low Pressure Gear Pump Housing

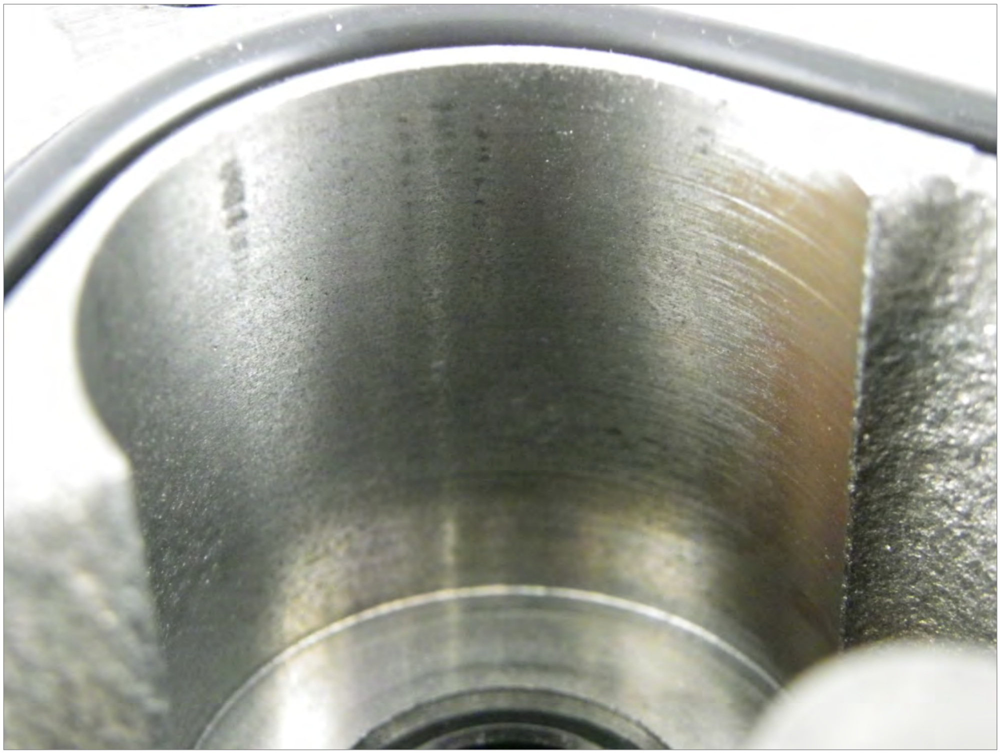

Figure H-10. Gear Pump Side Wall

Figure H-11. Gear Pump Pressure Relief Valve

Figure H-12. Pump Gears

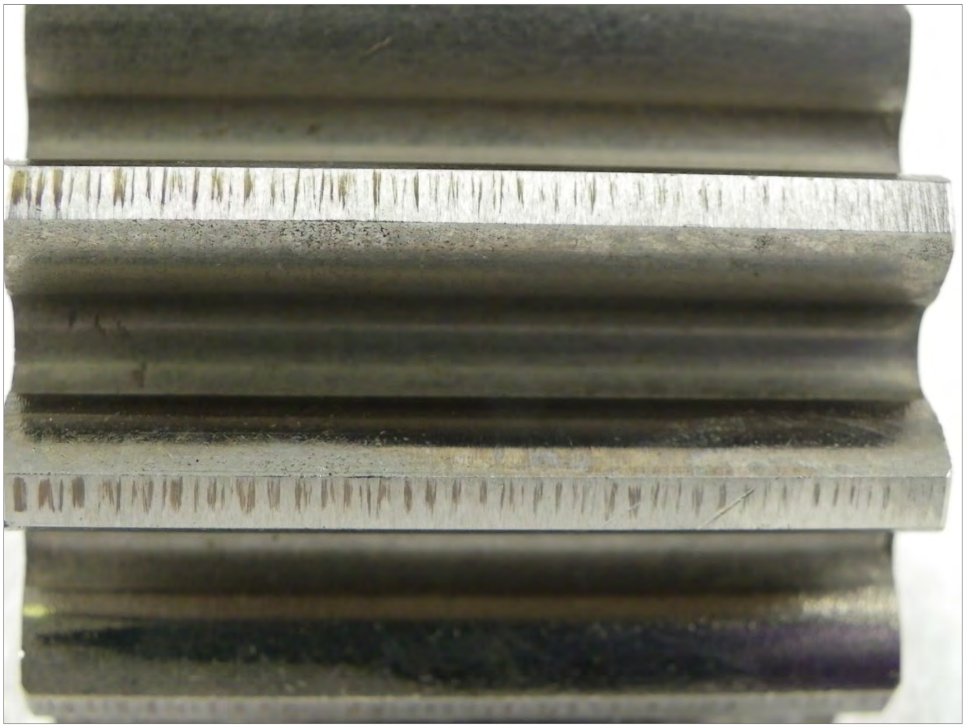

Figure H-13. Gear Tooth Wear

Fuel Injector

Figure H-14. Upper Injector Components

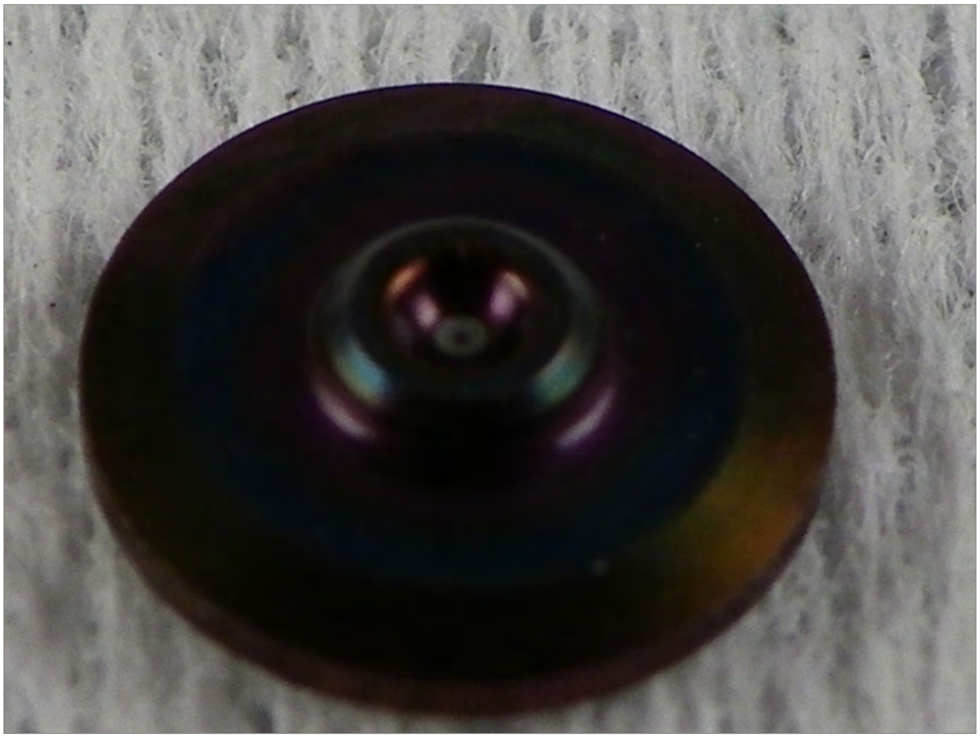

Figure H-15. Upper Ball Seat

Figure H-16. Lower Ball Seat

Figure H-17. Injector Needle Scuffing

Figure H-18. Injector Needle Tip

APPENDIX - I

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: SPK (no additive)
Test Number: NeatSPK-60C-XPI

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

Cummins XPI Fuel System

Test Fuel: SPK (no additive)
Test Number: NeatSPK-60C-XPI
Start of Test Date: October 27, 2011
End of Test Date: November 22, 2011
Test Duration: 400 Hours
Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) is working on a project with the U.S. Army TARDEC on synthetic and alternative fuels. The project goal is to assess the changing worldwide fuels supply with a focus on kerosene and diesel boiling range fuels, and of the impact that varying fuel properties may have on current and future military equipment and systems. One of the tasks associated with the project was to determine fuel property requirements of modern common rail fuel injection systems. SwRI was tasked to set up a test bench system to analyze lubricity impacts of various fuels. Using a test bench method is preferred over full scale engine testing due to the low fuel quantities that can be used for long duration testing. Testing was conducted using commercially available ULSD, JP-8, an FT SPK, manufactured by Syntroleum as S-8, treated with corrosion inhibitor/lubricity improver (CI/LI), and a 1:1 blend of the JP-8 and the synthetic fuels. The desire was to perform eight 400-hour durability tests with duty cycles similar to a NATO cycle engine test. Four tests (one for each of the four fuels) conducted at controlled fuel inlet temperatures of 60°C (140 °F) and up to four at 93.3°C (200 °F), for a total of eight tests. The lower temperature ULSD test is considered a baseline for comparison of other tests. As the project progressed, it was determined that the 93.3°C ULSD and full synthetic tests would be replaced with 60°C evaluations of Jet-A and the synthetic fuel without any lubricity improver.

Test System

Test fuel was evaluated in the Cummins XPI fuel system. This system was developed jointly between Cummins Inc. and Scania. Primarily targeted for Cummins midrange and Scania heavy duty applications, an oil-lubricated fuel pump allows the system to reach rail and injection pressures of up to 30,000 psi. The pump consists of a low pressure gear pump and high pressure piston pump. It is operated at half of the engine angular velocity for a rated condition speed of 1050 rpm. On the high pressure side of the pump, the camshaft drives two plungers which pressurize the fuel entering the rail. Each plunger is driven by three lobes which, when correctly timed, impart new fuel to the high pressure rail as each injector fires. This is designed to reduce pressure pulsations in the high pressure system lines. The low pressure side of the system consists of a gear pump which passes fuel through the final filter before entering the high pressure side. For each fuel test, new pump, filter, and injector components were used.

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The pump and hardware was mounted in a test stand specifically configured for the XPI system testing. System monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. Fuel injection and rail pressure were controlled by a Cummins CM2150 engine control module (ECM) modified for use with a bench system. Fluid temperatures were maintained with the use of liquid-to-liquid heat exchangers and heaters. The test was run using a 55-gallon drum as remote fuel source to the stand. A smaller day tank located at the stand provided a reservoir within the test cell. Fuel was drawn by an electric lift pump from the day tank to fill heating equipment and prime the main fuel pump. The fuel pump consisted of a low pressure gear pump to push fuel through a high efficiency filter and send it to the high-pressure cam driven pump. Fuel then flows to the rail before passing through the injectors. Bypass fuel collected from the high-pressure pump, rail relief valve, and injector returns was cooled as needed before returning to the day tank located on the test stand. Injected fuel was collected in a common manifold, cooled below its flash point, and returned to the remote drum. Fuel was checked throughout testing to monitor shifts in fuel lubricity that could impact test results. Every 100 hours of test operation, the 55-gallon fuel source was replaced. Samples of fuel were taken at the start of testing and completion of each 100 hour segment. A schematic of the stand layout is shown in Figure I-1.

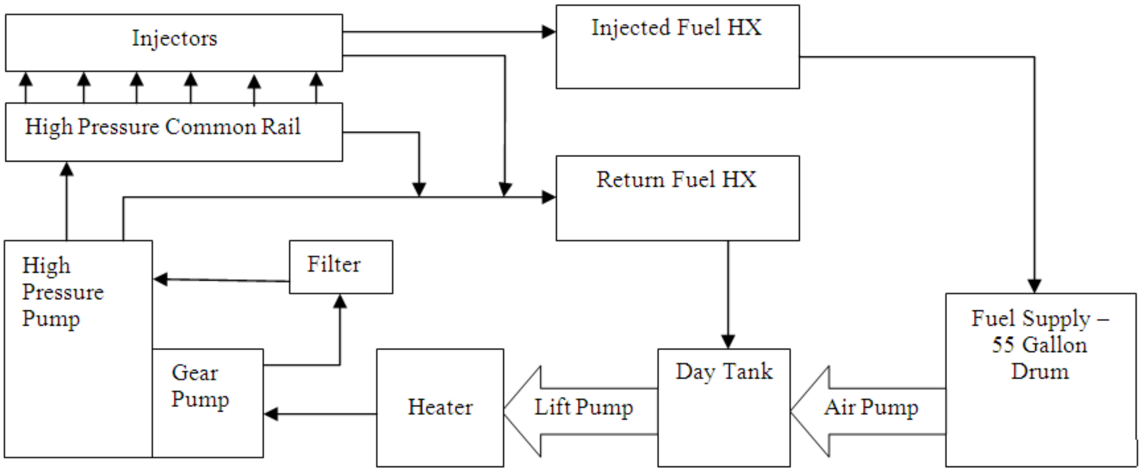

Figure I-1. XPI Stand Layout

Test Cycle

The NATO Standard Engine Laboratory Test AEP-5, Edition 3 is a 400-hour test consisting of repeated 10-hour cycles. Each cycle has 10 operating modes which speed and load are controlled to. Since there is no torque feedback available when using the fuel system alone, “load” was determined based upon the accelerator pedal percentage input given to the ECM. The pump was motored at the speed which it would turn if mounted on an engine, in this case half that of the crankshaft. The operating modes for the cycle are shown in Table I-1.

Table I-1. NATO Cycle for XPI Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	400	0	0.5
2	1050	100	2
3	1155	0	0.5
4	788	100	1
5*	400 to 1050	0 to 100	2
6	630	100	0.5
7	400	0	0.5
8	1081	70	0.5
9	650	100	2
10	650	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are average values for Mode 2 (rated conditions, 2 hours). Selected operating parameters are shown which provide an indication of system quality.

The stock mounted pressure transducer within the high pressure rail was shared by Prism and the Cummins ECM for monitoring purposes.

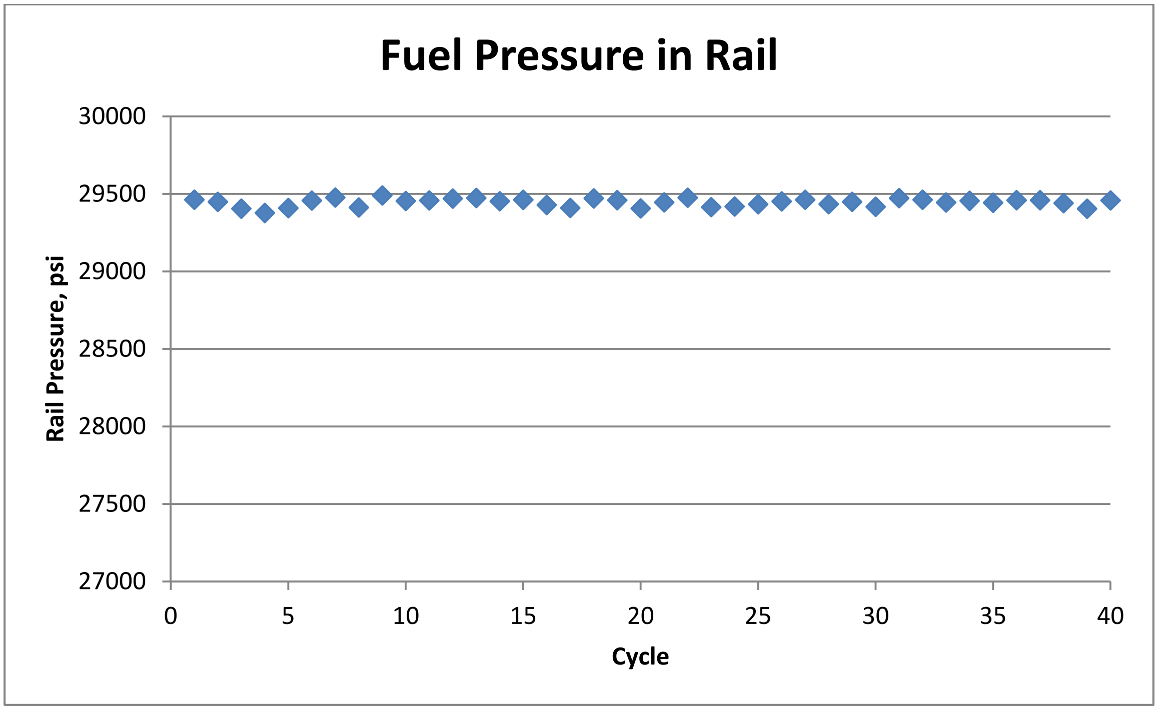

Figure I-2. Fuel Rail Pressure

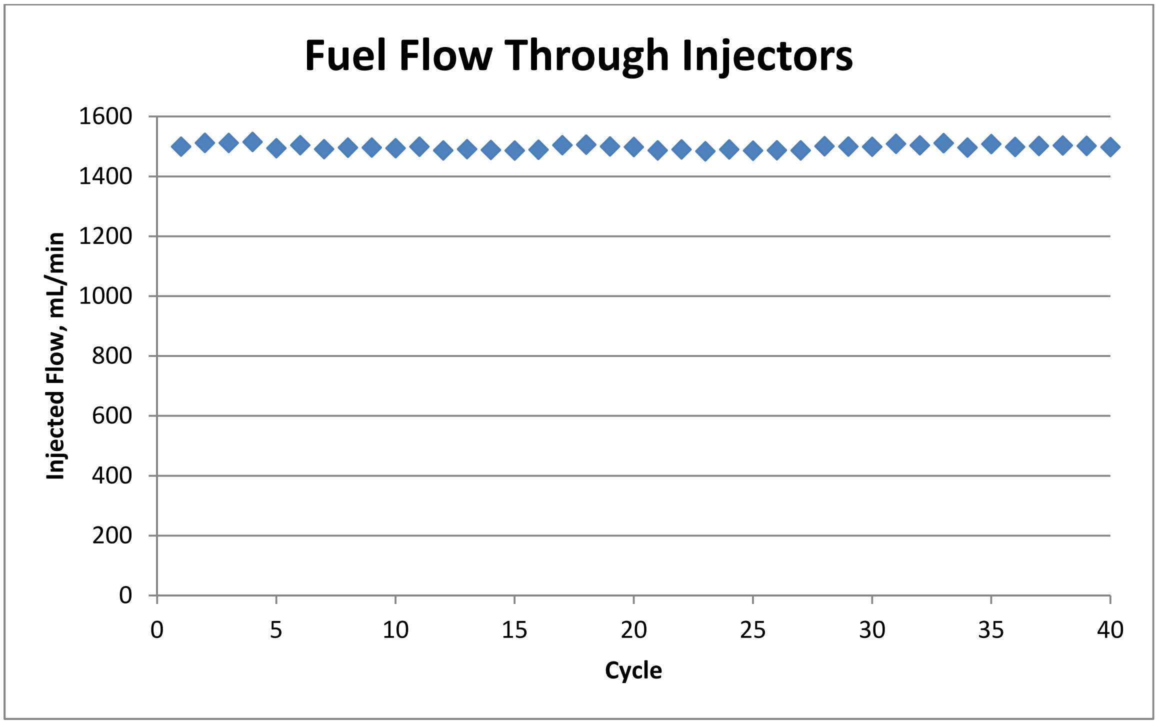

Figure I-3. Injected Fuel Flow

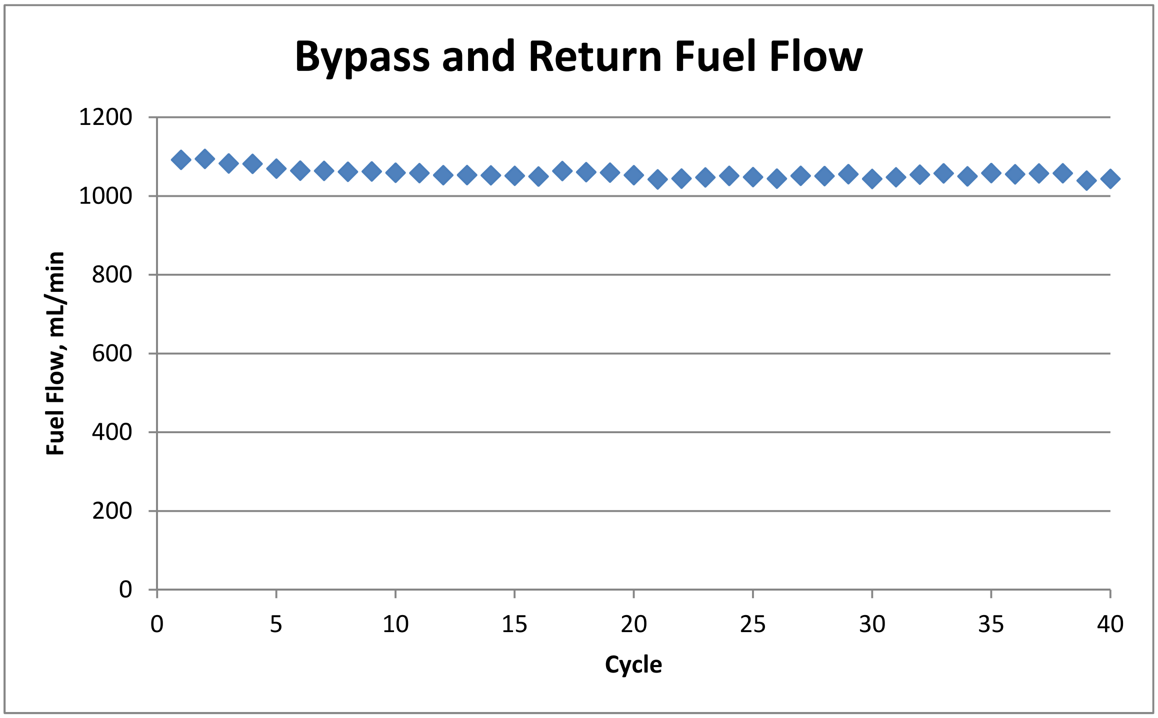

Figure I-4. Return Fuel Flow

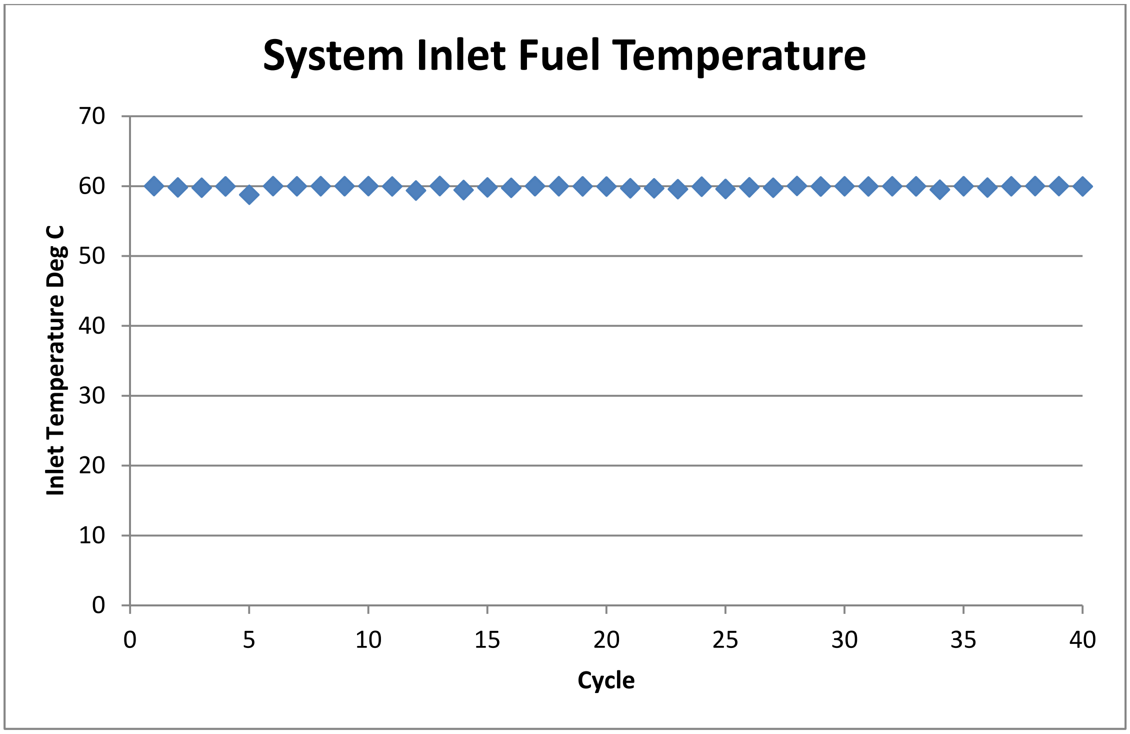

Figure I-5. System Inlet Fuel Temperature

Fuel filter inlet pressure is a measure of the pressure being developed by the gear pump portion of the XPI fuel pump.

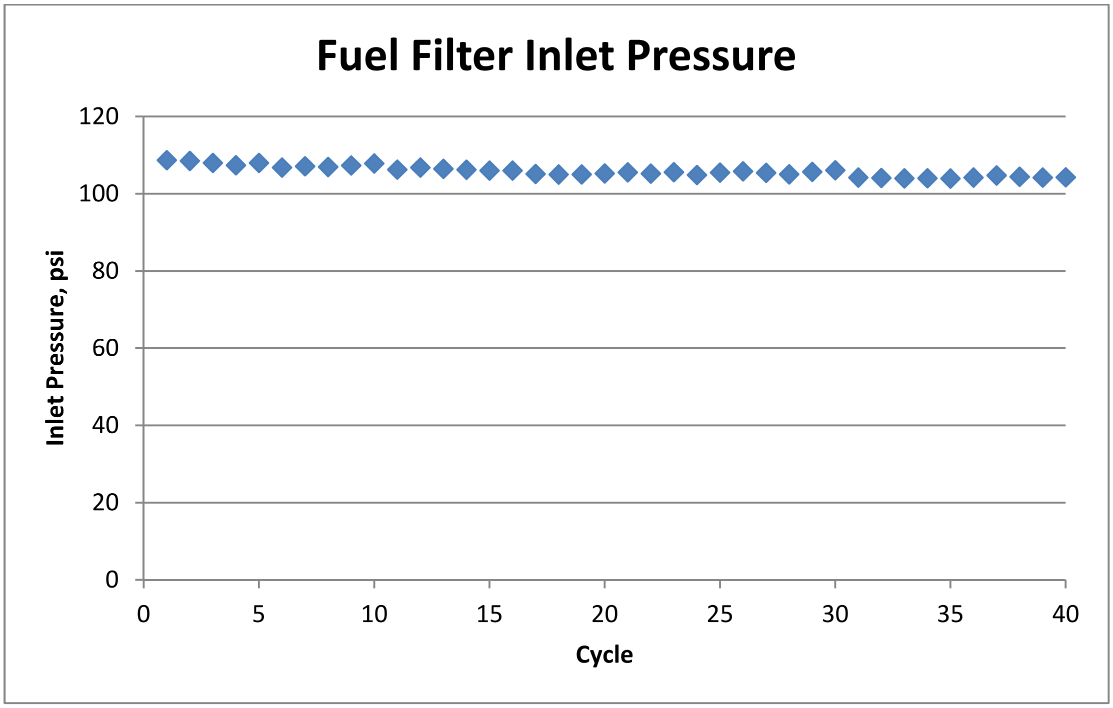

Figure I-6. Fuel Filter Pressure

Table I-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	59.9	1.3	46.8	63.3
Injected Fuel Temperature, deg C	161.6	6.1	103.9	168.3
Rail Pressure, psi	29439.8	272.1	28413.0	30181.6
Injected Flow Rate, mL/min	1501.4	22.9	1342.7	1547.2
Return Fuel Flow Rate, mL/min	1072.6	24.2	976.5	1143.3
Fuel Filter Inlet Pressure, psi	107.7	1.0	100.4	110.9
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	59.9	1.2	56.4	64.1
Injected Fuel Temperature, deg C	160.5	5.0	128.6	166.3
Rail Pressure, psi	29449.2	232.9	28643.6	30108.7
Injected Flow Rate, mL/min	1494.9	16.5	1438.3	1530.9
Return Fuel Flow Rate, mL/min	1054.9	19.8	997.7	1103.3
Fuel Filter Inlet Pressure, psi	105.8	1.0	96.9	108.9
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	59.9	1.1	56.7	64.6
Injected Fuel Temperature, deg C	160.2	5.2	127.7	167.4
Rail Pressure, psi	29440.8	202.8	28836.5	30119.7
Injected Flow Rate, mL/min	1491.1	15.8	1445.5	1532.4
Return Fuel Flow Rate, mL/min	1047.4	18.5	978.9	1098.1
Fuel Filter Inlet Pressure, psi	105.5	0.7	100.7	107.9
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	1.0	57.2	64.5
Injected Fuel Temperature, deg C	160.9	5.1	127.8	166.8
Rail Pressure, psi	29449.4	205.5	28501.6	29974.6
Injected Flow Rate, mL/min	1503.2	16.0	1445.9	1535.8
Return Fuel Flow Rate, mL/min	1051.5	19.7	987.7	1098.6
Fuel Filter Inlet Pressure, psi	104.2	1.0	90.2	108.4

Fuel Analysis

Fuel was evaluated at the beginning of the test and the end of each 100 hours, when the supply drum was changed. Results from ASTM D5001 and D6079 are shown in Figures I-7 and I-8. Since each drum was clay treated separately, there are four distinct "Fresh" sample values. Pre and post test fuel analysis did not indicate any unusually large changes in lubricity.

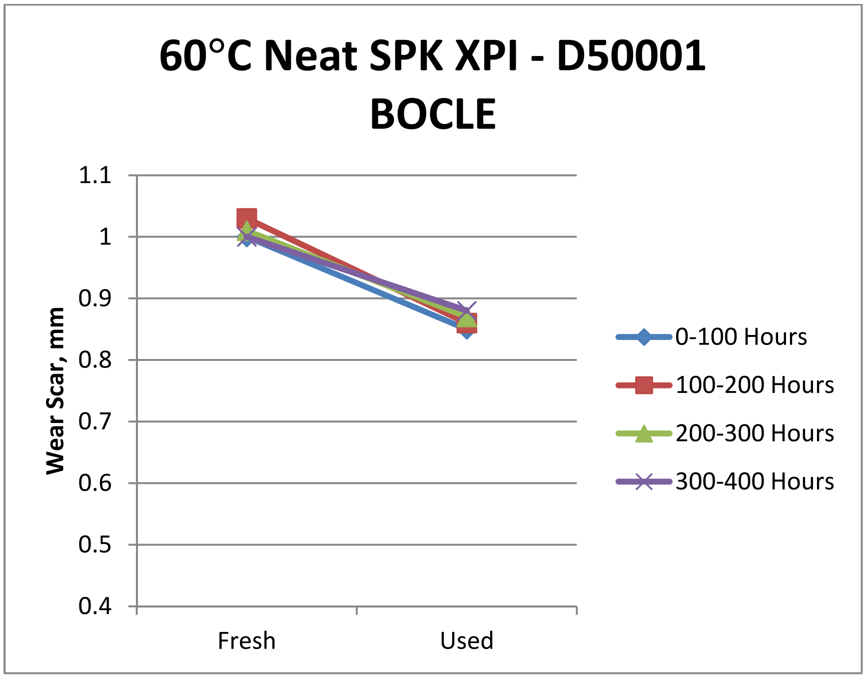

Figure I-7. ASTM D5001 BOCLE

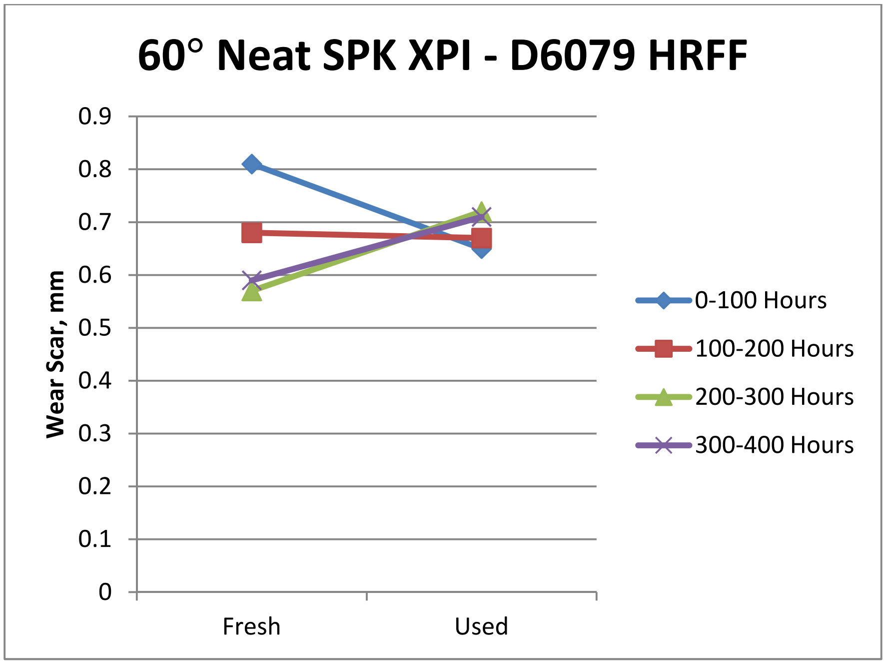

Figure I-8. ASTM D6079 HFRR

Component Wear

Post-test tear down of the pump and injectors was performed to evaluate typical wear operating on unadditized SPK. Only fuel wetted components are shown in the figures that follow.

Fuel Pump

Figure I-9. Low Pressure Gear Pump Housing

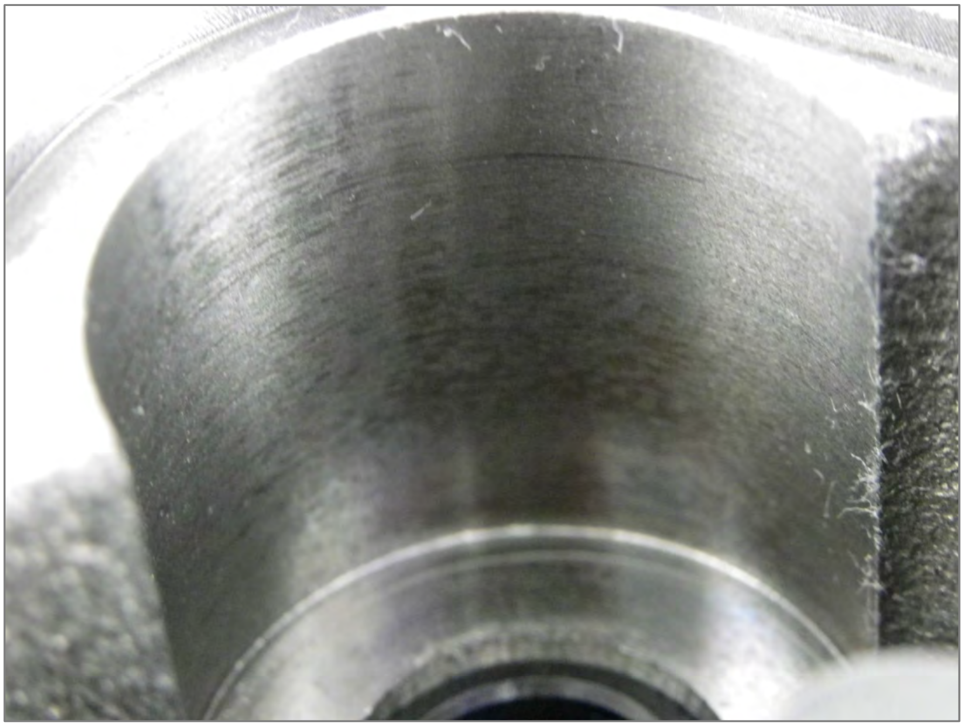

Figure I-10. Gear Pump Side Wall

Figure I-11. Gear Pump Pressure Relief Valve

Figure I-12. Pump Gears

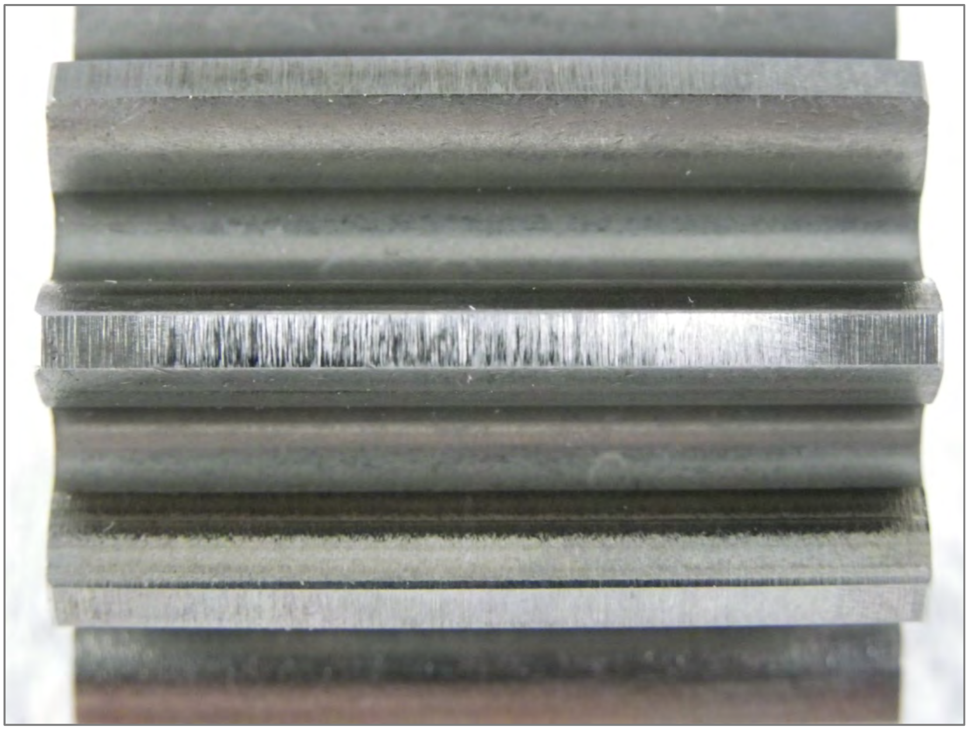

Figure I-13. Gear Tooth Wear

Fuel Injector

Figure I-14. Upper Injector Components

Figure I-15. Upper Ball Seat

Figure I-16. Lower Ball Seat

Figure I-17. Injector Needle Scuffing

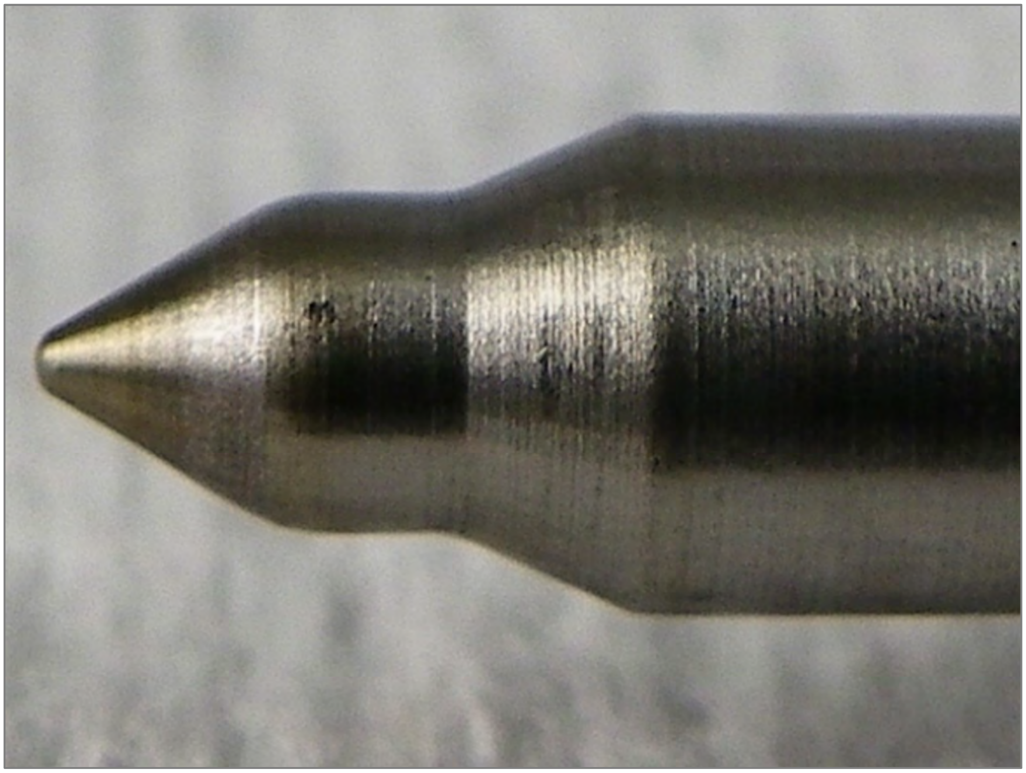

Figure I-18. Injector Needle Tip