ADA

EVALUATION OF FUTURE FUELS IN A HIGH PRESSURE COMMON RAIL SYSTEM – PART 3 JOHN DEERE 4.5L POWERTECH PLUS

INTERIM REPORT
TFLRF No. 433

by
Robert W. Warden, Edwin A. Frame, & Douglas M. Yost

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
Eric R. Sattler, Patsy A. Muzzell, & Nick C. Johnson

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

Contract No. W56HZV-09-C-0100 (WD0004 – Task XIX)

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14. ABSTRACT
A series of fuels were tested on a bench stand designed and constructed for the John Deere 4.5L Powertech Plus High Pressure Common Rail Fuel System manufactured by DENSO Corporation. Included were ULSD, an additized Jet A to represent JP-8, an FT SPK, and blend of the Jet A and SPK fuels. Testing occurred at 60, 82.8 and 93.3°C over a 400-hour NATO cycle. Fuel viscosity ranged from 0.57 to 1.90 cSt while lubricity wear-scar diameters were from 0.54 to 0.68 mm (ASTM D5001) and 0.47 to 0.84 mm (ASTM D6079). At the conclusion of each test, components were evaluated for wear and overall system performance with the ULSD test as a baseline for comparison. Results showed the system to be sensitive to fuel viscosity. The three evaluations which had a fuel viscosity at test temperature of 0.61 cSt or lower failed between four and five hours of test time. All other evaluations completed the full 400 hour cycle. The eccentric lobe on the fuel pump cam shaft was identified as the critical area for fuel compatibility. No issues were found within the fuel injectors regardless of viscosity or lubricity levels.

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EXECUTIVE SUMMARY

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FOREWORD/ACKNOWLEDGMENTS

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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.

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ACRONYMS AND ABBREVIATIONS

ASTM	American Society for Testing and Materials
BOCLE	Ball-On-Cylinder Lubricity Evaluator
cSt	CentiStoke
CI/LI	Corrosion Inhibitor/Lubricity Improver
˚C	Degrees Centigrade
˚F	Degrees Fahrenheit
ECM	Electronic Control Module
FT	Fischer-Tropsch
HDO	Heavy Duty Oil
HFRR	High Frequency Reciprocating Rig
HPCR	High Pressure Common Rail
JD	John Deere
JP-8	Jet Propellant 8, NATO code F-34
kW	Kilowatt
mm	Millimeter
NATO	North Atlantic Treaty Organization
OEM	Original Equipment Manufacturer
Ppm	Parts per million
Psi	Pounds per square inch
RPM	Revolutions per minute
SAE	Society of Automotive Engineers
SwRI	Southwest Research Institute
SPK	Synthetic-Paraffinic Kerosene
TARDEC	Tank Automotive Research, Development and Engineering Center
TFLRF	TARDEC Fuels and Lubricants Research Facility
ULSD	Ultra Low Sulfur Diesel
VFD	Variable Frequency Drive
WSD	Wear Scar Diameter

1.0 BACKGROUND AND OBJECTIVE

As aviation industries begin to incorporate renewable and synthetic fuel sources into the global supply chain, 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 their petroleum-based counterparts, evaluations are required to validate performance in reciprocating engine fuel injection systems. As environmental regulations drive commercial Original Equipment Manufacturers (OEMs) 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 designed for operation on ultra-low sulfur diesel. While many older vehicles in the military fleet do not utilize HPCR fuel systems, 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), a low lubricity JP-8 (Jet A with a minimum treat rate of 9 ppm DCI-4A corrosion inhibitor/lubricity improver (CI/LI) additive), a Fischer-Tropsch (FT) process Synthetic Parafinic Kerosene (SPK) with the minimum treat rate of 9 ppm DCI-4A, and a 50% blend of the JP-8 and synthetic fuels. The temperatures for the evaluations 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 more sensitive than those previously evaluated. Due to this, changes to the test plan were made. A summary of the final test fuels matrix is shown in Table 1.

Table 1. Project Test Fuels

Fuel	Test Temp. (°C)	Kinematic Viscosity [1] @ Temp. (cSt)	Lubricity (Fresh), WSD (mm)	
			ASTM D5001 [2]	ASTM D6079 [3]
Ultra Low Sulfur Diesel	60	1.90	0.54	0.47
Jet A (9 ppm CI/LI)	60	0.95	0.68	0.72
Jet A (9 ppm CI/LI)	93.3	0.68	0.68	0.72
SPK (9 ppm CI/LI)	60	0.78	0.67	0.84
SPK (9 ppm CI/LI)	93.3	0.57	0.67	0.84
50% Jet A, 50% SPK (9 ppm CI/LI)	60	0.85	0.67	0.75
50% Jet A, 50% SPK (9 ppm CI/LI)	93.3	0.61	0.67	0.75
50% Jet A, 50% SPK (22.5 ppm CI/LI)	82.8	0.68	0.63	0.74
50% Jet A, 50% SPK (22.5 ppm CI/LI)	93.3	0.61	0.63	0.74

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 during 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, as broadcast by the ECM, was read over the SAE 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 John Deere HPCR Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	800	0	0.5
2	2400	100	2
3	2560	0	0.5
4	1800	100	1
5*	800 to 2400	0 to 100	2
6	1440	100	0.5
7	800	0	0.5
8	2500	70	0.5
9	1500	100	2
10	1440	50	0.5

*Step 5 cycles between idle and rated conditions

2.3 TEST STAND AND FUEL SYSTEM

2.3.1 Fuel Pump

The John Deere 4.5L engine incorporates a DENSO manufactured fuel system. The same basic system is used for both the 4.5L and 6.8L John Deere engines by increasing the number of injectors from four to six. In some engine applications, fuel is supplied to the high pressure pump through a cam-actuated lift pump. For test stand evaluations, this was replaced with an electric lift pump to force fuel through temperature control equipment and filtration components. The high pressure pump consists of two plunger assemblies oriented in an opposed fashion and a transfer pump all driven from a common camshaft. The pump can be seen, installed for testing, in Figure 1.

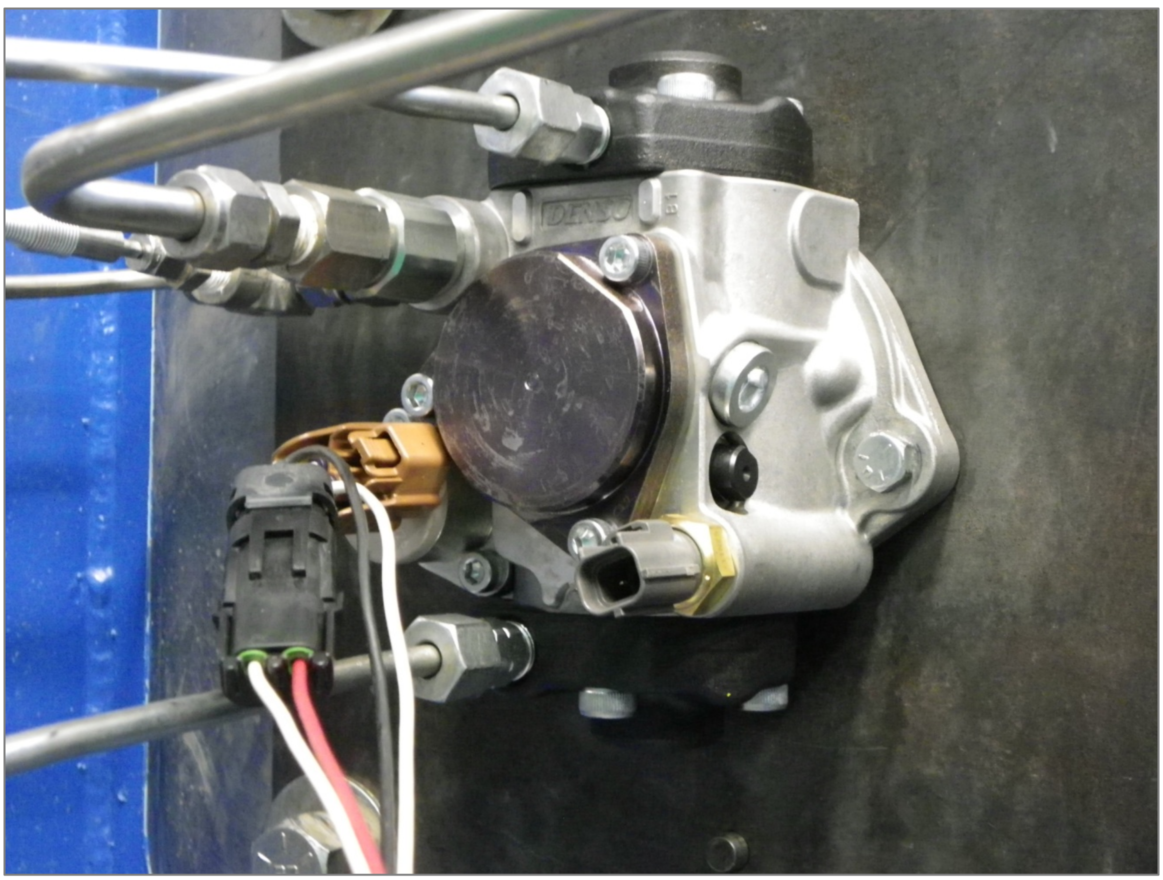


Figure 1. High Pressure Pump Assembly

Fuel enters the back of the pump and passes through a mesh filter before a low pressure pump driven by the rear of the internal camshaft. This area is shown in Figure 2, with the low pressure pump located under the blue-colored triangular cover.

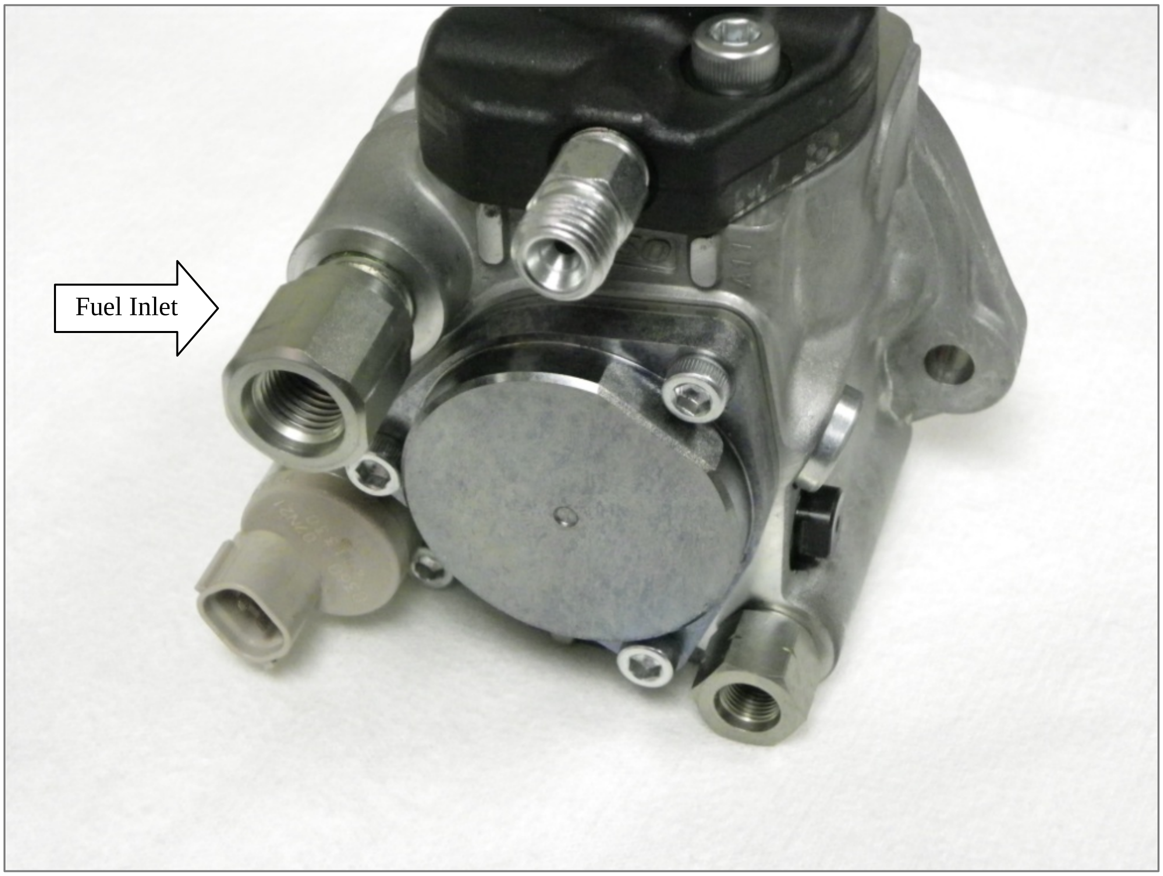


Figure 2. Low Pressure Pump Cover

The pump operates by rotating a gear within a ring on an offset centerline. As the camshaft turns the gear, the gap between the ring and gear opens allowing fuel to fill this space. Continuing through the rotation, the fuel is isolated from the inlet source and the ring-gear gap begins to decrease, forcing fuel through the outlet and pressurizing the pump body. This is illustrated in Figure 3.

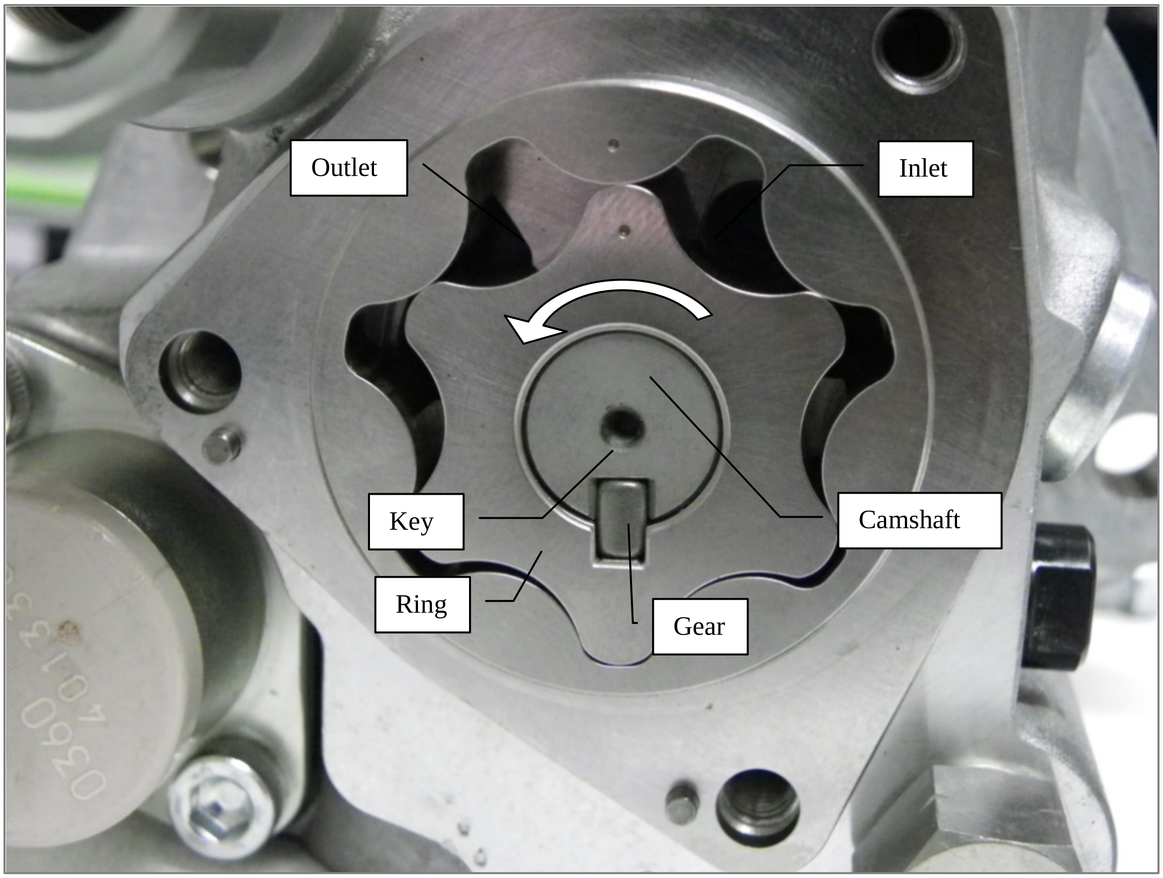


Figure 3. Low Pressure Pump

Once fuel passes the low pressure pump, it is fed either to the high pressure plungers or the main pump body for lubrication and cooling use. Some of the components which are fuel lubricated include the pump camshaft, ring cam, and thrust washers shown in Figure 4.

Figure 4. Fuel-lubricated Pump Components

Two thrust washers are utilized in the pump, one shown here, between the ring cam and pump body. The camshaft features an eccentric lobe to drive the plungers that produce high pressure fuel. This is illustrated in Figure 5. The distance each plunger protrudes into the pump body should be noted, along with the location of the ring cam in relation to the chamber walls.

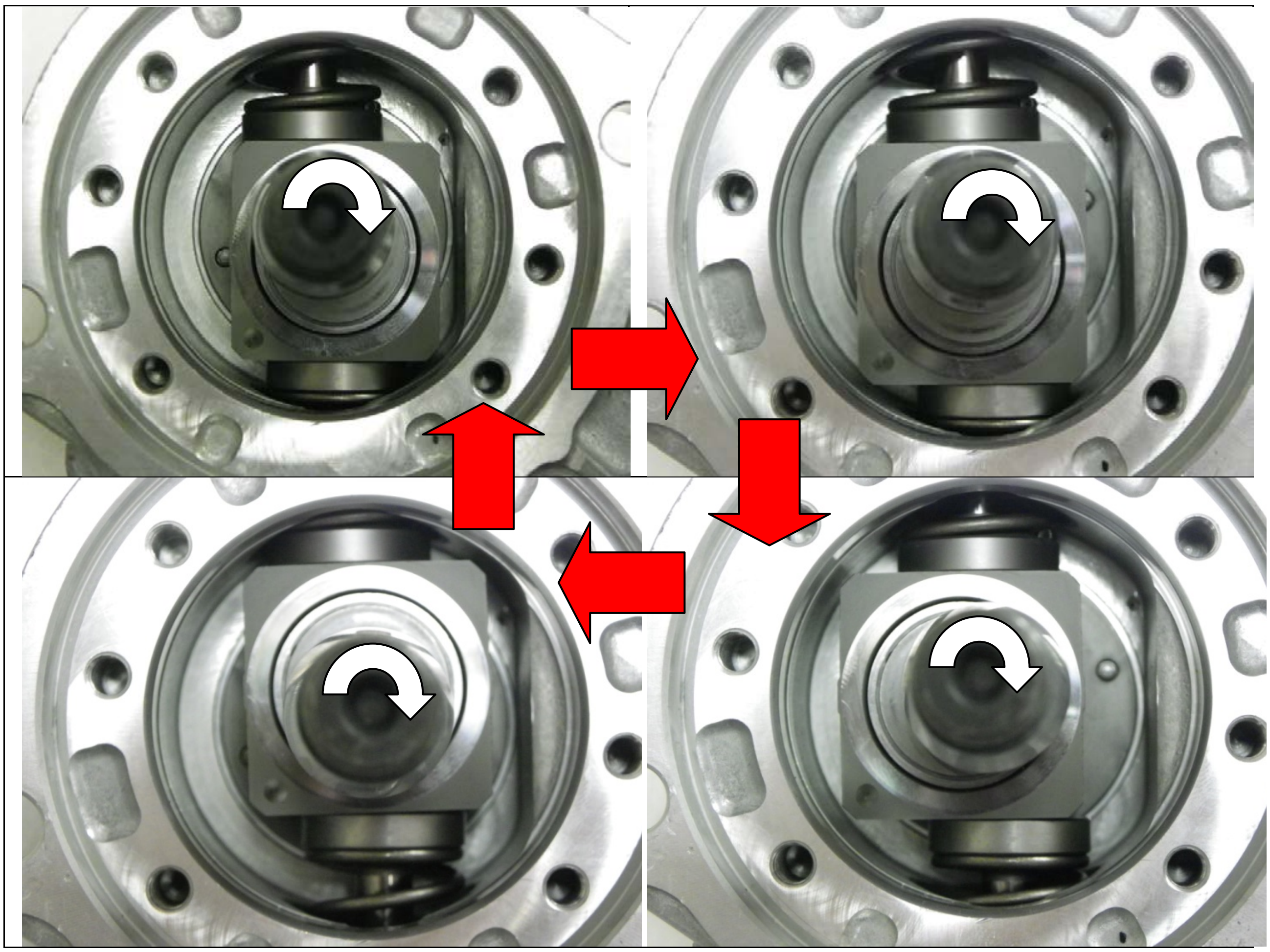


Figure 5. Rotation of Eccentric Lobe and Ring Cam

Each plunger is guided within a pump head containing a series of check valves to ensure correct flow direction. Fuel pressurized by the low pressure pump is forced into the chamber of the head on the plunger down-stroke. Once the compression stroke begins, and internal pressure rises, an inlet check valve closes preventing fuel from returning to the pump body. As the plunger drives up, an outlet check valve opens once the internal pressure exceeds that of the fuel rail. The plunger continues to drive up, forcing more fuel to the rail until the end of the stroke. At this point, the outlet check valve will close, maintaining rail pressure, and fuel will be able to flow back into the chamber once the internal pressure falls below that of the supply fuel. To ensure the plunger retracts to allow fuel to fill the chamber, and to maintain contact with the ring cam, a spring is located in-between it and the pump head. This is shown in Figure 6.

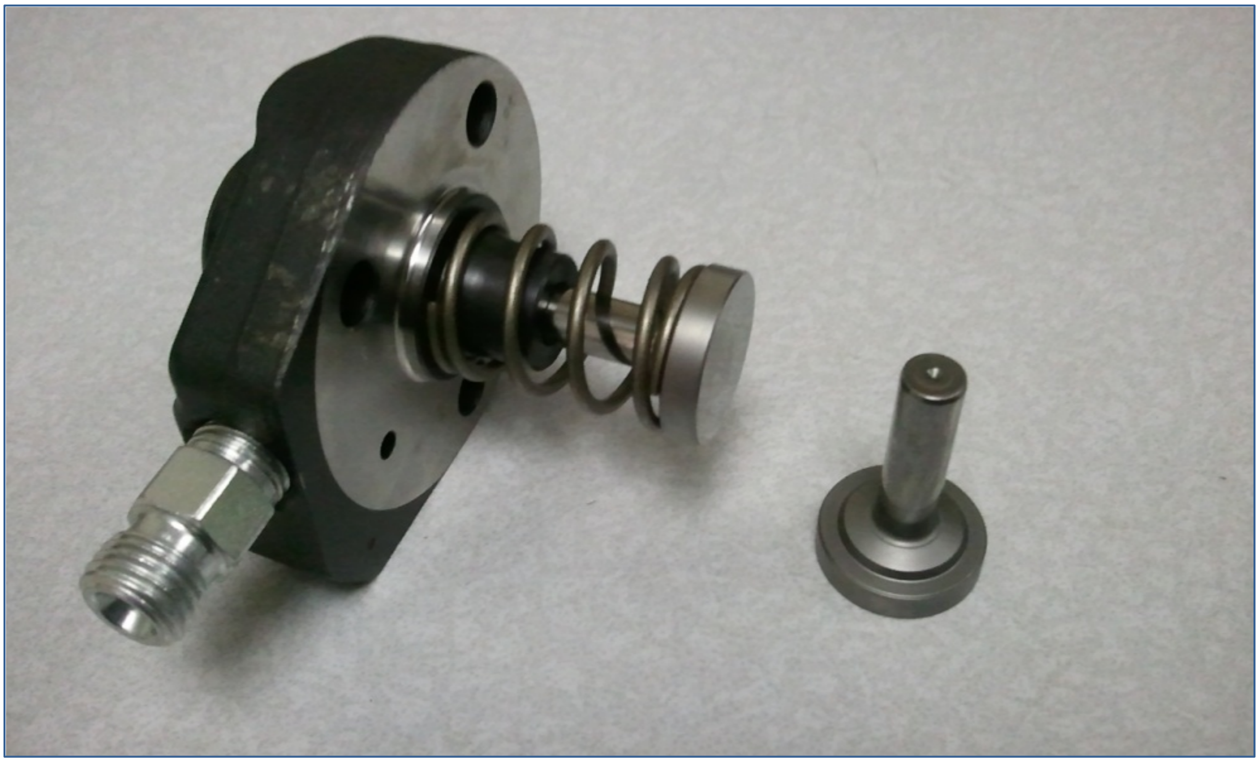


Figure 6. High Pressure Pump Head and Plunger

Prior to the entering the high pressure pump heads, fuel is metered through a control valve which acts as a safety cut-off and rail pressure control. The ECM sends a pulse-width modulated signal to this valve, allowing it to open as increased fuel rail pressure or fuel flow are required. If power were lost to the vehicle, this valve would close, resulting in engine shut down. This valve can be seen in the lower left-hand corner of Figure 2.

From the injection pump, fuel is supplied by two high pressure lines to the common rail, shown in Figure 7 installed on the test stand.

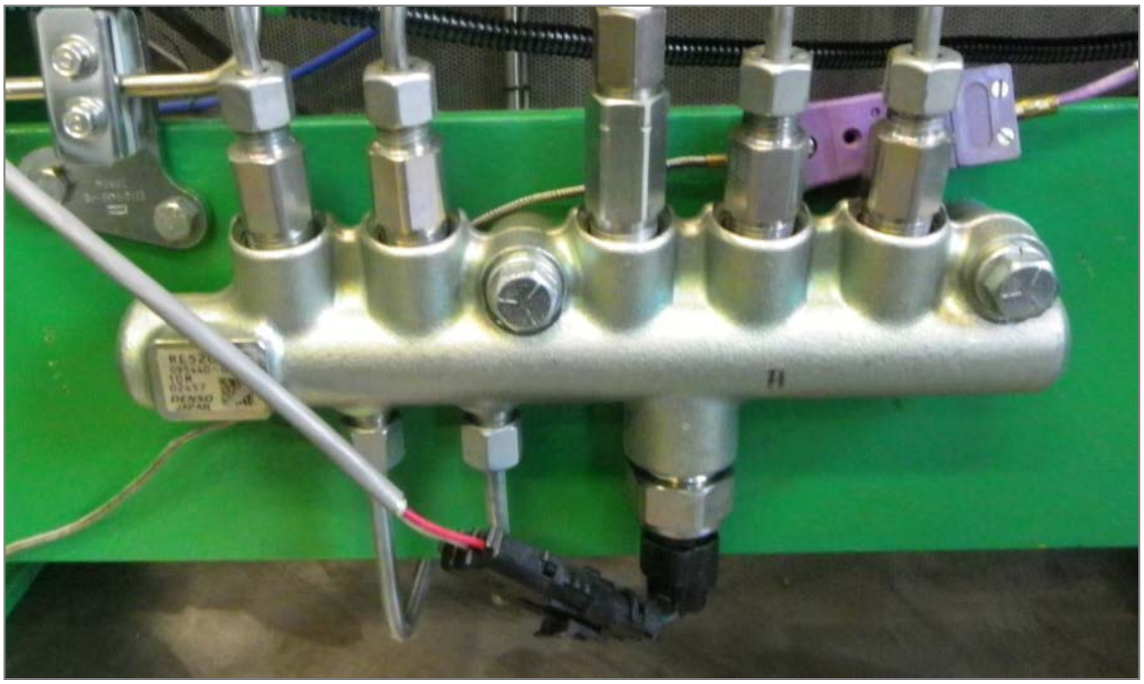


Figure 7. Common Fuel Rail

The rail acts as an accumulator to maintain a constant pressure fuel supply to each injector. It features an over-flow prevention valve on each injector line. In the case of an injector failure in an open state, the pressure differential due to high flow rate causes a shut-off valve to close. This reduces the impact of a catastrophic failure from fuel spray and potential equipment damage to a loss of power due to cylinder cut out. The middle line located on top of the rail acts as an over-pressure relief safety valve. A pressure transducer located on the underside of the rail sends a signal to the ECM for control purposes.

2.4 FUEL INJECTORSS

Injectors for the system are a solenoid driven style, shown in Figure 8.

Figure 8. Fuel Injector

As the injector is actuated, the solenoid allows a sealing ball to lift and fuel to flow from the bottom of the injector to the top portion. This flow changes the pressure balance on the needle allowing it to lift and fuel to exit into the chamber. The design is very similar to that seen in other HPCR testing [4]. An expanded view of the internal components can be seen in Figure 9, with some damage due to disassembly visible. The solenoid is located at the top of the figure with the needle directly below it at the bottom. The intermediate components consist of sealing plates and actuation pins that allow for precise control of needle lift.

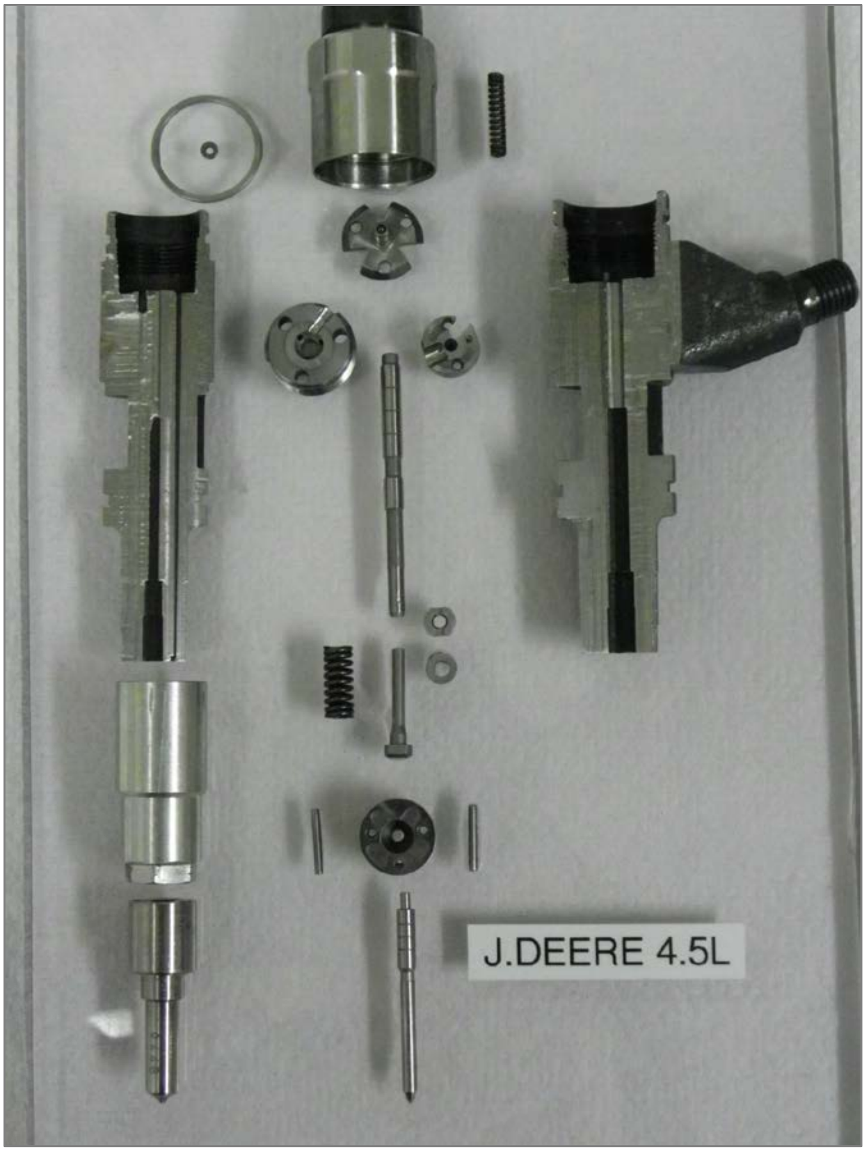


Figure 9. Injector Components

2.4.1 Stand Configuration

Fuel was routed through system components in a similar path as would occur on an engine. Where possible, production parts were used to maintain a realistic evaluation of the fuel system. Figure 10 provides an visual of the major component installation.

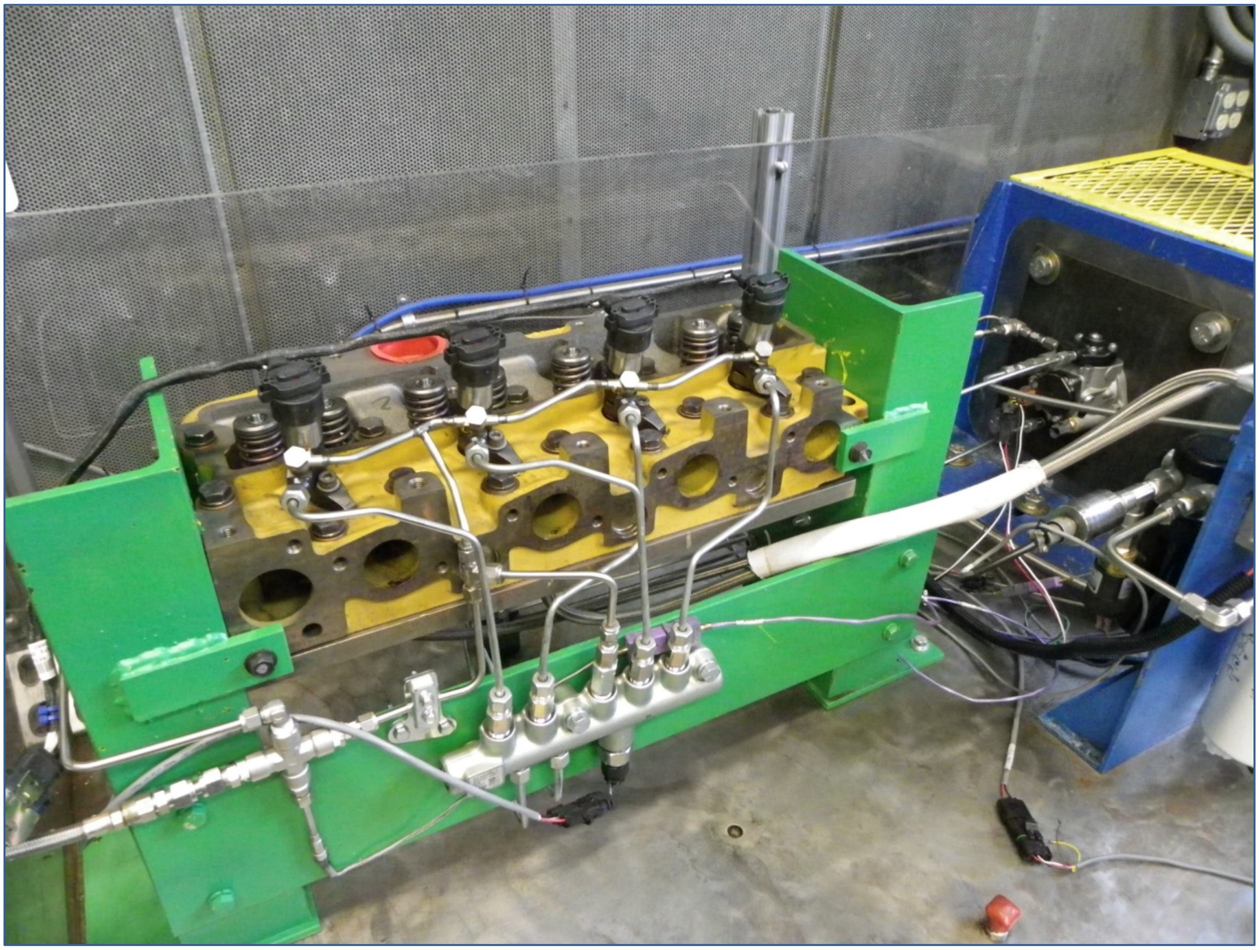


Figure 10. Test Stand Configuration

A production cylinder head was utilized for injector placement. This allowed for the injector supply and return fuel lines to be obtained off-the-shelf as well. A fixture was created to hold the cylinder head and fuel rail. The rail was supplied by two custom high pressure lines due to the orientation of the high pressure pump. Injected fuel was collected by a machined plate mounted under the cylinder head using a head gasket to provide sealing. The full flow layout for the system is shown in Figure 11.

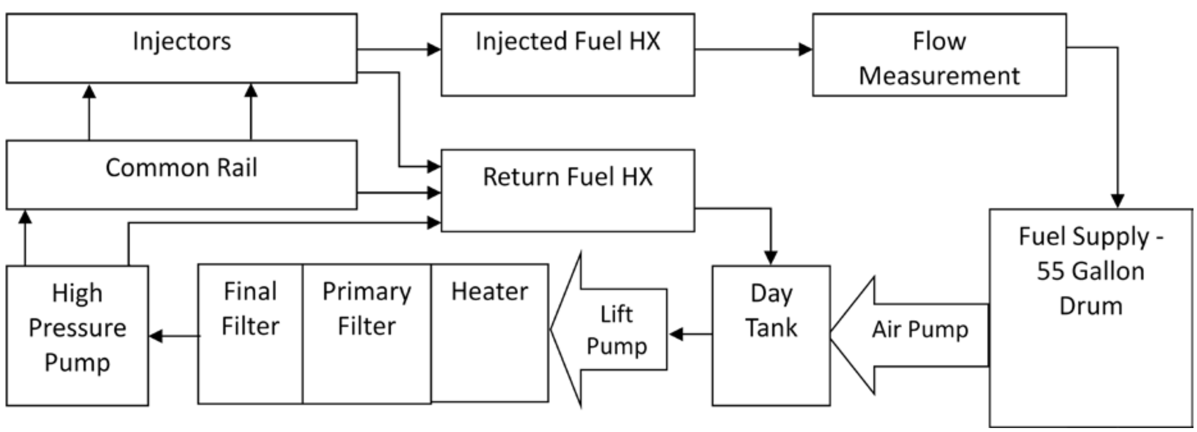


Figure 11. Fuel Flow Layout

2.4.2 Test Components

For each test the fuel pump, injectors, and fuel filters were replaced. 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 fuel source. Every 100 hours of test time, or 10 cycles, the drum was sampled and replaced with a fresh fuel drum.

3.0 EVALUATION RESULTS

Individual test reports can be found for each evaluation attached as Appendices B through G.

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 that completed the full 400 hours. Data logging was conducted 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. Information on evaluations which experienced early termination follows. Data shown prior to pump failure is at a rate of 10Hz from the end of NATO Step 4 (75% speed, full throttle) through pump failure during Step 5 (alternating idle and rated conditions). Included with the failed tests is the performance of the 82.8°C blended fuel test with 22.5 ppm DCI-4A for comparison purposes.

3.1.1 Completed Test Rail Pressure

The rail pressure for the six tests which completed all 400 hours of the NATO cycle is shown in Figure 12.

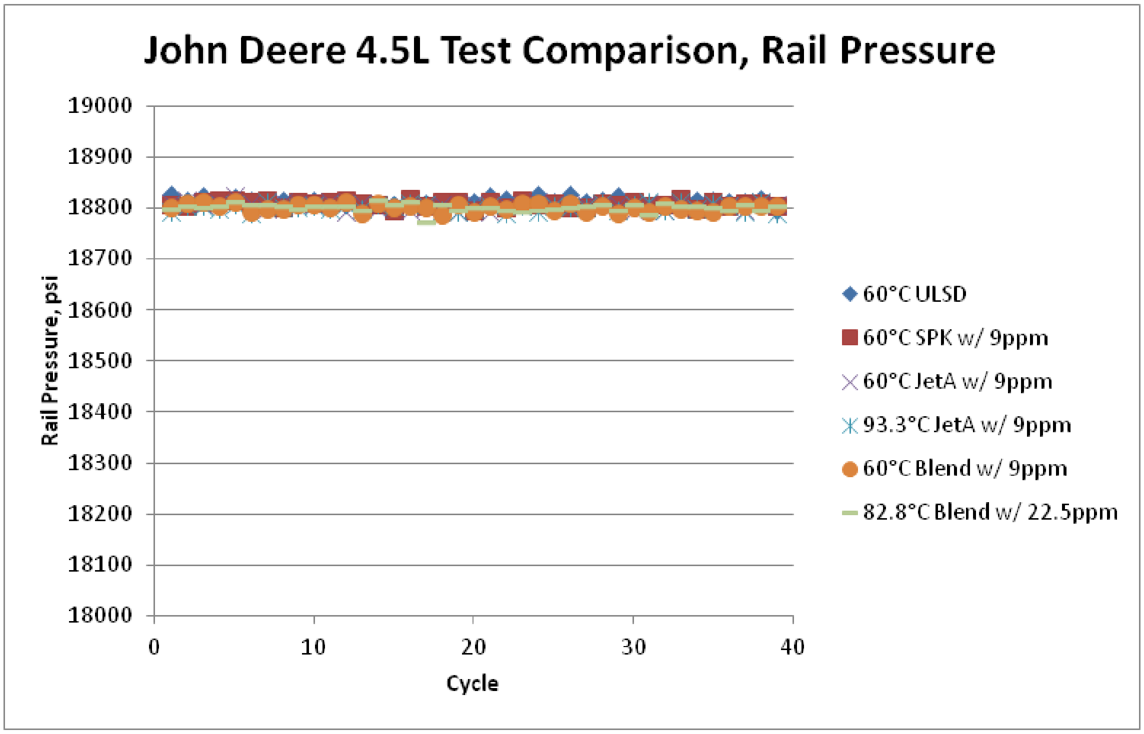


Figure 12. Completed Test Rail Pressure

Rail pressure was controlled by the ECM throughout testing. The 0-5V signal from the OEM pressure transducer was also monitored by the test stand data acquisition system. At no point during the tests shown did the rail pressure deviate in a way that would indicate an impact on system performance. Since the rail acts as a buffer between the pump and injectors, monitoring its pressure may be a better indication of ECM functionality than small changes in hardware performance due to wear. If an injector were to fail and stop drawing fuel, the ECM would be able to reduce the metering valve output in the pump to control the rail pressure at the desired value. However, a substantial loss of pump output, or supply line failure, would be noticeable in the rail pressure once the maximum metering valve output had been requested by the ECM.

3.1.2 Completed Test Pump Supply Filter Pressure

The supply filter pressure for the six tests which completed all 400 hours of the NATO cycle is shown in Figure 13.

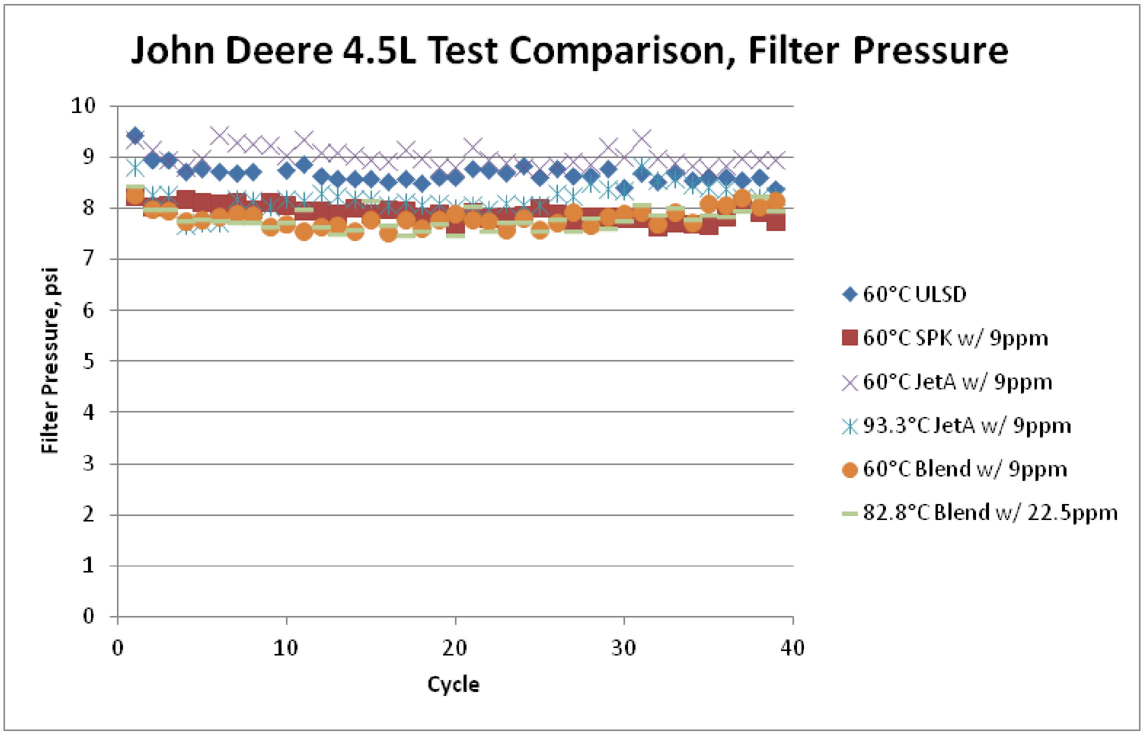


Figure 13. Completed Test Pump Supply Filter Pressure

The inlet filter pressure was measured prior to the final high-efficiency fuel filter. This pressure was created by the electric lift pump which provided fuel through the temperature control equipment. Factors which impact this value are leakage within the pump or injectors, return fuel flow rate, injected fuel flow rate, and filter plugging. The slight decrease in pressure seen over the first four to five cycles of each test is likely an effect of component break-in. Initial pressure variation from test to test is within the range that could be expected with new production filters and hardware.

3.1.3 Completed Test Injected Fuel Flow Rate

Injected fuel flow rate for the six tests which completed all 400 hours of the NATO cycle is shown in Figure 14.

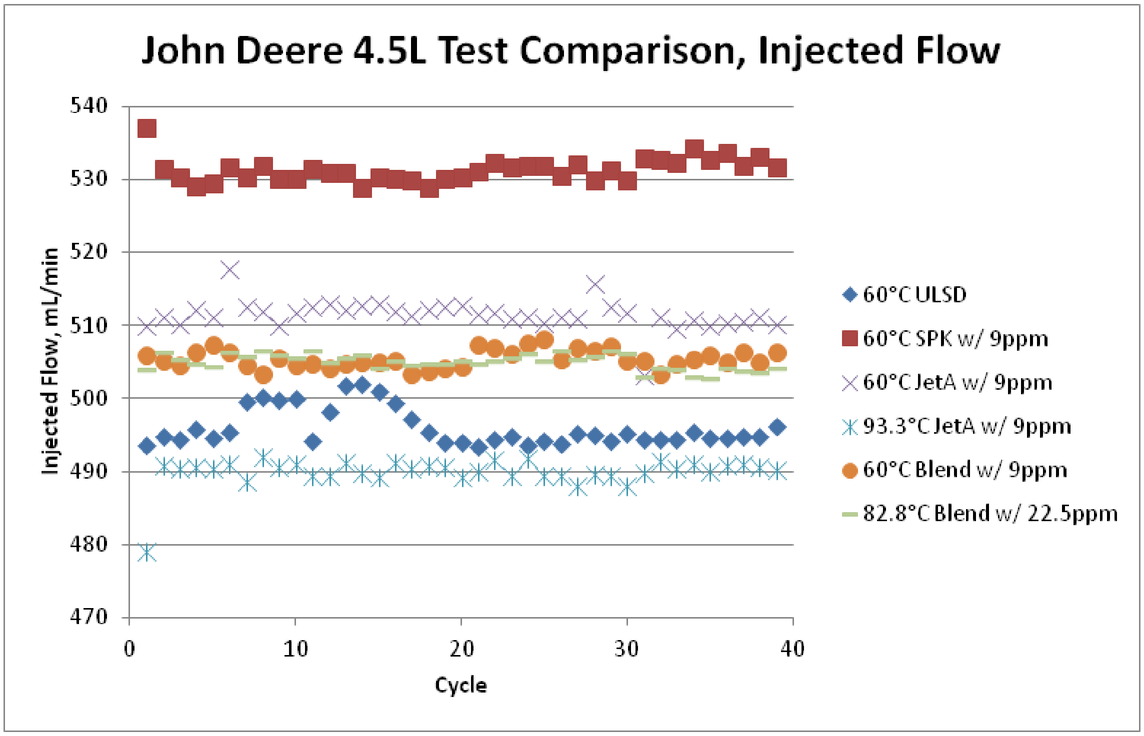


Figure 14. Completed Test Injected Fuel Flow

Some minor mid-test variation was seen in the injected fuel flow rate during the ULSD test. Two other instances of this were seen during the 60°C Jet A evaluation, however all variation was within a 1.8% band of the total flow rate. When taking into account the type of change in flow rate previously noted when injector failure occurs, the variation noted here does not appear to be due to a serious change in hardware condition. The solenoid driven injectors appears to be robust with regards to the fuels shown and maintain a stable flow rate through the 400 hour evaluations. In previous testing, the lighter density and lower viscosity fluids have at times shown a tendency for increased flow rates compared to ULSD in HPCR systems. This is believed to be due to passing through the small diameter injector holes at a higher rate while the needle is held open for a constant time interval. As seen in Figure 14, the elevation of temperature, and therefore reduced density and viscosity, for both Jet A and Blended fuels did not result in increased flow.

For the higher temperature Jet A test, the flow rate unexpectedly decreased. The most likely explanation for this was differences in production hardware.

3.1.4 Completed Test Bypass and Return Fuel Flow Rate

Return fuel flow rate for the six tests which completed all 400 hours of the NATO cycle is shown in Figure 15.

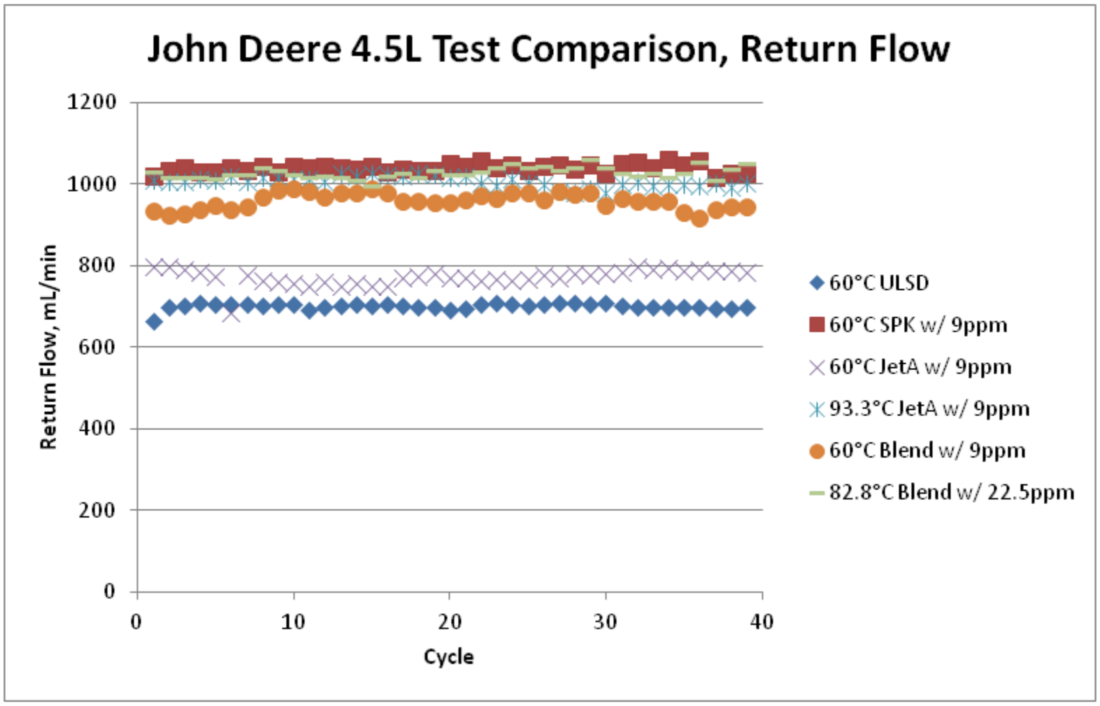


Figure 15. Completed Test Return Fuel Flow Rate

Return fuel flow, unlike injected rates, showed a tendency for lower density and viscosity fuels to produce elevated values. A large component of the return fuel is what flows from the high pressure pump. This fuel is used for both lubrication of sliding surfaces as well as a cooling fluid. The lower viscosity fuels are able to flow through the clearances within the pump and injector returns at an increased rate. A lower point at Cycle 6 for the 60°C Jet A evaluation was due to a faulty temperature controller, an issue which was corrected prior to the next cycle. Additional cooling impacted the measured volumetric flow rate of fuel returning to the stand tank.

3.1.5 Completed Test Drive Motor Power Output

The required electrical power for the motor to drive the high pressure pump for the six tests which completed all 400 hours of the NATO cycle is shown in Figure 16.

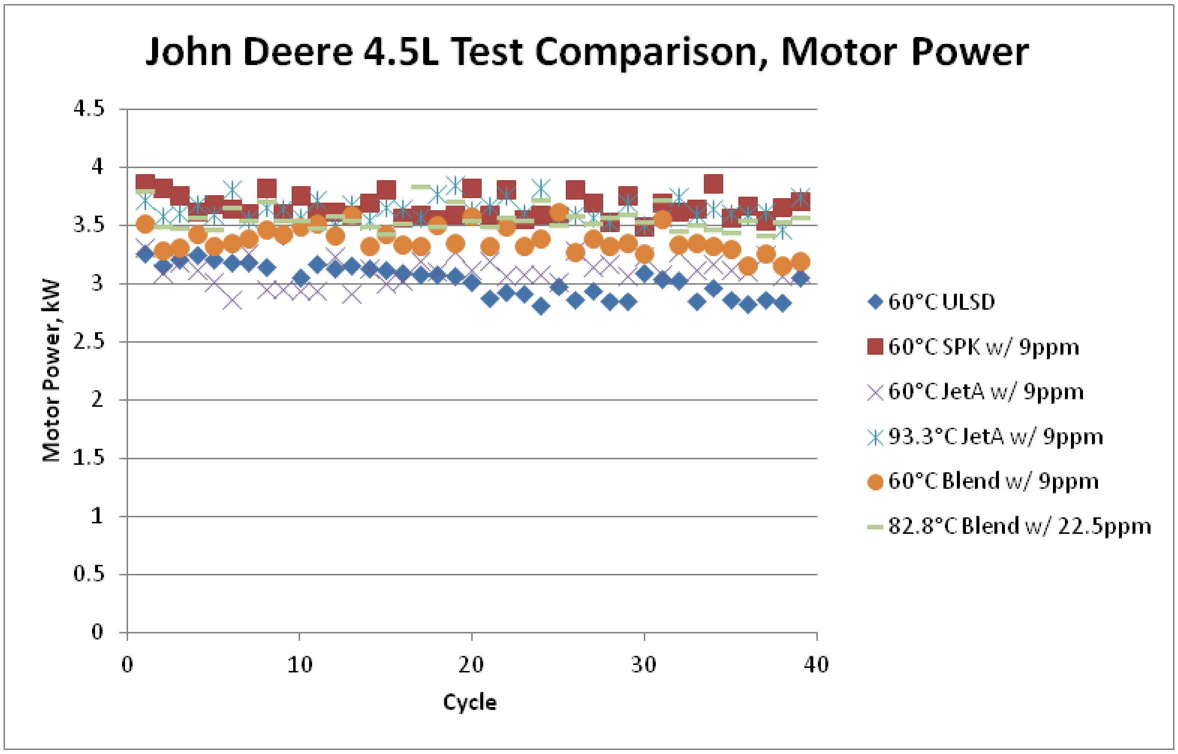


Figure 16. Completed Test Motor Power Output

The motor power parameter was a function of the total fuel flow rate, rail pressure, input fuel pressure, and frictional losses in the pump. Provided by the Variable Frequency Drive (VFD), there was a higher than desired level of noise in the signal due to the cyclical pulsations of the high pressure pump. While there are likely some drivetrain inefficiencies not accounted for in coupling VFD output energy and pump input power, it can be assumed that these remained consistent through each test. Based upon rail pressure stability previously noted, Figure 12, it can be expected that power changes seen are primarily influenced by fuel flow rates and frictional wear in the pump. While there was a consistent decrease in power required between the first and second cycles of each test, it is difficult to establish a meaningful trend of increasing or decreasing power requirement over the test duration.

3.1.6 Test Failure Modes

The first fuel to experience a failure of the high pressure pump was the 93.3°C SPK with 9 ppm DCI-4A. When a failure occurs, of which the physical process is discussed in section 3.4, the data acquisition system stores the information immediately preceding a shutdown at a rate of 10Hz rather than the slower logging rate commonly used for durability testing. This allows for post-failure analysis at an improved resolution. Figure 17 shows this data from the first pump using 93.3°C SPK with 9 ppm DCI-4A.

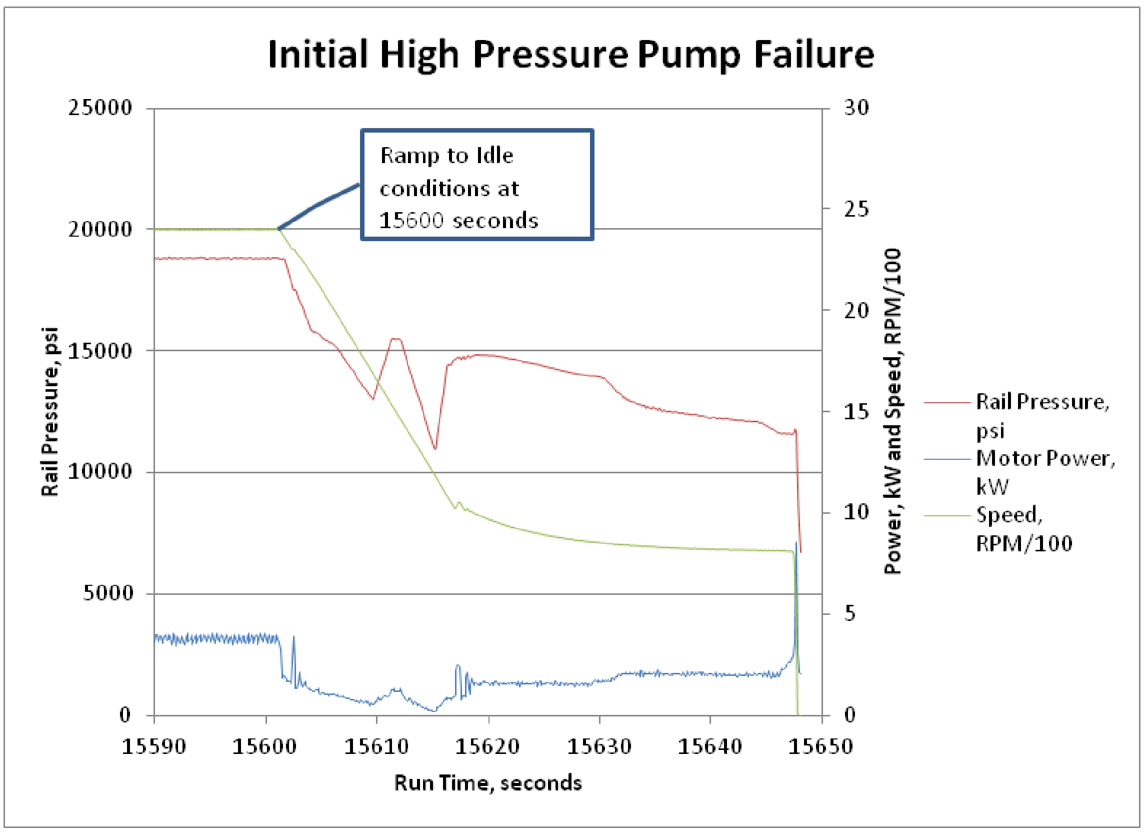


Figure 17. Initial High Pressure Pump Failure

Data shown is for Step 5 of the NATO Cycle, four minutes of idle conditions followed by six minutes of rated conditions with a specified moving command of three seconds. While the command was over three seconds, controller lag within the VFD and the rotational inertia within of the system flywheel result in a change of speed much slower than this. Between 15640 and 15650 seconds, the motor power can be seen to spike as the speed rapidly dropped. The rail pressure follows the loss of speed as no additional fuel was being imparted to the rail. Following this test, being the first failure witnessed, it was decided to replace the high pressure pump and restart testing with the same fuel as a confirmation of the problem. A similar failure occurred which is shown in Figure 18.

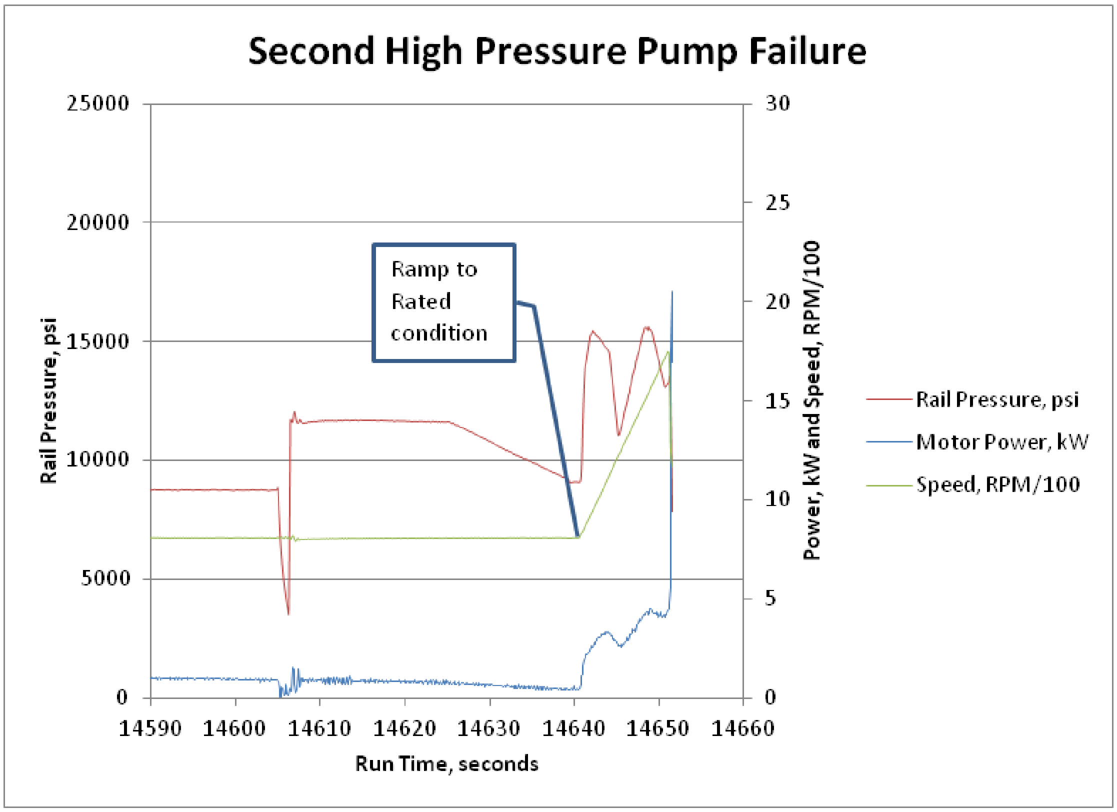


Figure 18. Second High Pressure Pump Failure

Unlike the first failure, the second pump stopped functioning during the ramp from idle to rated conditions. This occurred the first time through the idle to rated cycle of Step 5, where the first pump was able to complete two full cycles. One indication of system issues can be seen at around 14605 seconds. There is a rapid loss of rail pressure followed by an increase and slow return to normal pressure (~8000 psi for idle condition) prior to the ramp. Once the ramp command was given, speed was increased by the VFD, but never reaches the full rated speed of 2400 rpm. As the pump speed passed 1700 rpm, the motor power rapidly rose from near 4kW to a briefly measured peak of 20kW before catastrophic pump failure occurred. At this point, it was confirmed that the pump failure was not an isolated event and should be considered valid. Following this, each fuel was tested to failure in one pump prior to a test change rather than confirming the result using a second assembly. Safety shutdowns were incorporated into the test programming in an effort to stop the VFD when output power was measured above 4.5kW. This, in some cases, prevented component destruction which can be seen in Figure 22.

3.1.7 Failed Test Motor Power

The required electrical power for the motor to drive the high pressure pump for the tests resulting in premature failure of the high pressure pump are shown in Figure 19 along with the final 50/50 blend evaluation with 22.5 ppm DCI-4A at 82.8°C for comparison. Data shown is at a rate of 10 Hz immediately prior to failure, and at one log per minute aside from that.

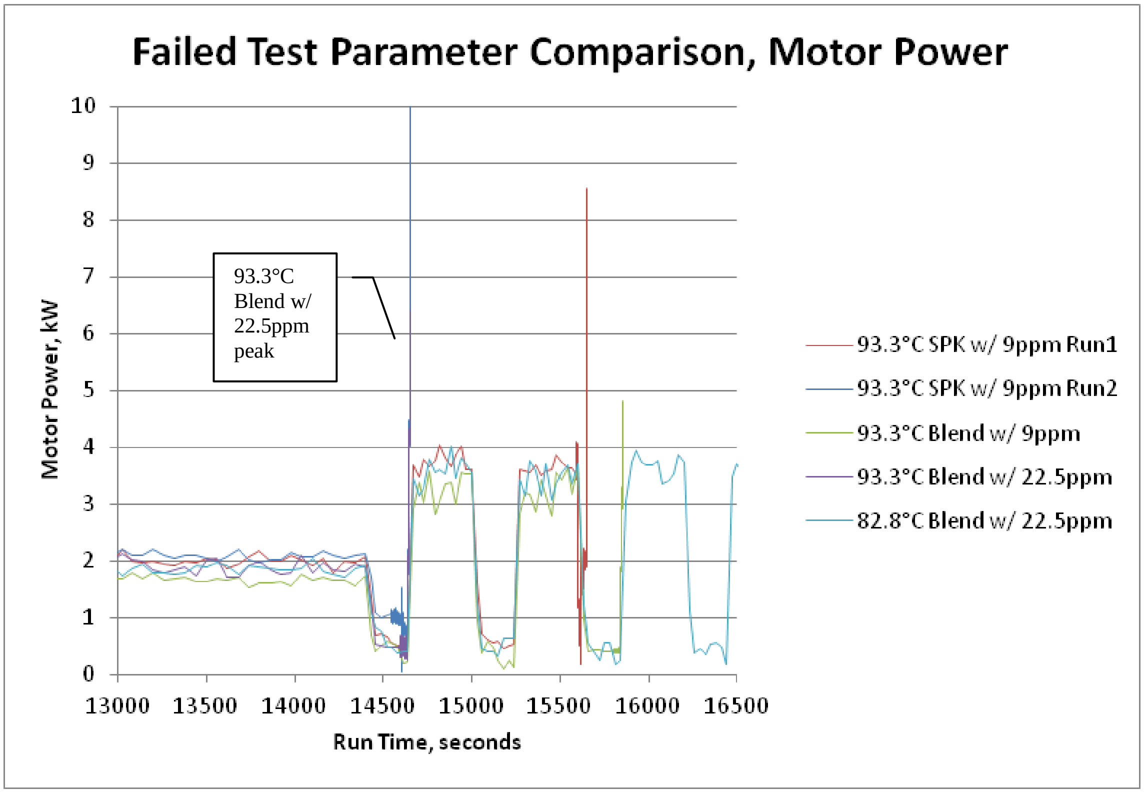


Figure 19. Failed Test Motor Power

Through 14400 seconds of Run Time, the data shown is for Step 4, full throttle and 75% speed. Following this the program enters Step 5 as previously described. Aside from the first 93.3°C SPK with 9 ppm DCI-4A test, each pump failed while ramping from idle to rated conditions, and all within the early stages of the same step. The 20 minute window within which failures occurred represents 0.083% of the 400 hour cycle. Prior to failure, each system showed consistent power requirements through the end of Step 4.

3.2 LOW PRESSURE PUMP HOUSING

Figure 20 shows the condition of the low pressure pump housing at the end of each test.

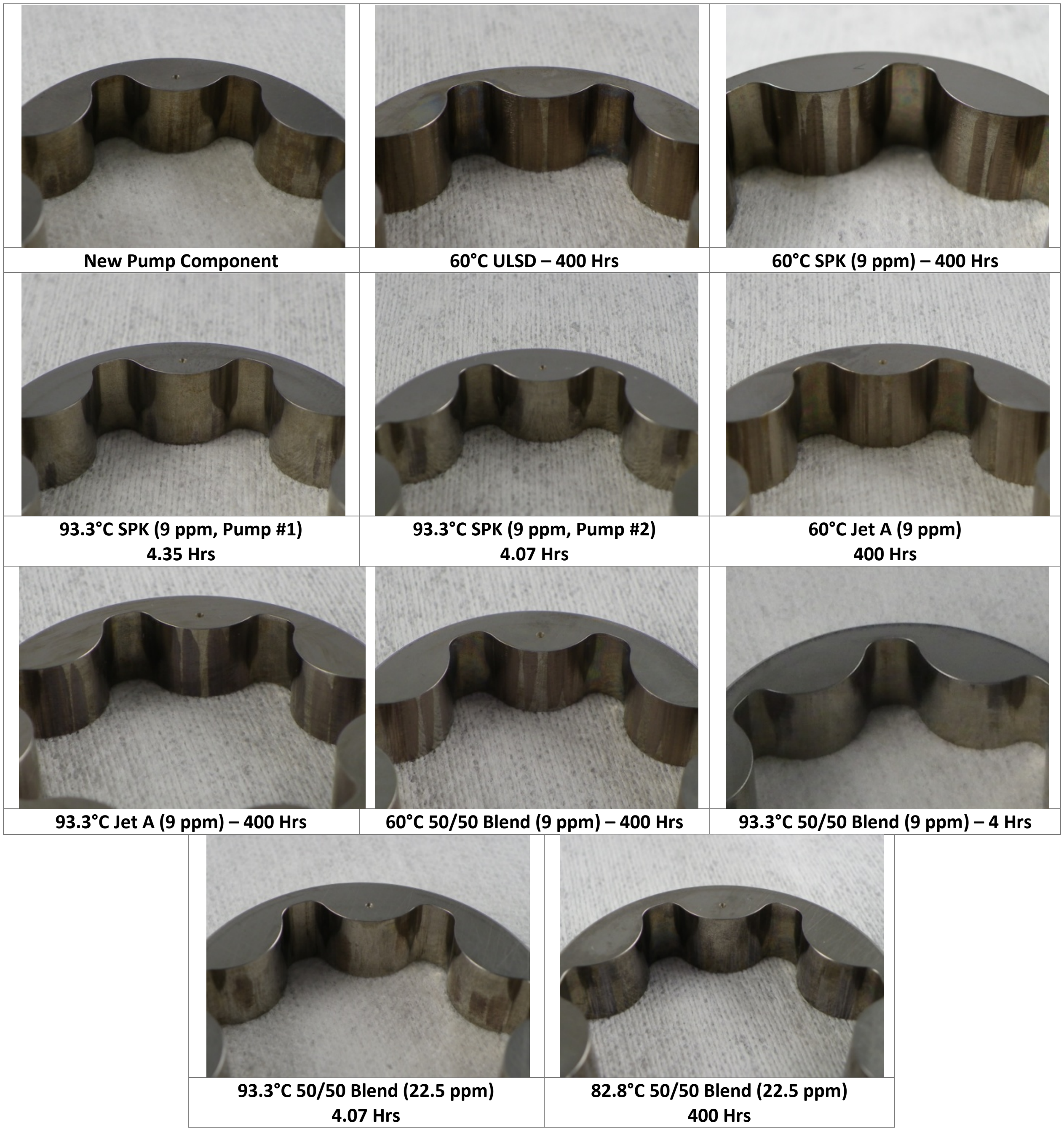


Figure 20. Low Pressure Pump Housing

Each test that completed the full 400 hours of operation showed some amount of wear on the pump ring. Based upon appearance, the ULSD and high temperature Jet A with 9 ppm DCI-4A tests showed the largest wear patterns. Despite a limited number of operational hours, there were well developed areas of wear on a number of the failed tests as well. While the pumps typically failed in a somewhat dramatic fashion, the marks visible do not appear to be due to heavy shock loading or impact. In no instance were the components shown difficult to remove from the pump at the end of test. Existing in a relatively low pressure area of the pump, it would not be expected that this component would suffer major damage over time or be the initial cause of pump failure with the use of poor lubricity or viscosity fluids.

3.3 LOW PRESSURE PUMP GEAR

Figure 21 shows the condition of the low pressure pump gear at the end of each test. The condition of the low pressure pump gear matched closely with that of the housing ring. In this case, even the unused component has some very minor signs of wear, likely due to a performance check following manufacturing. Again, the duration of test appeared to be the driving factor for the formation of a pronounced wear scar. There is wear visible along the side face of the gear, however this appears to be minor compared to the marks on the tooth edges. With continued operation and wear, this location has the potential for impacting pump performance. While the curved profile of the gear teeth limit the risk of tooth failure due to loading, at some point the wear present may result in seizure of the pump ring around the gear. This failure mechanism would result in either overwhelming load placed on the pump camshaft, or a failure of pump housing integrity. Another possible result of further wear would be excessive leakage from one chamber to the next as the ring rotates. Within insufficient sealing, the fuel would not be properly pressurized and forced into the main pump body or high pressure areas. This might result in a loss of desired rail pressure and inadequate lubrication and cooling of pump components.

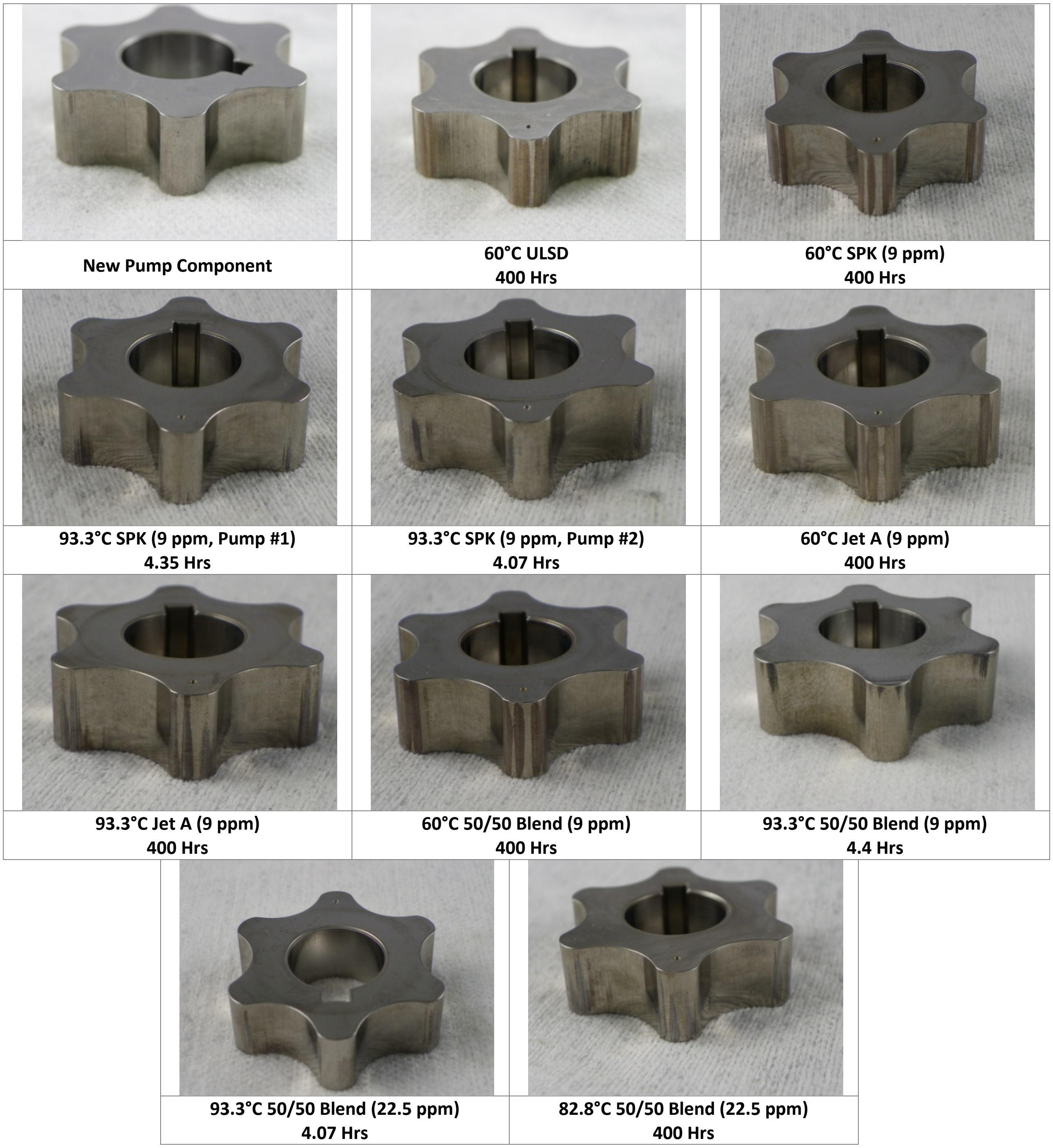


Figure 21. Low Pressure Pump Gear

3.4 UPPER PLUNGER FACE

Figure 22 shows the condition of the upper plunger face at the end of each test.

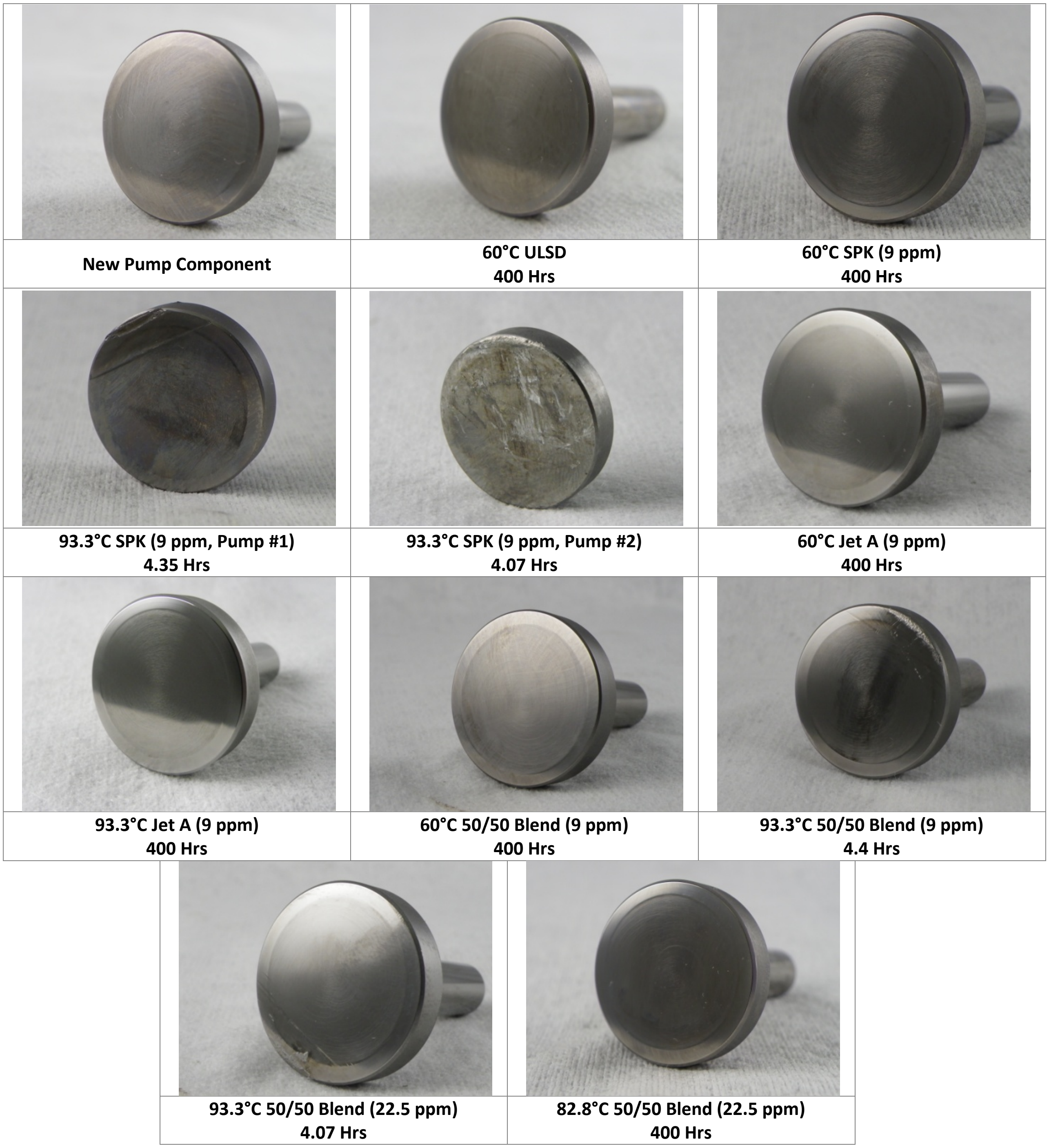


Figure 22. Upper Plunger Face

This surface is the contact location between the high pressure plunger and the ring cam. Components shown for the 93.3°C SPK tests are lacking the plunger shaft visible for the other tests. In these instances, the shaft snapped off within the pump head and the section of the component visible was able to move freely in the main pump housing. Damage on the edge of the slider can be seen for all testing the prematurely ended. This is the result of the ring cam seizure on the cam shaft causing it to produce all contact forces at the corner edge. This is illustrated in Figure 23.

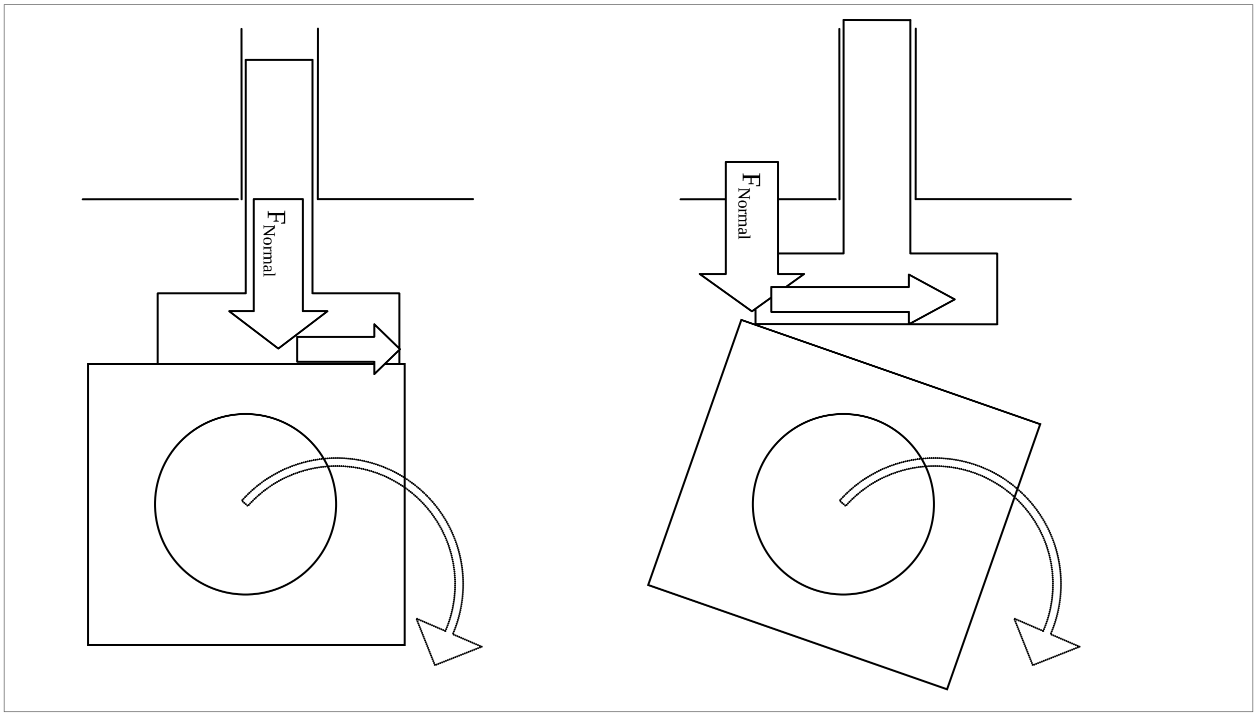
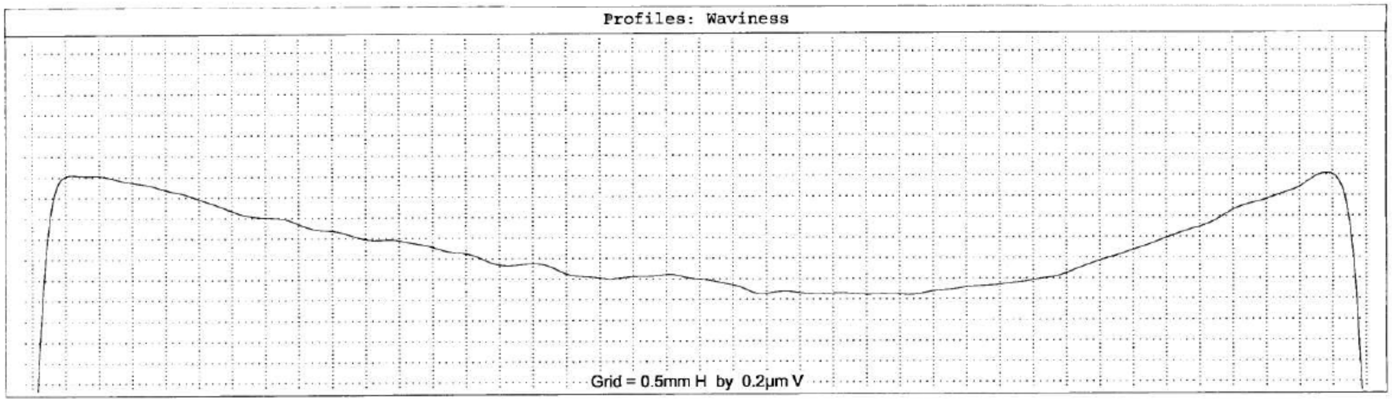


Figure 23. Plunger Failure

The ring cam rotation, Figure 5, would cease to occur in the proper orientation with full contact between the flat, sliding surfaces (shown on left). When all contact forces were transferred through the outer edge of the plunger (right), this caused the head to snap off. Under typical operation, the normal force acting between the two surfaces is a combination of spring force, sliding friction along the plunger shaft, and rail pressure that must be overcome to force fuel from the pumping chamber. The side loading is the result of the friction produced by this normal force and the coefficient based upon surface finish of the plunger head and ring cam using the fuel as a lubricant. These forces are spread over the entire contact area and reduce effects of imbalanced loading as the plunger travels through the pump head. In the case of component failure, the entire contact area had moved to one edge of the plunger head.

While appearing flat, the surface of the plunger face has a small amount of concavity which allows for a pocket of fuel to be maintained between it and the ring cam. Profile traces for the unused, ULSD and high temperature Jet A evaluations can be seen in Figure 24, Figure 25, and Figure 26. Since no pre-test measurements are available for the two components that underwent 400 hours of testing, it is difficult to determine if there is a loss of concavity over the course of the test. While the ULSD component shows a larger measure distance of vertical change than the high temperature Jet A test, the unused part falls in-between the two indicating that manufacturing tolerances be the largest contributor to the amount of concavity measurable on each part. For the used components, there exists a high level of horizontal symmetry as well as a lack of flattened areas on the outer edges, both of which would be possible effects of long-term wear. This indicates that the plunger may have been the harder of the two components under contact and not expected to suffer surface wear.

SWRI- UNIT # 1



Settings

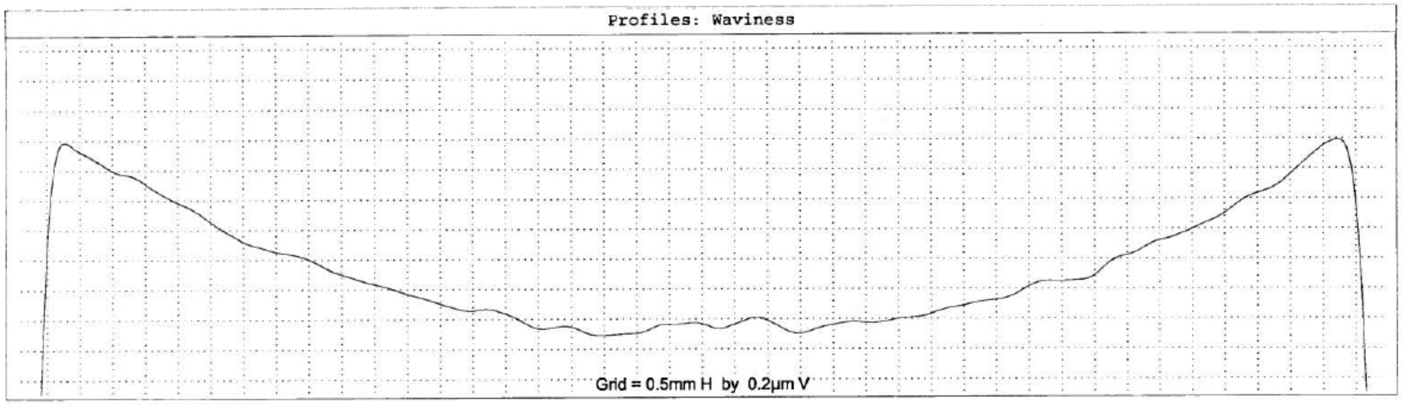
```
Software: 2.46; Advanced; 3.95
Data
  Collected: Fri Dec 14 07:38 2012
  By: Kerry McCubbin
  At: SWRI- UNIT # 1
  Tracer Used: PDT-2-522
  Sampled Length: 22.78 mm
  Sample Spacing: 0.48 µm
Description
  Unused Plunger Face
  *
  *
  File: C:\S-2000-2\DATA\MISC\PLUNGER.001
Instrument
  Name: MicroAnalyzer 2000
  Serial #: S-2000-3027
  Current Tracer:PLT-2-522
  Travel Distance: 22.78 mm
  Trace Velocity: 0.75 mm/s
Form
  Form Type: Two-Point Line
Roughness Filter
  Type: Gaussian
  Cutoff: 0.80 mm
  No Filter Width Removal at Ends
Parameter Calculation Settings
  Peak Count Threshold: 0.50 µm
  High Spot Count Threshold: 0.50 µm
  tp Reference Percent: 5 %
```

Parameters

```
PARAMETER    VALUE     UNITS
---------    -----     -----
Summary
  Standards System = ANSI/ASME B46.1 1995
Waviness Parameters:
  Wt         1.18      µm
```

Figure 24. Unused Plunger Face

SWRI- UNIT # 1



Settings

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Data
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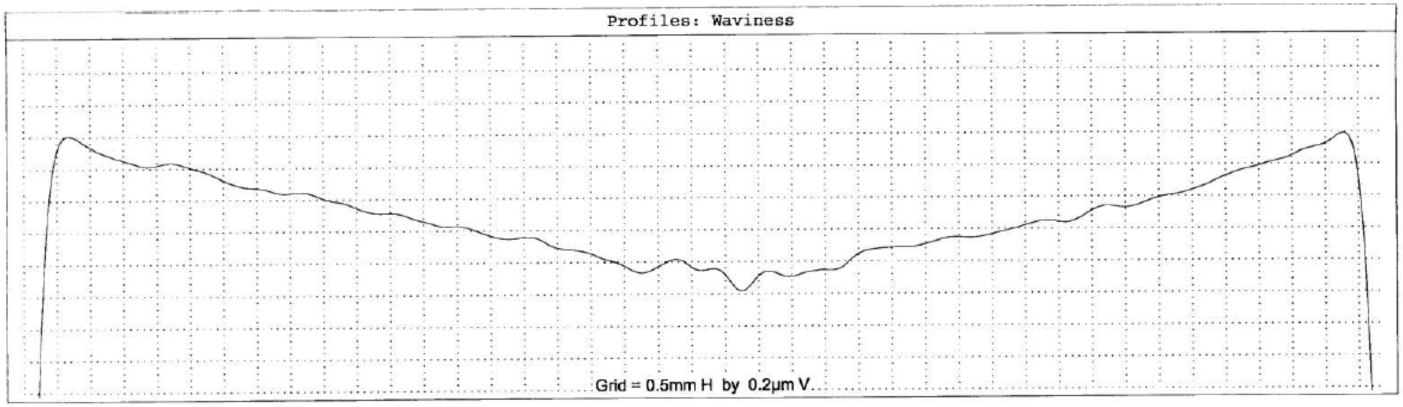
  By: Kerry McCubbin
  At: SWRI- UNIT # 1
  Tracer Used: PLT-2-522
  Sampled Length: 22.16 mm
  Sample Spacing: 0.48 µm
Description
  ULSD Plunger Face
  *
  *
  File: C:\S-2000-2\DATA\MISC\PLUNGER.002
Instrument
  Name: MicroAnalyzer 2000
  Serial #: S-2000-3027
  Current Tracer:PLT-2-522
  Travel Distance: 22.16 mm
  Trace Velocity: 0.75 mm/s
Form
  Form Type: Two-Point Line
Roughness Filter
  Type: Gaussian
  Cutoff: 0.80 mm
  No Filter Width Removal at Ends
Parameter Calculation Settings
  Peak Count Threshold: 0.50 µm
  High Spot Count Threshold: 0.50 µm
  tp Reference Percent: 5 %

Parameters

PARAMETER	VALUE	UNITS
Summary		
Standards System = ANSI/ASME B46.1 1995		
Waviness Parameters:		
Wt	1.30	µm

Figure 25. 60°C ULSD Plunger Face – End of Test

SWRI- UNIT # 1



Settings

Software: 2.46; Advanced; 3.95
Data
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  By: Kerry McCubbin
  At: SWRI- UNIT # 1
  Tracer Used: PLT-2-522
  Sampled Length: 21.43 mm
  Sample Spacing: 0.48 μm
Description
  HT JetA Plunger Face
  *
  *
  File: C:\S-2000-2\DATA\MISC\PLUNGER.003
Instrument
  Name: MicroAnalyzer 2000
  Serial #: S-2000-3027
  Current Tracer:PLT-2-522
  Travel Distance: 21.43 mm
  Trace Velocity: 0.75 mm/s
Form
  Form Type: Two-Point Line
Roughness Filter
  Type: Gaussian
  Cutoff: 0.80 mm
  No Filter Width Removal at Ends
Parameter Calculation Settings
  Peak Count Threshold: 0.50 μm
  High Spot Count Threshold: 0.50 μm
  tp Reference Percent: 5 %

Parameters

PARAMETER	VALUE	UNITS
Summary		
Standards System = ANSI/ASME B46.1 1995		
Waviness Parameters:		
Wt	0.99	μm

Figure 26. 93.3°C Jet A (9 ppm) Plunger Face – End of Test

3.5 UPPER RING CAM FACE

Figure 27 shows the condition of the upper ring cam face at the end of each test. All cases, regardless of fuel, experienced some level of wear on the ring cam faces which sliding contact occurred. The tests which ended prematurely have a noticeable mark on one edge. This matches the damage noted from the upper plunger sliding face. The wear at this location appears in some cases to be due to impact rather than sliding contact over time. As the plunger seized in its bore, or the ring cam seized onto the camshaft, the pump may have been able to complete a few cycles without proper contact between the two components. As the ring cam began upward travel, an impact may have occurred at this corner. Scoring across the face of the second 60°C SPK test with 9 ppm DCI-4A was due to debris in the pump body as the failure occurred. A contrast can be seen between the ULSD test and those conducted on the aviation and synthetic fuels. The condition of the ULSD ring cam face indicates that an adequate level of lubrication was maintained between the majority of the two surfaces. While there are signs of wear in the location the plunger reached at maximum horizontal travel of the ring cam, this mark is relatively minor compared to those formed by all other fuels. Even over the duration of the four hour long failed tests, component conditions indicate a high level of boundary contact resulting in the scuffing and grinding seen.

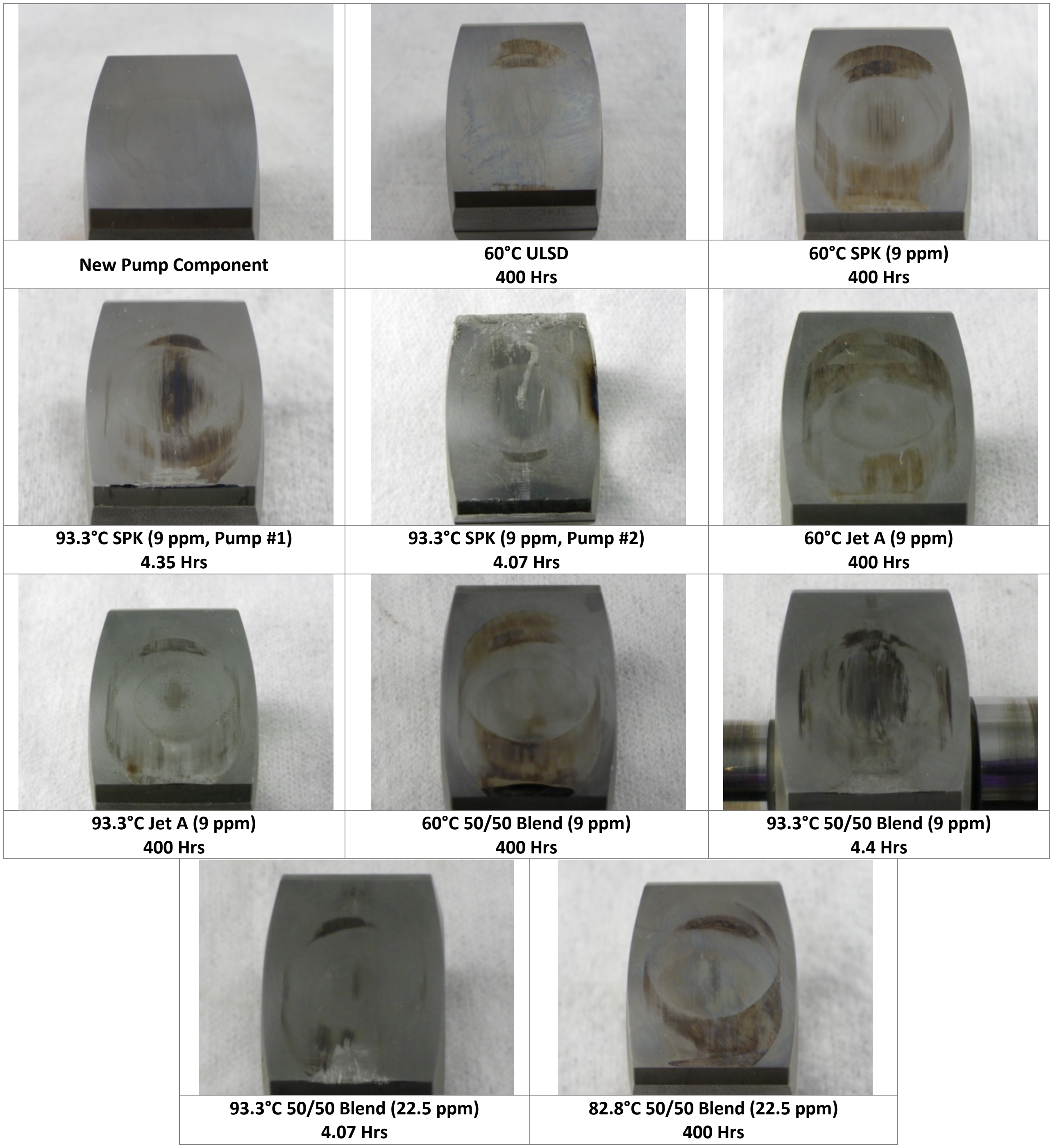


Figure 27. Upper Ring Cam Face

3.6 LOWER PLUNGER FACE

Figure 28 shows the condition of the lower plunger face at the end of each test. The condition for each component is very similar to that of the upper plunger. The exception to this are tests which experienced a cracked upper plunger shaft, an event which did not occur for any of the lower plungers. The gouging seen in the second iteration of the 93.3°C SPK test with 9 ppm DCI-4A is due to debris which formed in the pump body and were ground between the plunger and cam ring.

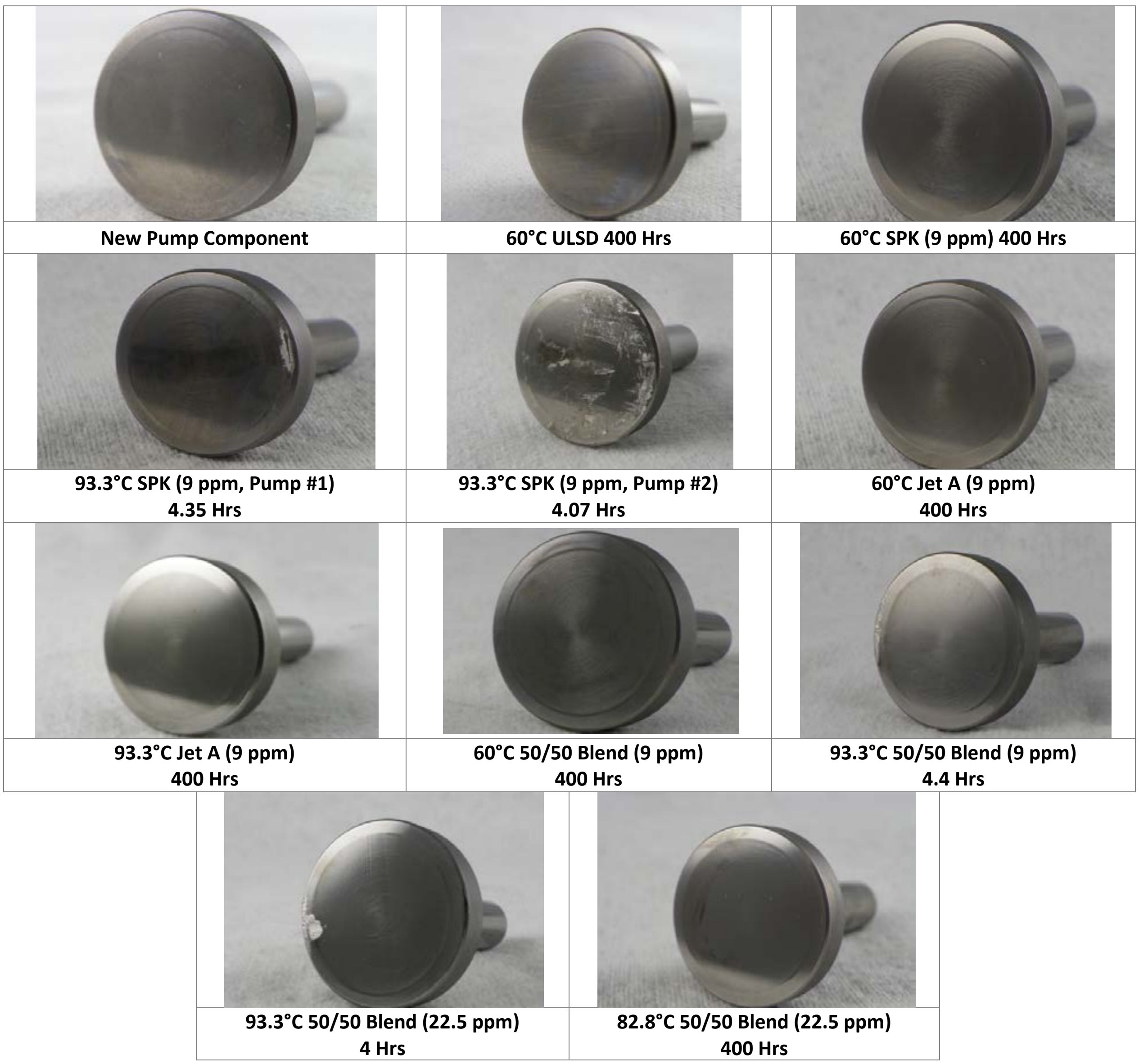


Figure 28. Lower Plunger Face

3.7 LOWER RING CAM FACE

Figure 29 shows the condition of the lower ring cam face at the end of each test. As with the plunger, the condition of the lower ring cam is similar to that of the upper side.

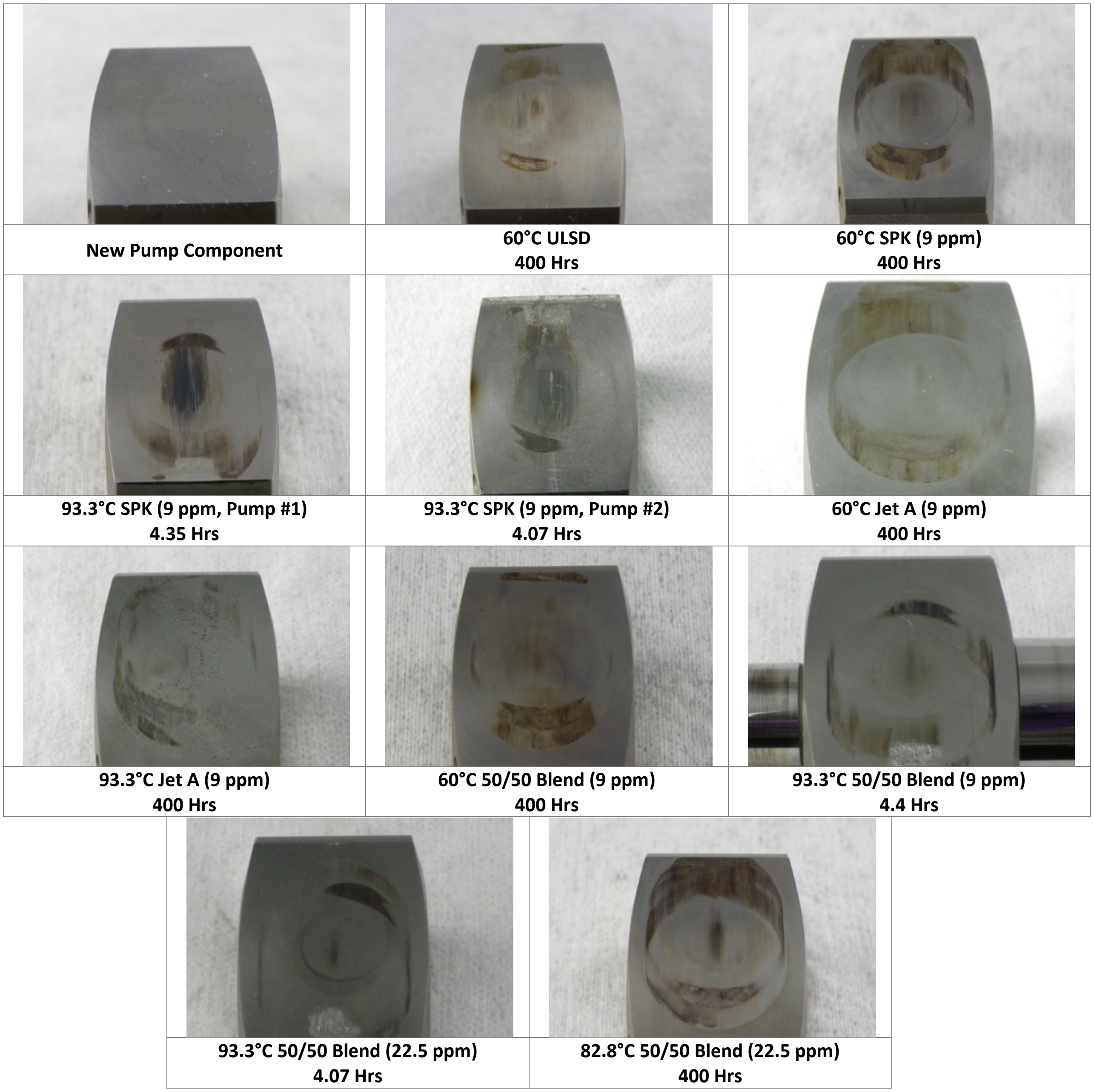
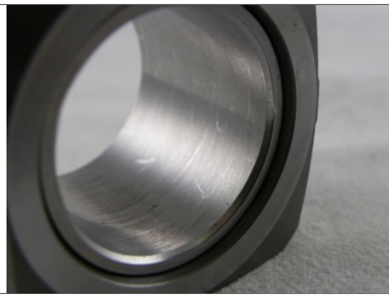
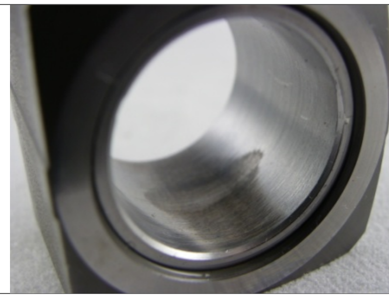
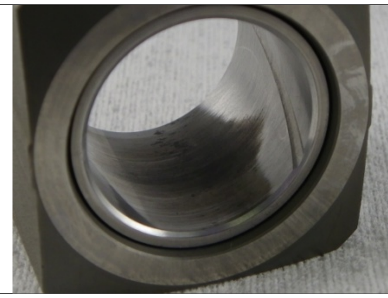
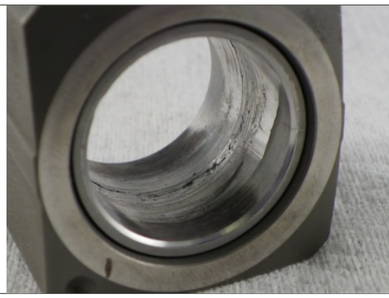
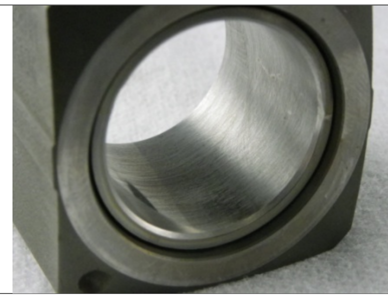
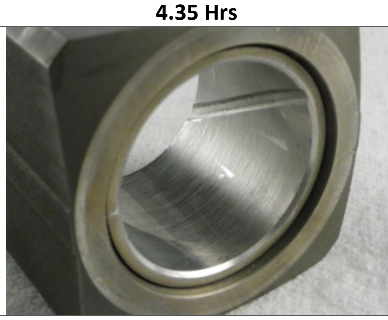
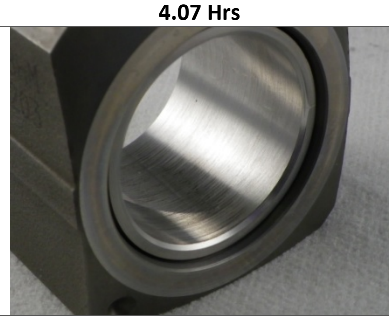


Figure 29. Lower Ring Cam Face

3.8 RING CAM BUSHING

Figure 30 shows the condition of the ring cam bushing at the end of each test. This bushing is press fit into the ring cam and does not move relative to the ring. A diagonal slot across the bushing surface helps fuel to flow between the bushing and camshaft lobe. This slot is not visible in all images shown in Figure 30. In some of the tests which did not reach 400 hours, there was material transfer from the rest of the bushing into this slot, filling it in and eliminating the fuel passage. In the case of the high temperature SPK testing, there appears to be extensive wear and cracking of the bushing material. The lower viscosity of the heated fuel allowed for the development of additional wear in the case of the Jet A evaluations with 9 ppm DCI-4A, and failure in other elevated temperature comparisons (the blended fuel at 82.8°C does not have a direct 60°C comparison). With a kinematic viscosity at the test temperature of 1.9 cSt, the ULSD fuel exhibited double the kinematic viscosity of the next highest fuel (60°C Jet A with 9 ppm DCI-4A at 0.95 cSt) and over three times that of the lowest (93.3°C SPK with 9 ppm DCI-4A at 0.57 cSt). For a given operating mode, the system would have had a consistent operating speed from test-to-test. The bearing unit load would also remain nearly consistent since it is a function of rail pressure and spring force. This leaves absolute viscosity (kinematic viscosity times the mass density of the fluid) as the main variable to influence the lubricating regime which the bushing and cam system operated in. ULSD, with a higher kinematic viscosity and density, would remain in hydrodynamic lubrication at a heavier load than any of the aviation fuels or blends. If the fuels were allowing for mixed-film or extensive metal-to-metal contact, bushing material filling in the fluid passage groove could be expected.

		
New Pump Component	60°C ULSD 400 Hrs	60°C SPK (9 ppm) 400 Hrs
		
93.3°C SPK (9 ppm, Pump #1) 4.35 Hrs	93.3°C SPK (9 ppm, Pump #2) 4.07 Hrs	60°C Jet A (9 ppm) 400 Hrs
		Not available, ring cam siezed on shaft
93.3°C Jet A (9 ppm) 400 Hrs	60°C 50/50 Blend (9 ppm) 400 Hrs	93.3°C 50/50 Blend (9 ppm) 4.4 Hrs

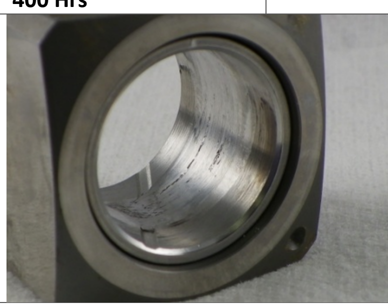
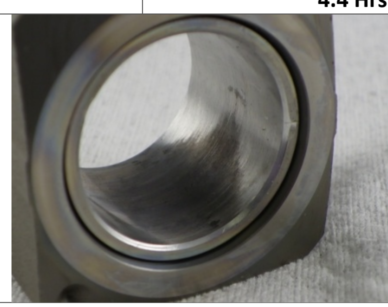
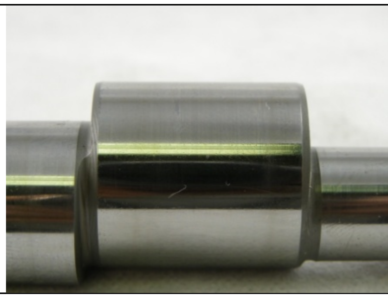
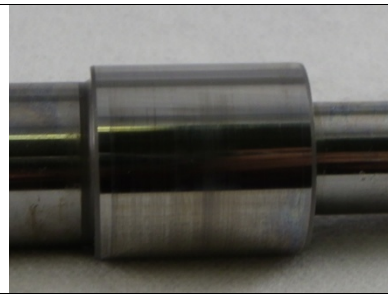
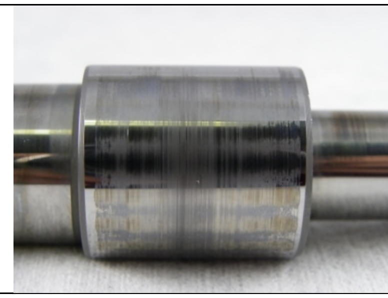
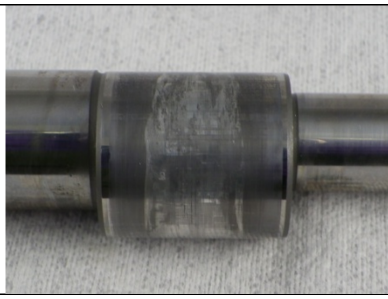
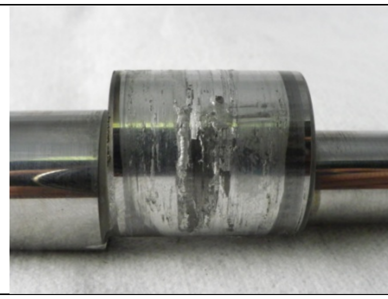
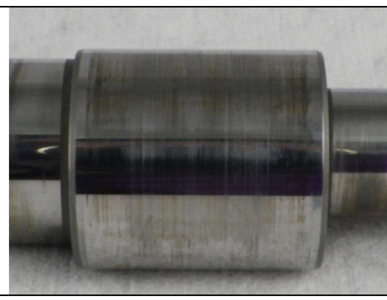
	
93.3°C 50/50 Blend (22.5 ppm) 4.07 Hrs	82.8°C 50/50 Blend (22.5 ppm) 400 Hrs

Figure 30. Ring Cam Bushing

3.9 CAMSHAFT LOBE

Figure 31 shows the condition of the cam shaft lobe at the end of each test. The condition of the lobe for each evaluation is generally better than the corresponding bushing. The most common feature to develop on the surface of the lobe was a series of scuff marks. These formed on the side of the lobe which corresponds to the heaviest loading as the plunger is driven into the bore. In most cases, some level of the original polish was maintained. Only the high temperature SPK testing showed extensive damage, likely due to the catastrophic failure of the pump. This interface between the camshaft lobe and the ring cam bushing appears to be the most sensitive area within the pump.

		
New Pump Component	**60°C ULSD** **400 Hrs**	**60°C SPK (9 ppm)** **400 Hrs**
		
93.3°C SPK (9 ppm, Pump #1) **4.35 Hrs**	**93.3°C SPK (9 ppm, Pump #2)** **4.07 Hrs**	**60°C Jet A (9 ppm)** **400 Hrs**
		**Not available, ring cam siezed on shaft**
93.3°C Jet A (9 ppm) **400 Hrs**	**60°C 50/50 Blend (9 ppm)** **400 Hrs**	**93.3°C 50/50 Blend (9ppm)** **4.4 Hrs**

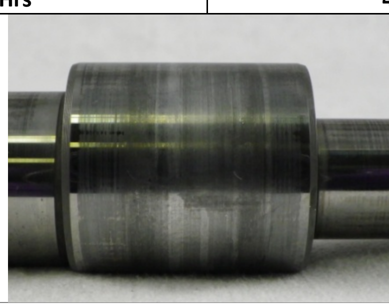
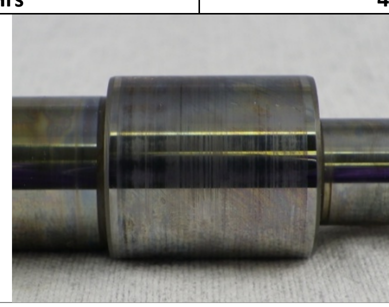
	
93.3°C 50/50 Blend (22.5 ppm) **4.07 Hrs**	**82.8°C 50/50 Blend (22.5 ppm)** **400 Hrs**

Figure 31. Camshaft Lobe

3.10 UPPER INJECTOR CONNECTING PIN

Figure 32 shows the condition of the upper injector connecting pin at the end of each test.

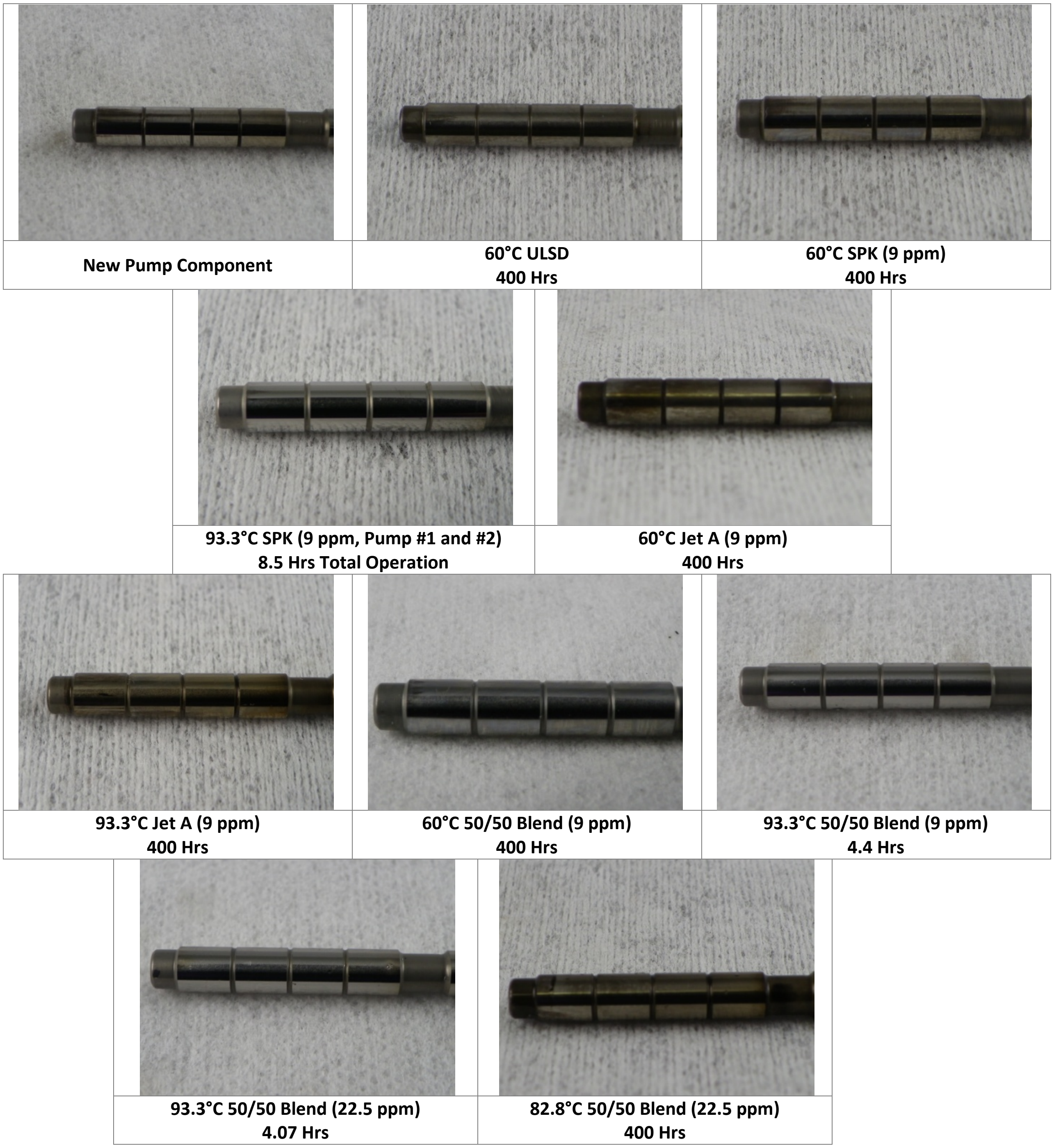


Figure 32. Upper Injector Connecting Pin

The only noticeable wear feature on this internal injector component is a small area of axial marking on the upper (left) end. Formation of these lines occurred on all testing that reached the full 400 hours. There appears to possibly be a light tempering effect, based on color, occurring in the injectors for the components which were evaluated at the higher fuel temperatures. The 93.3°C Jet A with 9 ppm DCI-4A and 82.8°C 50/50 Blend with 22.5 ppm DCI-4A tests have a darker yellow/straw appearance consistent with steel tempered near 220 to 230°C. The fuels evaluated at lower temperatures show a slight tingle of yellow which may begin to form in steel heated to 215°C. While no direct measurement is available for the internal injector temperature, the fuel temperature downstream of the injectors, after some cooling would have occurred, is shown in Figure 33.

It would not be unrealistic for the highly pressurized fuel within the injector body to experience localized temperatures much greater than those measured downstream. While no issues were noted with the injector components at the temperatures tested, if fuel was supplied above 93.3°C some considerations should be given to changes in material properties over time due to heating.

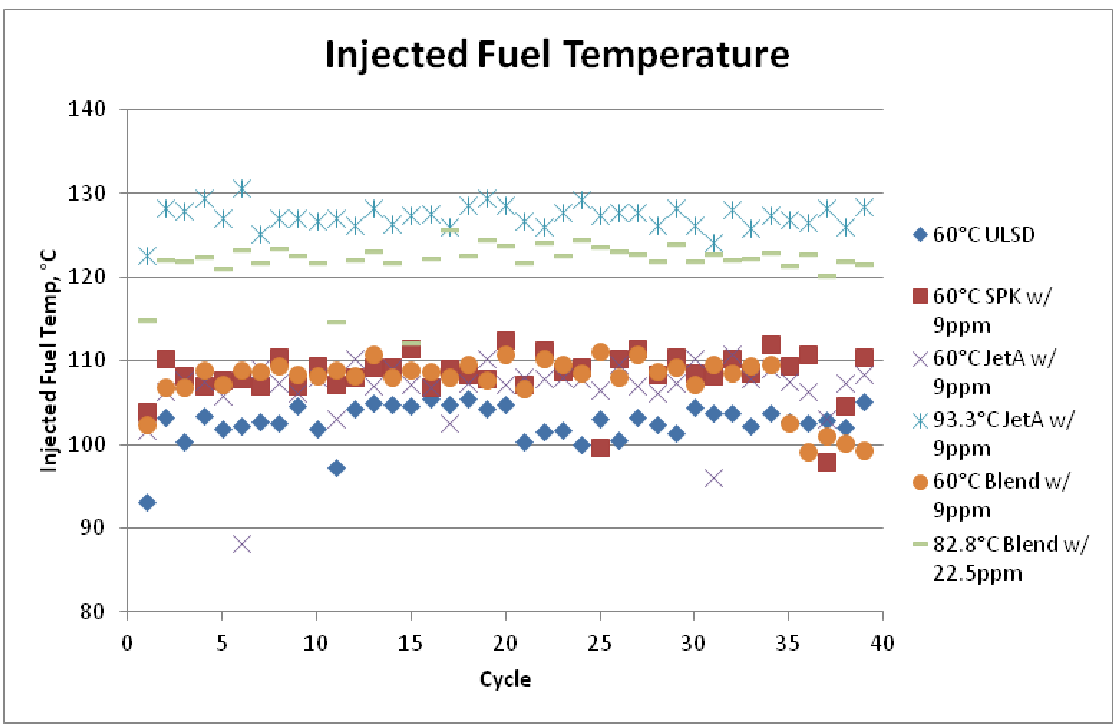


Figure 33. Injected Fuel Temperature

3.11 LOWER INJECTOR CONNECTING PIN

Figure 34 shows the condition of the lower injector connecting pin at the end of each test.

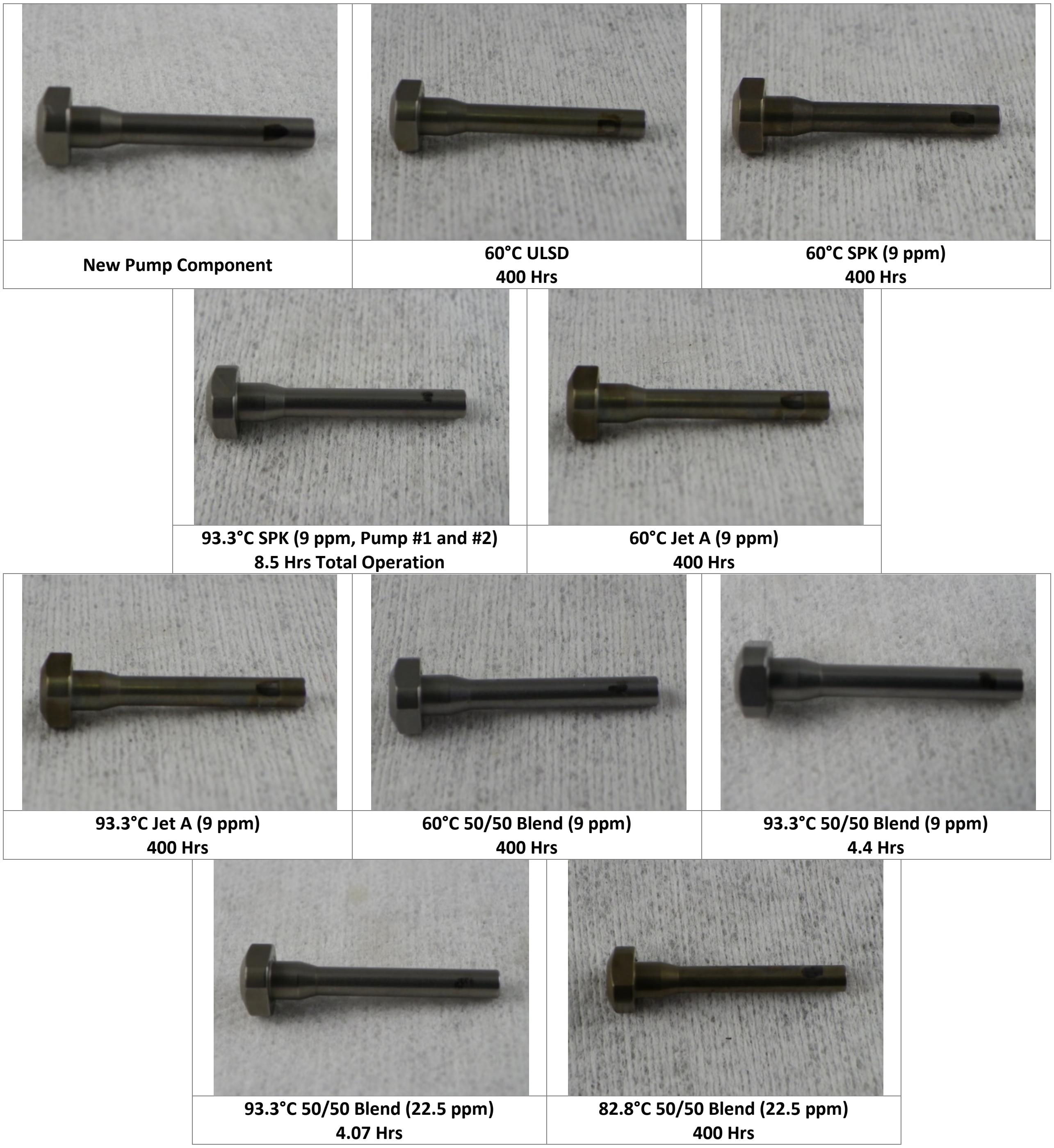


Figure 34. Lower Injector Connecting Pin

The connecting pin which sits just above the injector needle showed only one spot of wear. This can be seen on the right side of each image in Figure 34 including that of the unused component. As with the upper connecting pin, there is appearance of color on the high temperature test components. This item does not appear to be a point of concern for the function of the injector assembly with any of the fuels evaluated.

3.12 INJECTOR NEEDLE

Figure 35 shows the condition of the injector needle at the end of each test. There appeared to have been a hardware change made by the manufacturer to add a surface treatment to the needle between the first and subsequent tests. Hardware was obtained through a local supplier at two different times for the program, once during the design and installation phase of the fuel system and again once the system was functional. The components used in the ULSD test were from the first set of parts received while all other injectors arrived at a later date. The dark, nearly black, appearance was consistent for each injector regardless of test length and neither solvent nor light scraping removed the finish. The coating change was likely an effort to reduce the effects of long-term wear around the seat of the needle and the injector tip. Leakage between the sealing face of the needle and the injector could result in poor engine performance, increased fuel consumption, and failure to comply with emissions targets. Similar coatings have been noted on internal injector components in other HPCR systems tested to improve hardness and reduce friction. There did not appear to be any degradation of the needle during testing.

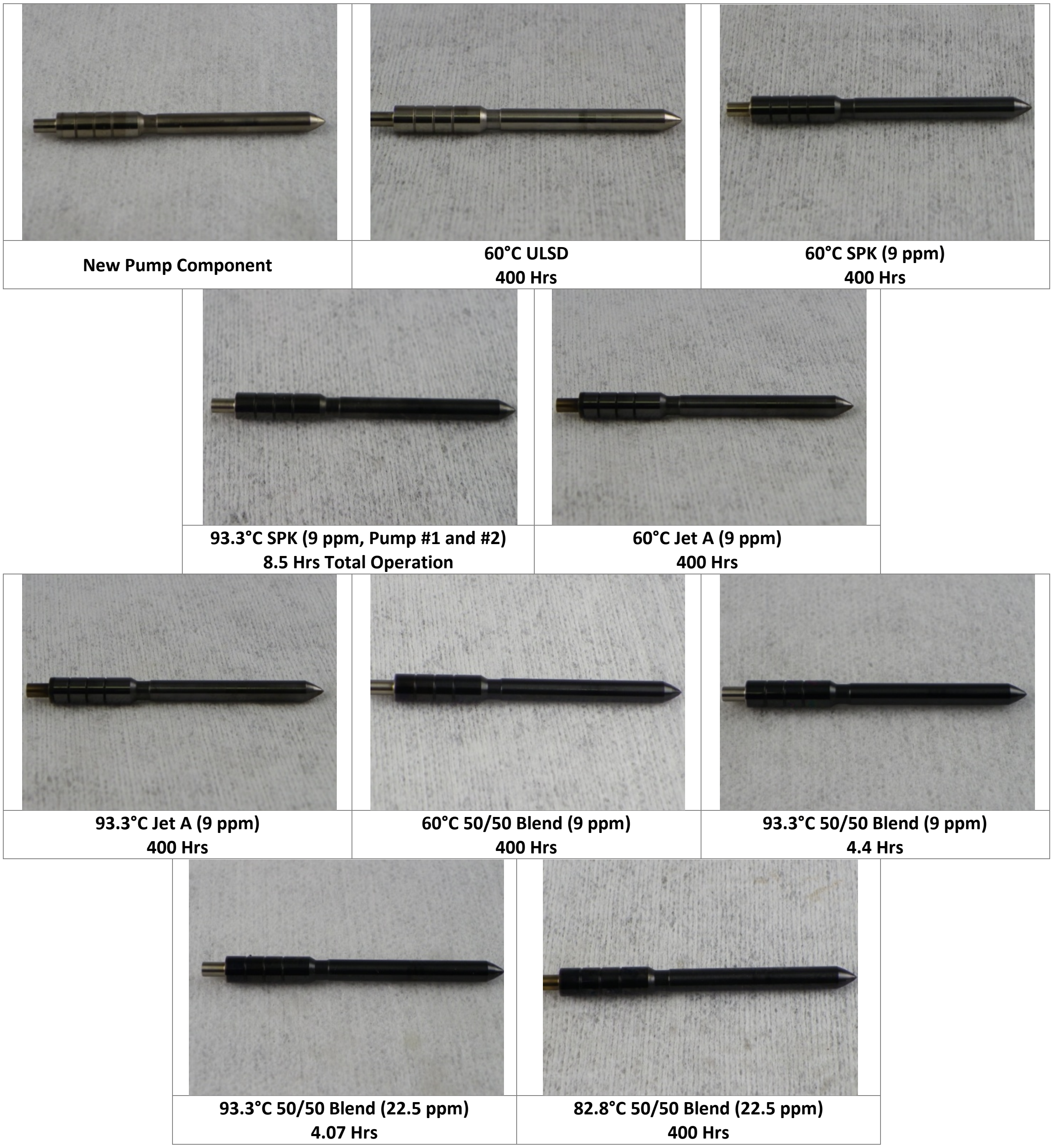


Figure 35. Injector Needle

4.0 SUMMARY AND CONCLUSIONS

Results from the system evaluated indicated a sensitivity to synthetic aviation fuels not seen in other modern HPCR equipment. Post-test component analysis indicated that the critical area for system failure was the interaction between the ring cam and camshaft within the high pressure pump. A driving factor for the ability of the pump to survive the test was the fuel viscosity at the test temperature. Figure 36 and Figure 37 show the fresh fuel BOCLE and HFRR results compared with the kinematic viscosity at test temperature. For each figure, there was a minimum viscosity value below which the pump experienced the previously described failure.

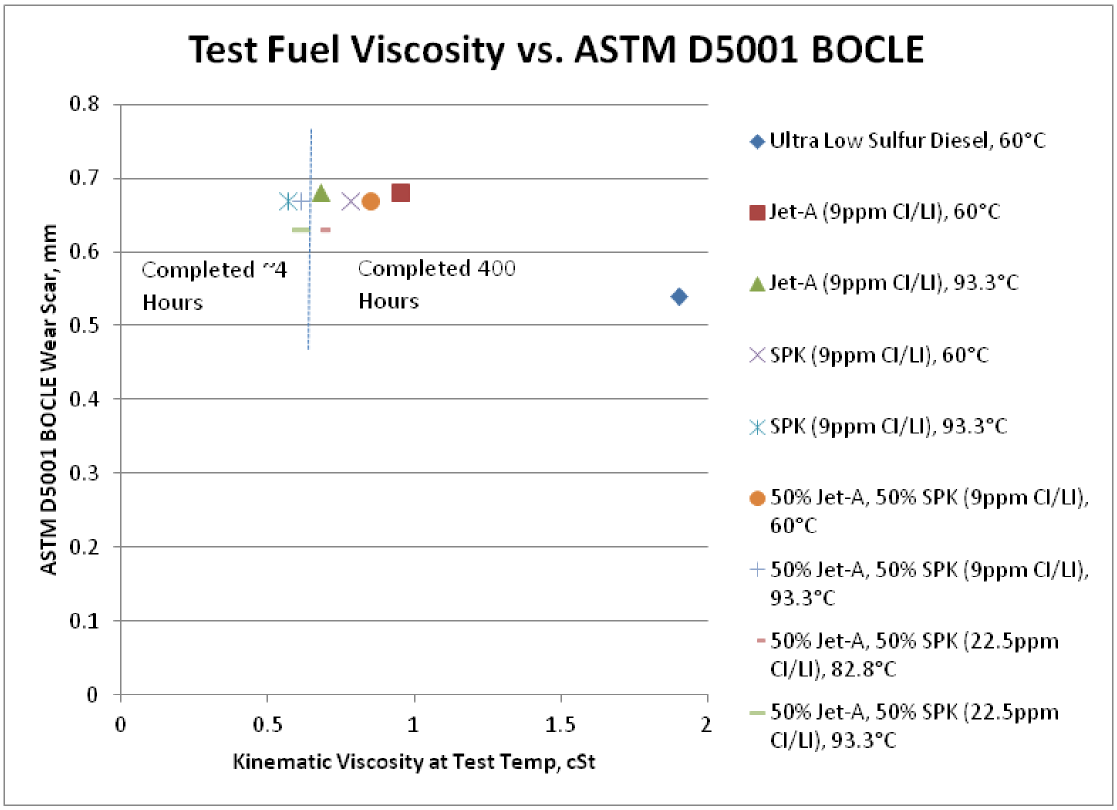


Figure 36. Viscosity and BOCLE Comparison

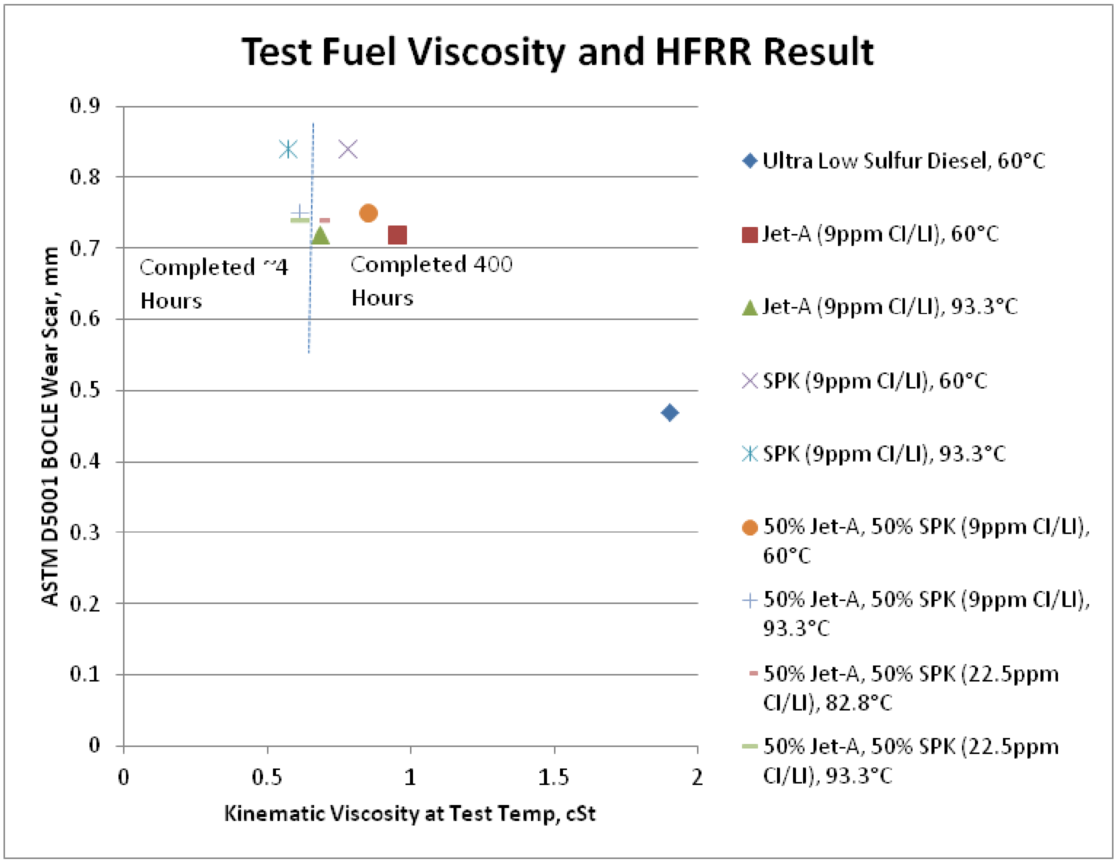


Figure 37. Viscosity and HFRR Comparison

The minimum value for fuel viscosity which resulted in a completed test was 0.68 cSt. Using the 50/50 Blended fuel with the maximum treat rate, a difference of 10.5°C in temperature increased the test duration by nearly 396 hours. The same fuel in moving from the minimum to maximum treat rates of DCI-4A had no meaningful change in test duration. For the future use of the system in military applications, fuel selection should take into consideration the expected vehicle tank temperatures. Operation in lower temperature environments may allow for the use of higher blend rates of low viscosity synthetics while high ambient may require solely petroleum based fuels. These results may be summarized as follows:

- Minimum acceptable viscosity for completed tests: 0.68 cSt
- FT-SPK and Blended fuels with the minimum treat rate of lubricity improver provided acceptable protection at 60°C
- Jet A with DCI-4A showed compatibility with the HPCR system up to 93.3°C
- The further addition of CI/LI in the Blended fuel at 93.3°C, from 9 to 22.5 ppm, did not improve system durability

5.0 RECOMMENDATIONS

Future investigation with the system may be of benefit in the following areas:

- Low viscosity fluid tests with a modified camshaft and ring cam. Modification options may include increased groove for fuel flow or surface treating for improved component hardness
- Determine compatibility with unadditized Jet A and synthetic fuels at temperatures which provide adequate fluid viscosity
- Longer duration testing with multiple high pressure pumps to isolate critical areas within the injector
- Modification of internal pump components to address the friction developing between sliding contact

Outside of the low viscosity issues previously discussed, the John Deere 4.5L Powertech Plus fuel system appears appropriate for use in many military applications where excessive heat is not expected to be an issue.

6.0 REFERENCES

1. 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/D6079-11

2. 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/D5001-10

3. 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/D6079-11

4. Warden, R.W., Frame, E.A., Yost, D. M., *"Evaluation of Future Fuels in a High Pressure Common Rail System Part 1 – Cummins XPI"*, Interim Report TFLRF No. 429, October 2012.

APPENDIX A

Test Stand Development

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

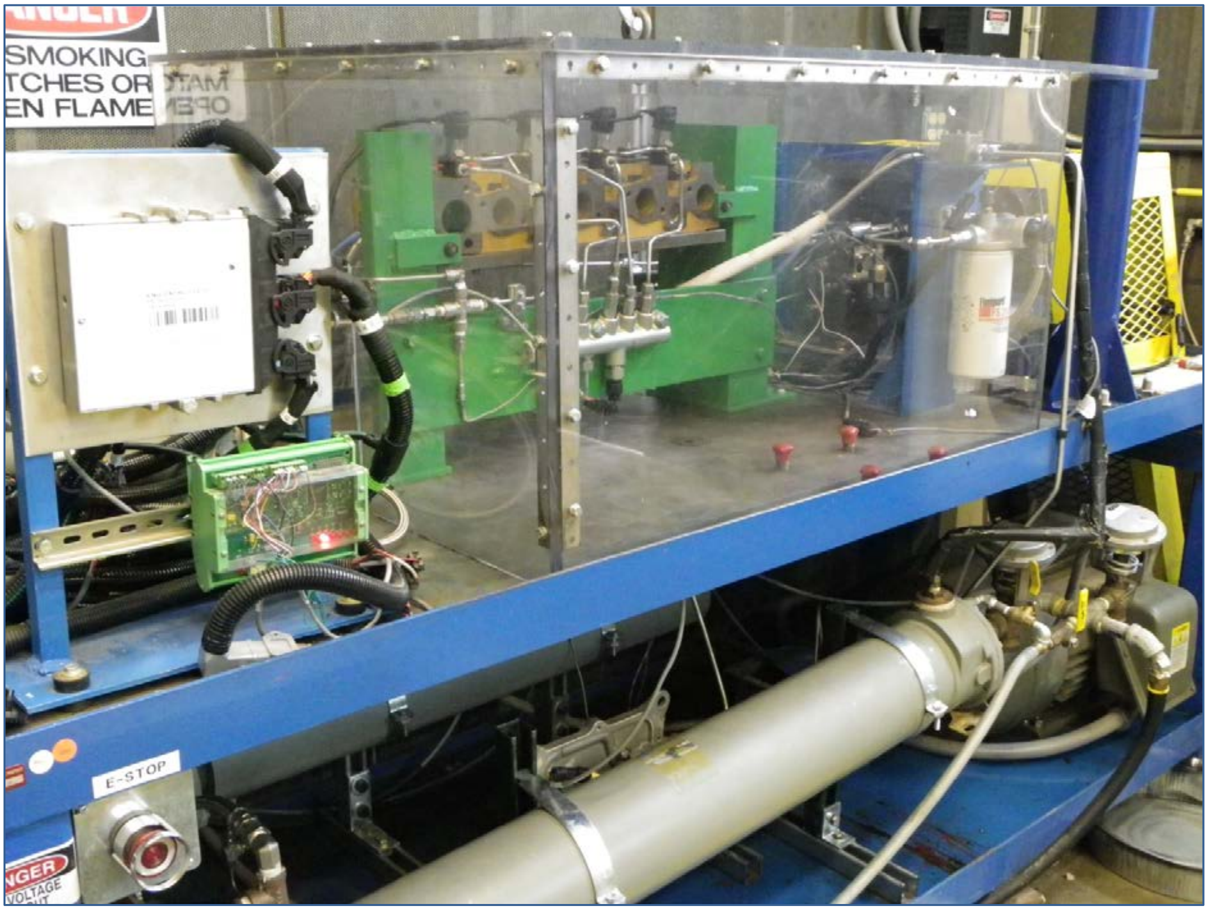


Figure A-1. John Deere 4.5L Powertech Plus HPCR Fuel System Test Stand

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. 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 forcing fuel out the vent port. 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 through a pulse-with-modulation controller. After injection, warm fuel was passed through a large liquid-to-liquid heat exchanger prior to flow measurement. This did not impact volumetric flow as 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 data acquisition software, came from a 3600 pulse-per-revolution rotary encoder. An engine timing gear was fitted to provide the ECM with appropriate signal input. 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 & tube	ITT Standard
Return Fuel and Oil System HX	3” Diameter, 14” Length, Stainless Steel shell & 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

APPENDIX B

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: Ultra Low Sulfur Diesel
Test Number: ULSD-AF7947-60°C-JD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

John Deere 4.5L Powertech

Test Fuel: Ultra Low Sulfur Diesel
Test Number: ULSD-AF7947-60°C-JD
Start of Test Date: March 5, 2012
End of Test Date: March 30, 2012
Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

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

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Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) performed a project for US Army TARDEC on synthetic and alternative fuels. The project goal was 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 and viscosity impact of various fuels. Using a test bench method was 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, Jet A, an FT SPK treated with corrosion inhibitor/lubricity improver (CI/LI), and a 1:1 blend of 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. The lower temperature ULSD test is considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the John Deere 4.5L Powertech fuel system manufactured by Denso. The fuel-lubricated high pressure pump allows the system to reach rail pressures of up to 20,000 psi. It is operated at the same rotational speed as the engine crankshaft for a rated condition of 2400 rpm. Within the pump, the camshaft drives two plungers, in an opposed orientation, which pressurize the fuel entering the rail. Each plunger is driven by a single ring cam which rotates on an eccentric lobe of the pump shaft. The low pressure system consists of an external electric lift pump and filter combination to remove large particles and water along with a high efficiency final filter before entering the high pressure pump. An internal transfer pump pressurizes fuel prior to entry into the high pressure plunger bore. Injectors are solenoid driven and controlled by the ECM. For each fuel test a new high pressure pump, filters, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand modified for Powertech Plus 4.5L 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 an engine control module (ECM) modified by John Deere 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 pump consisted of two plungers which compressed fuel to reach the desired rail pressure. Fuel then flowed 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 under the cylinder head, cooled to a consistent temperature, 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 B-1.

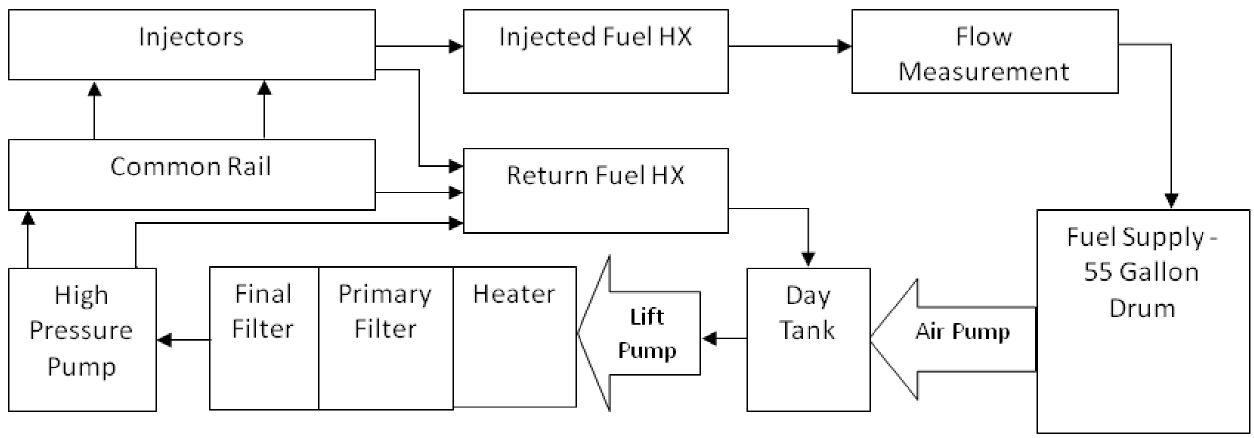

Figure B-1. Fuel System Layout

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 John Deere 4.5L Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	800	0	0.5
2	2400	100	2
3	2560	0	0.5
4	1800	100	1
5*	800 to 2400	0 to 100	2
6	1440	100	0.5
7	800	0	0.5
8	2500	70	0.5
9	1500	100	2
10	1440	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 Deere supplied ECM for monitoring purposes, shown in Figure B-2. Calibration of this channel was performed using the Deere service tool through the SAE J1939 CAN bus. The system did not experience any performance issues related to rail pressure during the course of the test.

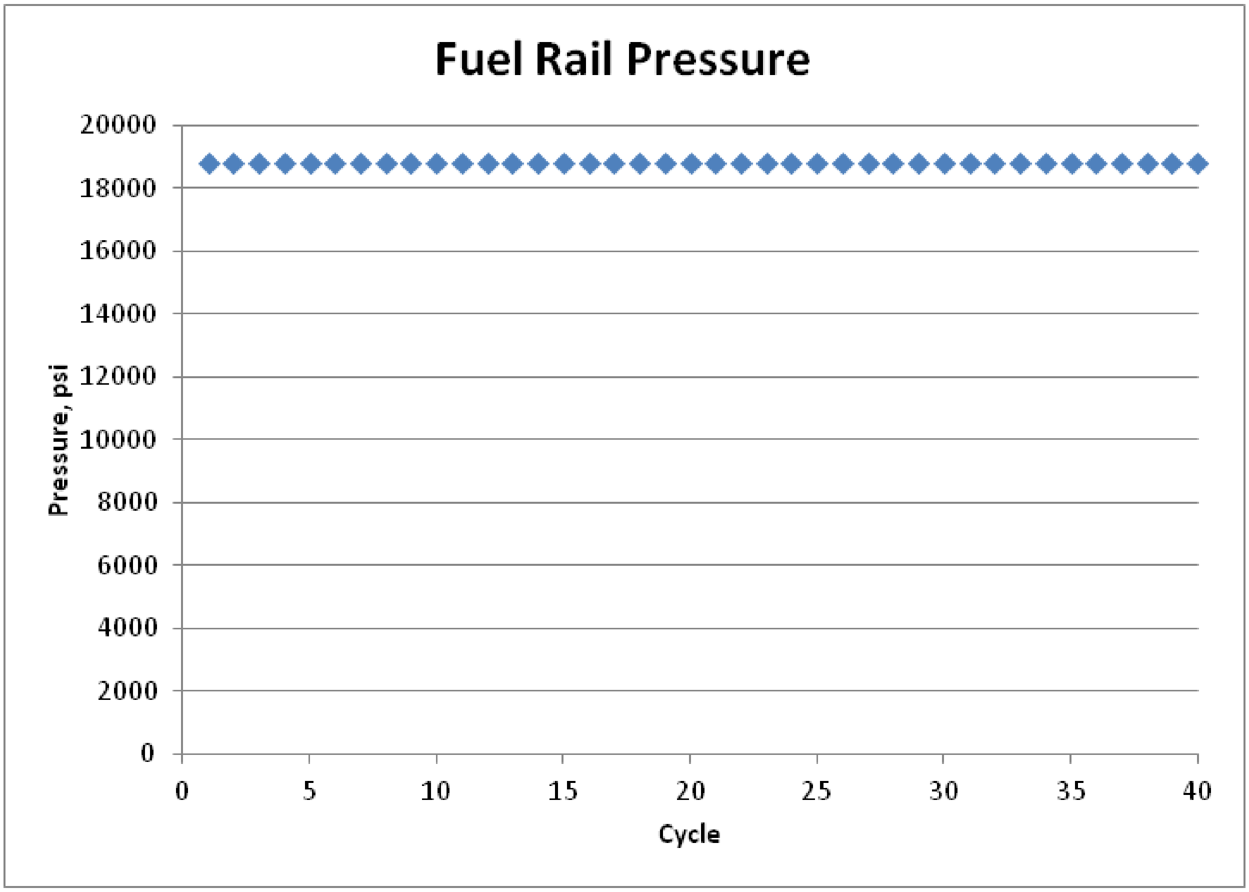

Figure B-2. Fuel Rail Pressure

The flow rate for injected fuel is shown in Figure B-3. There is no major change in fuel flow rate over the duration of the test.

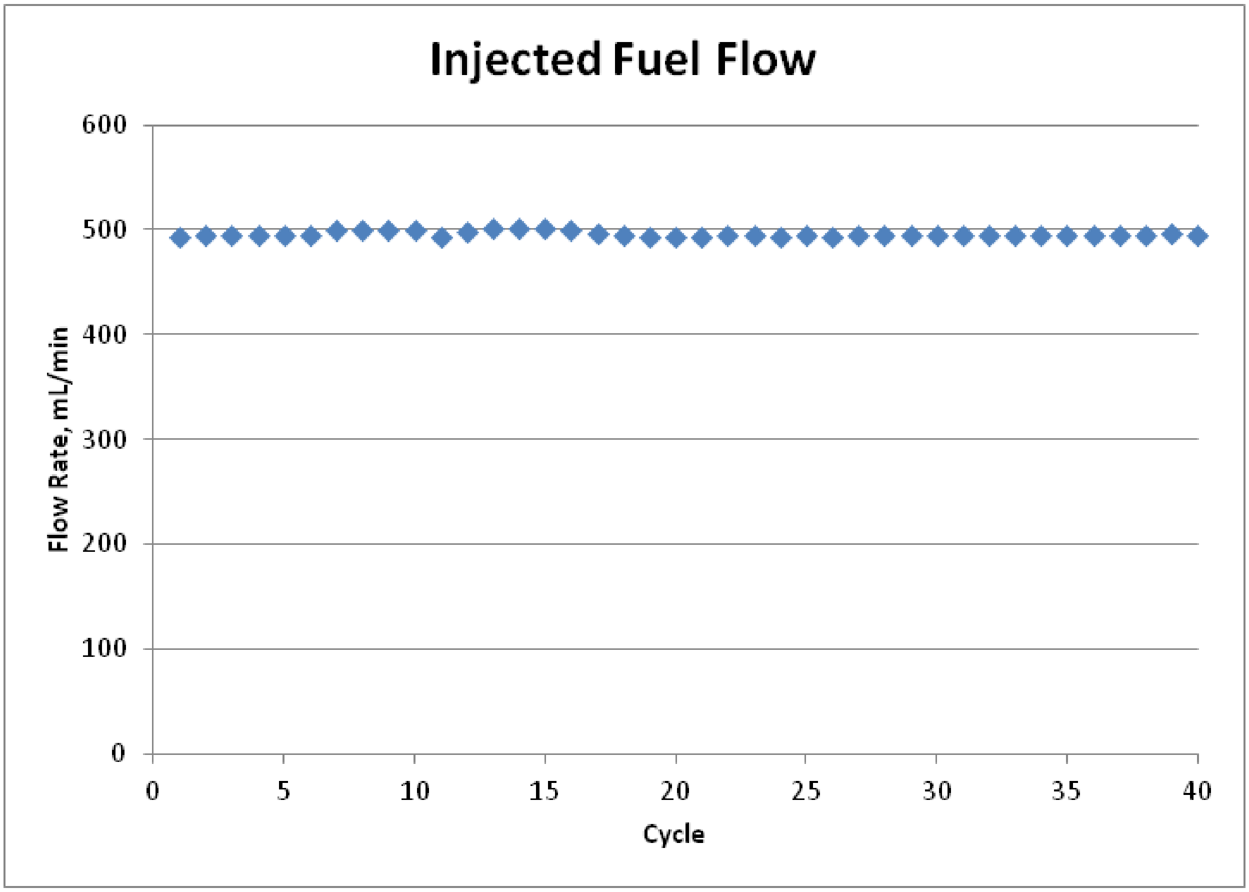

Figure B-3. Injected Fuel Flow

Figure B-4 shows the return fuel from the injectors, rail, and high pressure pump. There is an increase between the first and second cycles as components reach a steady temperature.

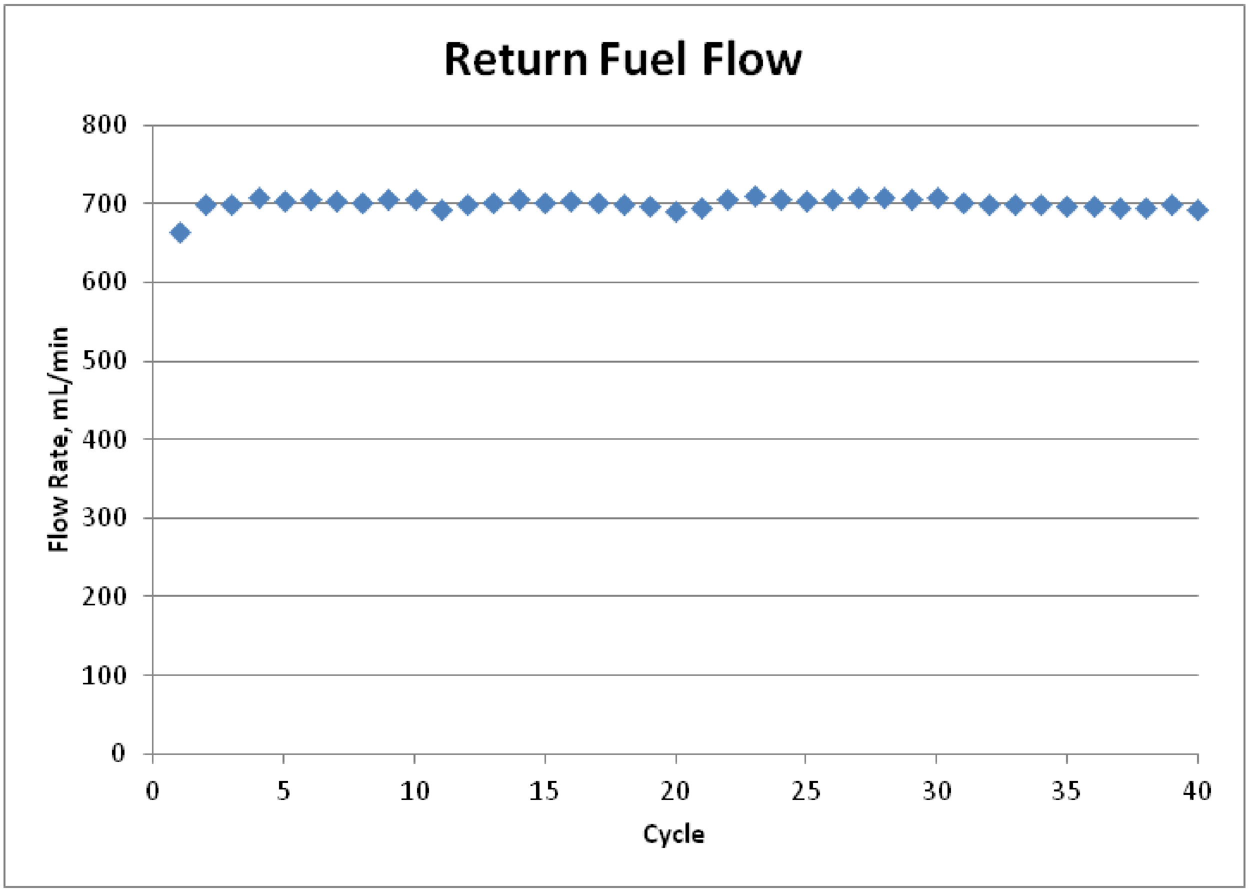

Figure B-4. Return Fuel Flow

Figure B-5 shows the system inlet temperature. This was controlled through a pulse-width modulated heater element. Temperature remained within proper control through the test.

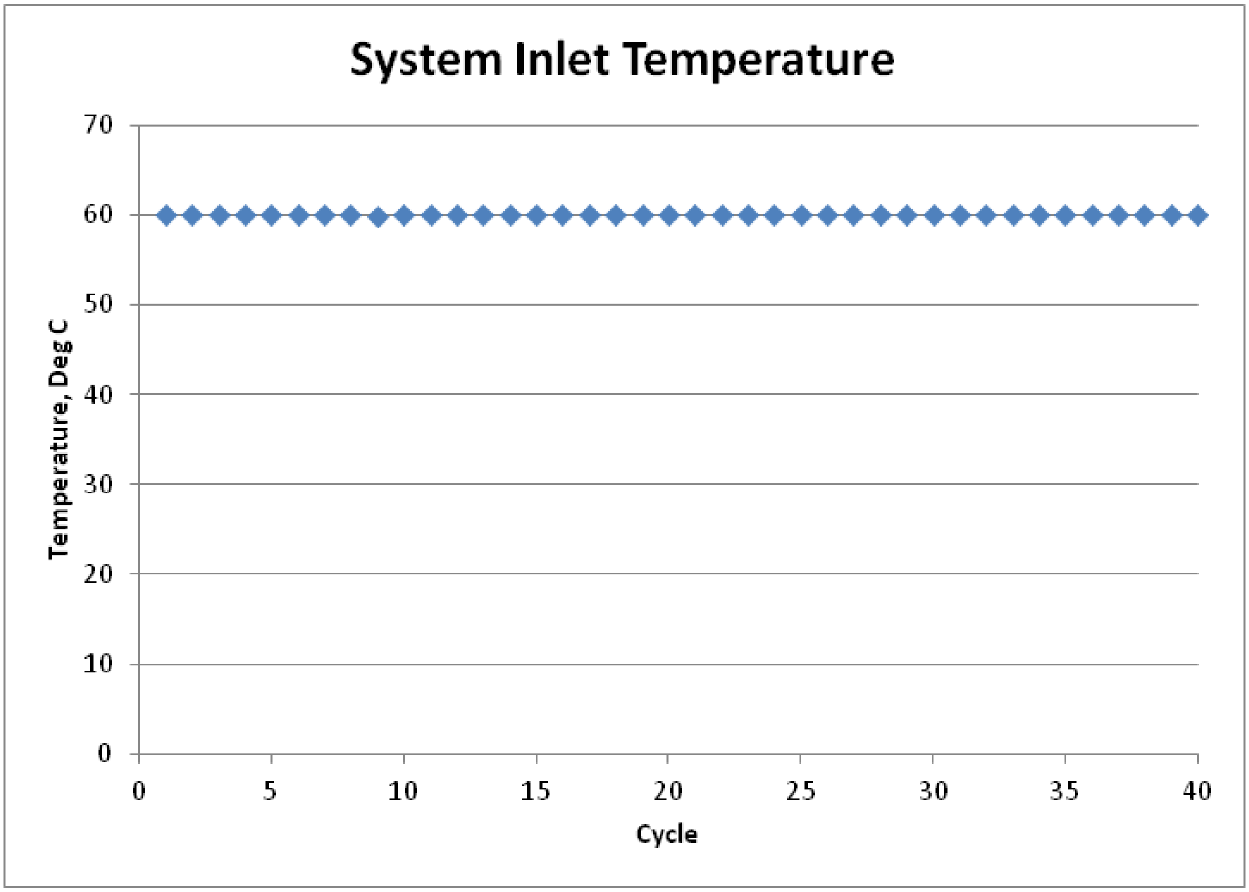

Figure B-5. System Inlet Fuel Temperature

Figure B-6 shows a measure of the fuel pressure as it was supplied to the final filter element by the electric lift pump.

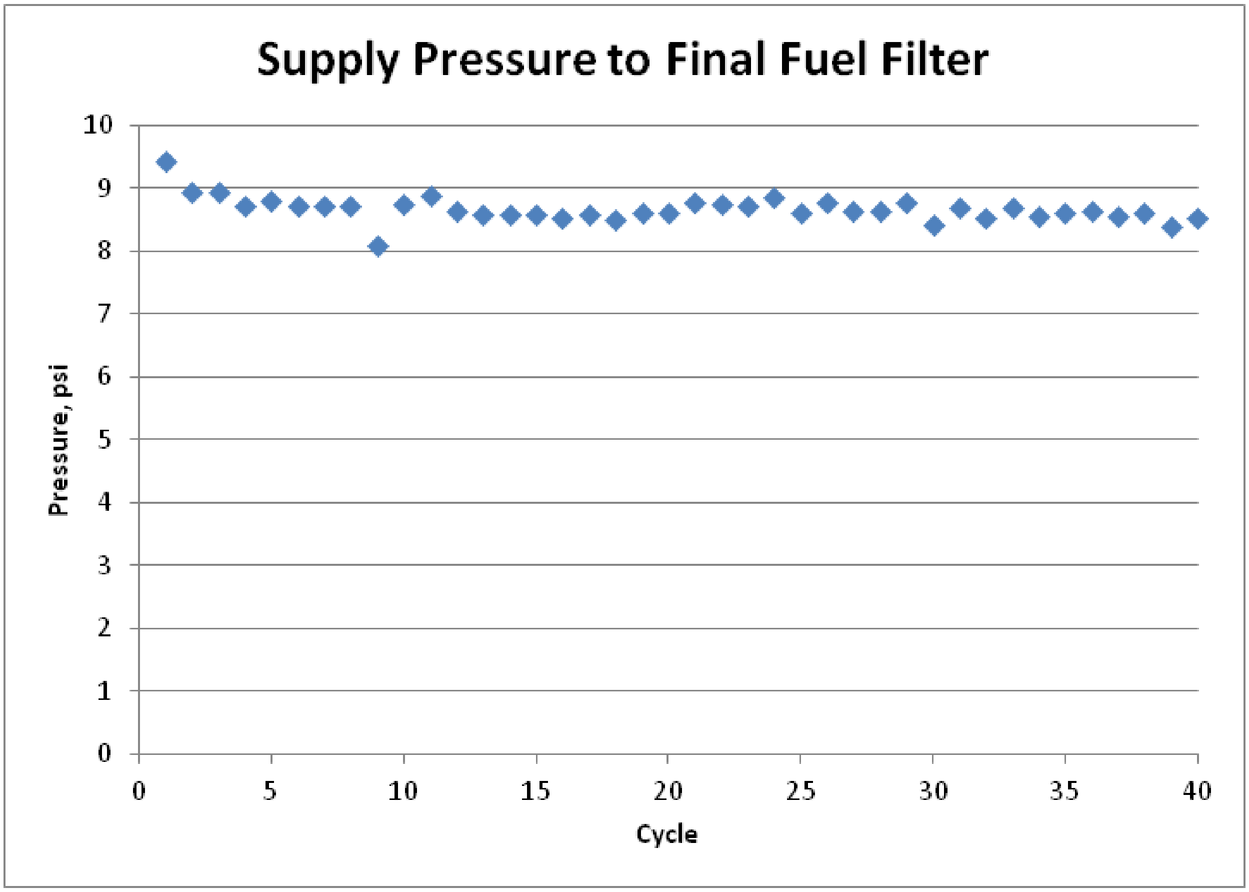

Figure B-6. Fuel Filter Pressure

A summary of the operating conditions for each 100 hour period are provided in Table B-2.

Table B-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.8	57.1	62.6
Bypass Fuel Temperature, deg C	99.1	10.1	64.1	110.1
Rail Pressure, psi	18817	17	18753	18900
Injected Flow Rate, mL/min	496.7	3.4	484.0	503.8
Return Fuel Flow Rate, mL/min	699.2	19.5	604.2	752.8
Fuel Filter Inlet Pressure, psi	8.8	0.4	6.5	9.9
Test Hours 100-200				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.4	57.1	61.8
Bypass Fuel Temperature, deg C	86.0	9.6	60.6	106.3
Rail Pressure, psi	18808	25	18635	18975
Injected Flow Rate, mL/min	497.6	3.6	486.6	504.3
Return Fuel Flow Rate, mL/min	698.8	14.4	618.3	749.3
Fuel Filter Inlet Pressure, psi	8.6	0.2	8.3	9.6
Test Hours 200-300				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.5	57.0	62.1
Bypass Fuel Temperature, deg C	92.3	10.8	56.6	110.3
Rail Pressure, psi	18819	26	18611	18968
Injected Flow Rate, mL/min	494.3	1.6	485.0	500.0
Return Fuel Flow Rate, mL/min	704.5	16.8	631.2	757.5
Fuel Filter Inlet Pressure, psi	8.7	0.2	8.2	9.7
Test Hours 300-400				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.4	57.2	62.0
Bypass Fuel Temperature, deg C	90.9	12.0	59.7	110.8
Rail Pressure, psi	18811	46	18495	19099
Injected Flow Rate, mL/min	494.8	1.7	480.2	499.1
Return Fuel Flow Rate, mL/min	697.0	14.2	626.5	740.5
Fuel Filter Inlet Pressure, psi	8.6	0.2	8.1	9.4

Lubricity Fuel Analysis

Fuel lubricity 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 Figure B-7 and Figure B-8.

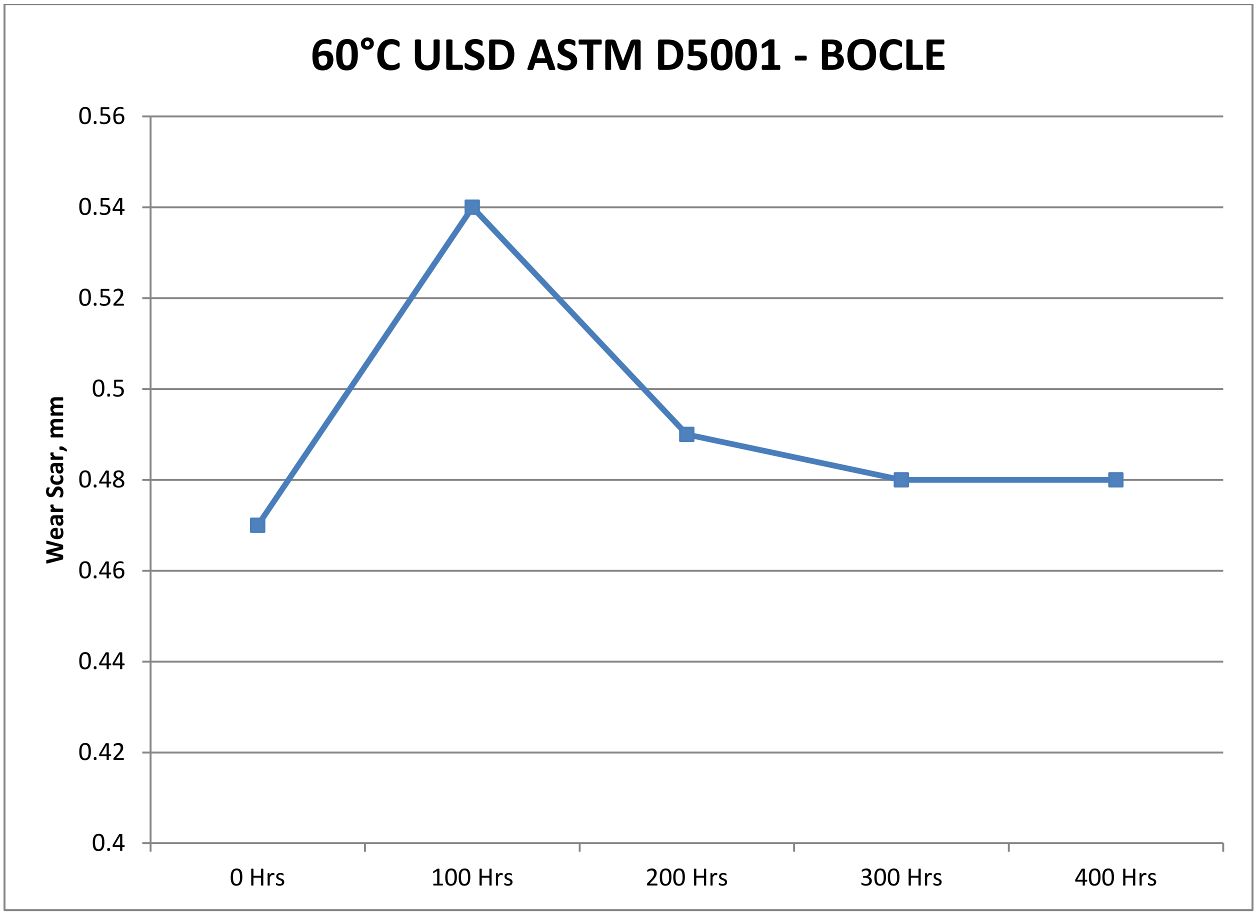

Figure B-7. ASTM D5001 BOCLE

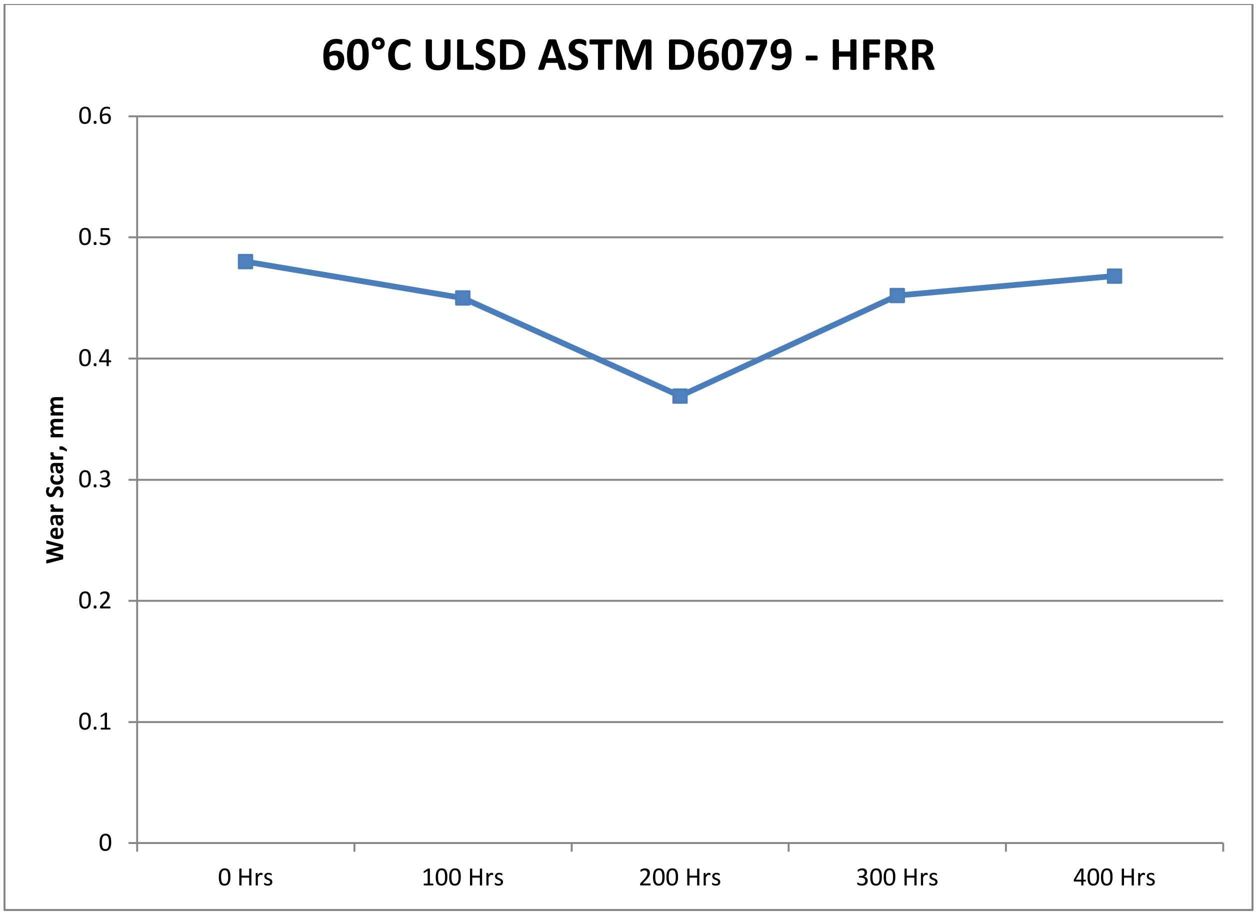

Figure B-8. ASTM D6079 HFRR

Component Wear

Post-test tear disassembly of the pump and injectors was performed to evaluate wear operating on ULSD at 60°C inlet temperature. The following figures highlight various areas of the pump and injectors.

Fuel Pump

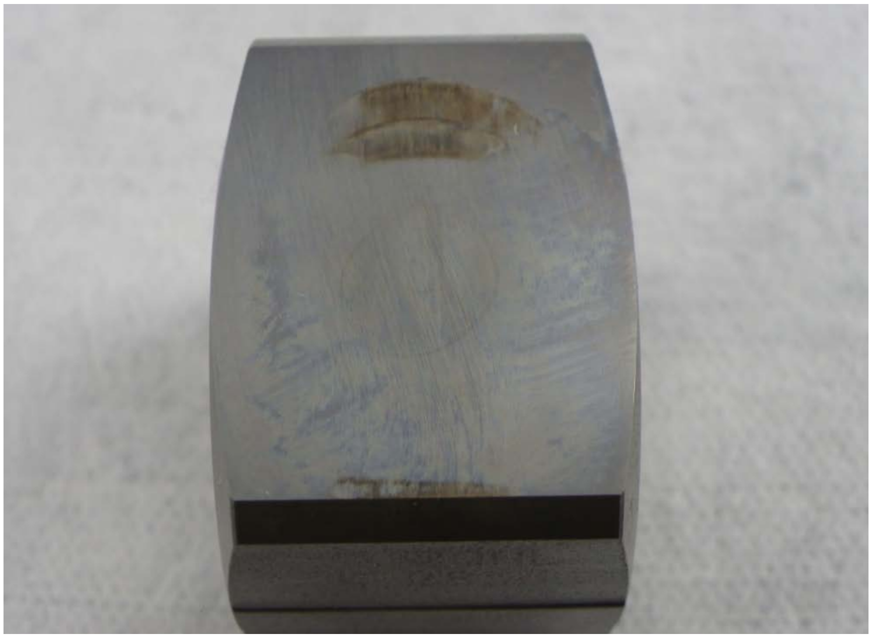

Figure B-9. Ring Cam - Top

Figure B-10. Plunger Face - Top

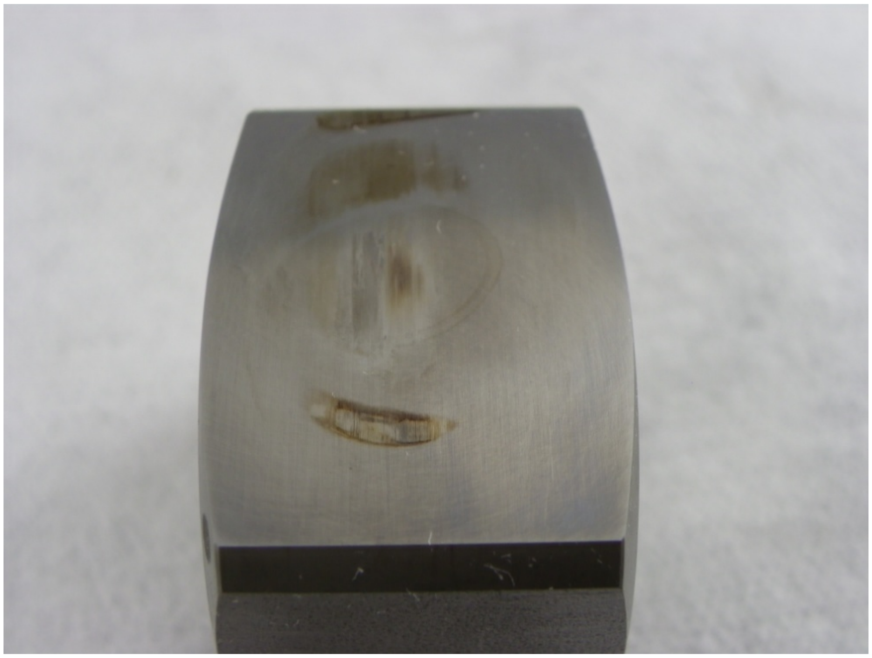

Figure B-11. Ring Cam - Bottom

Figure B-12. Plunger - Bottom

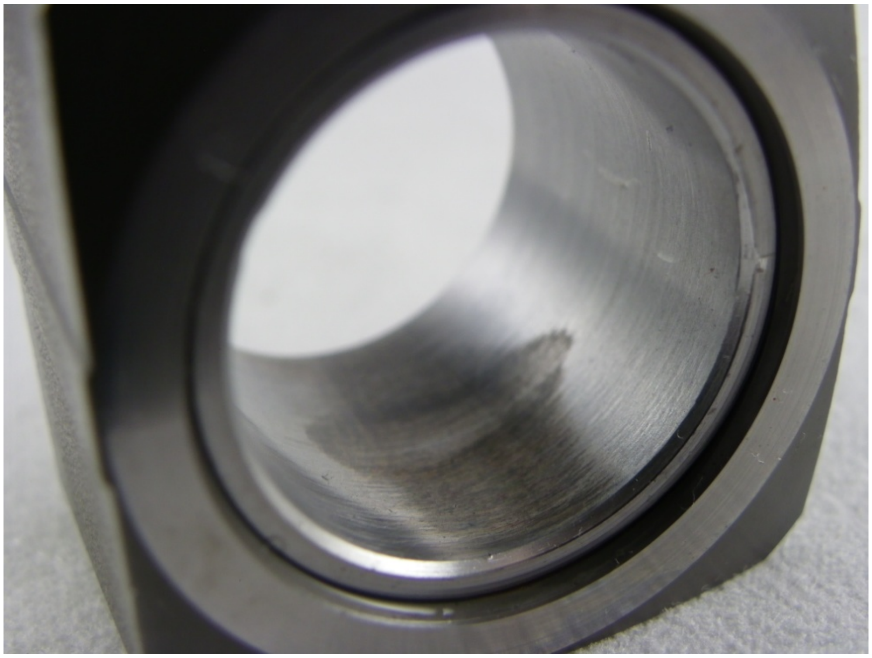

Figure B-13. Ring Cam – Front

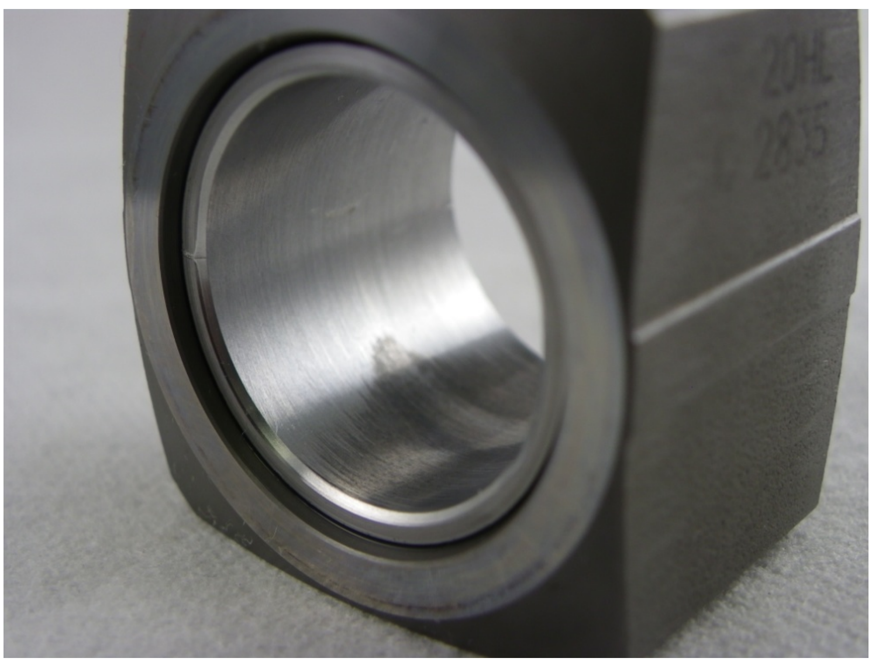

Figure B-14. Ring Cam - Rear

Figure B-15. Eccentric Cam Lobe

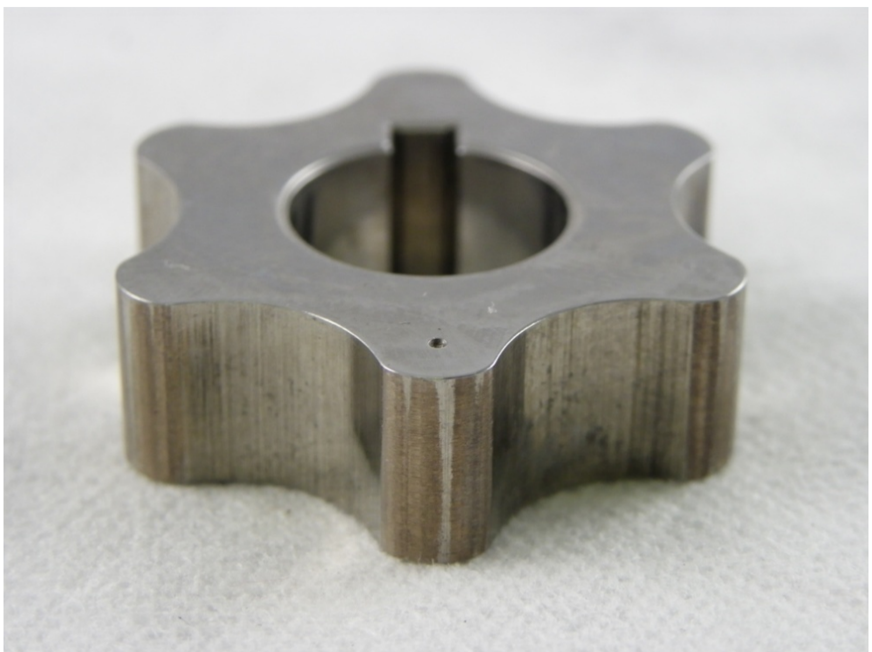

Figure B-16. Transfer Pump Gear

Fuel Injector

Figure B-17. Injector Needle

Figure B-18. Lower Injector Connecting Pin

Figure B-19. Upper Injector Connecting Pin

APPENDIX C

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: FT-SPK with 9 ppm DCI-4A
Test Number: SPK-9 ppm-60°C-JD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

John Deere 4.5L Powertech Plus

Test Fuel: FT-SPK with 9 ppm DCI-4A
Test Number: SPK-9 ppm-60°C-JD
Start of Test Date: April 12, 2012
End of Test Date: May 8, 2012
Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

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

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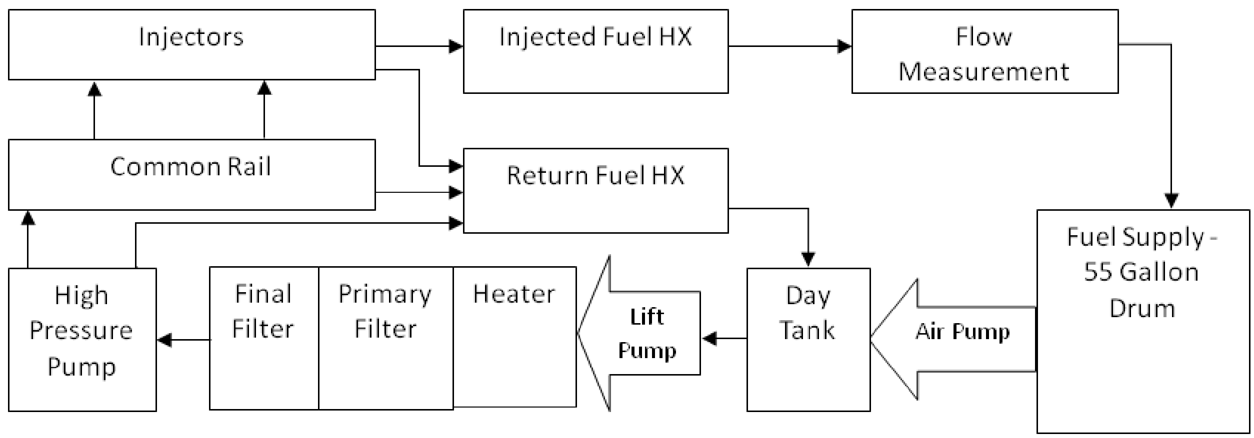

Figure C-1. Fuel System Layout

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6	1440	100	0.5
7	800	0	0.5
8	2500	70	0.5
9	1500	100	2
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*Step 5 cycles between idle and rated conditions

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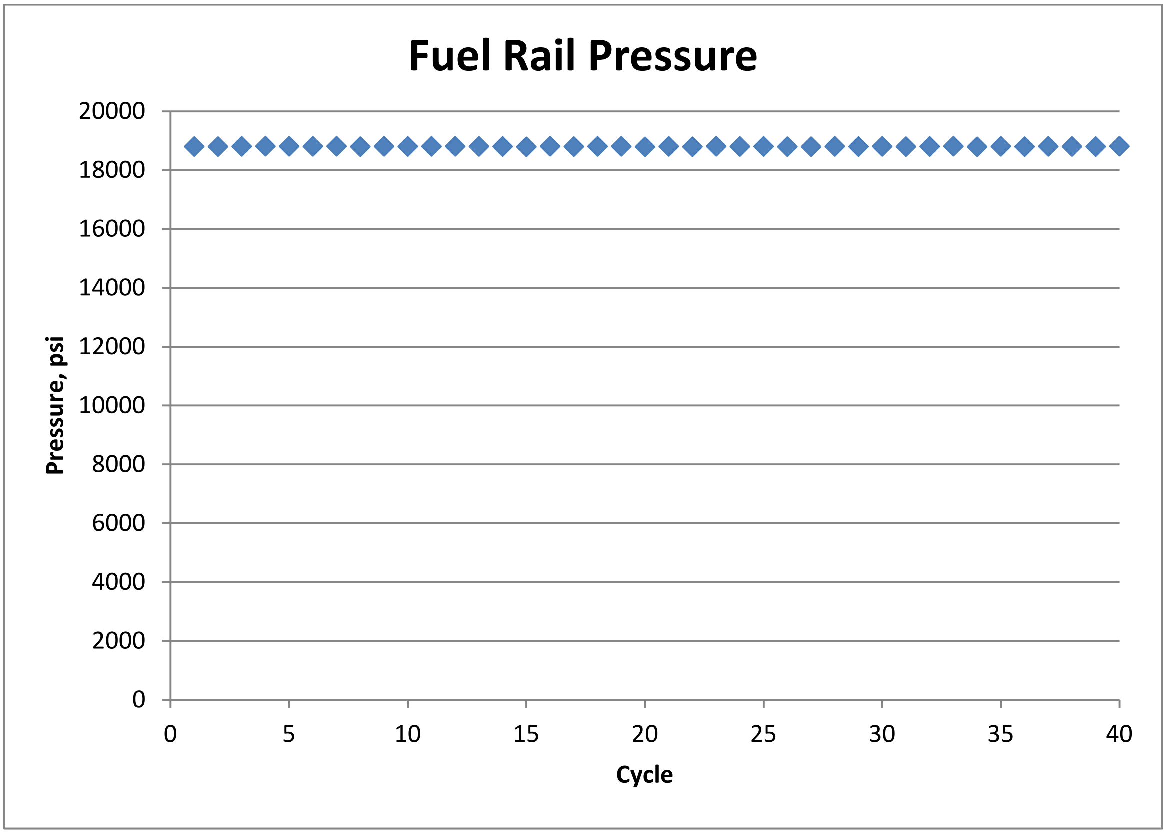

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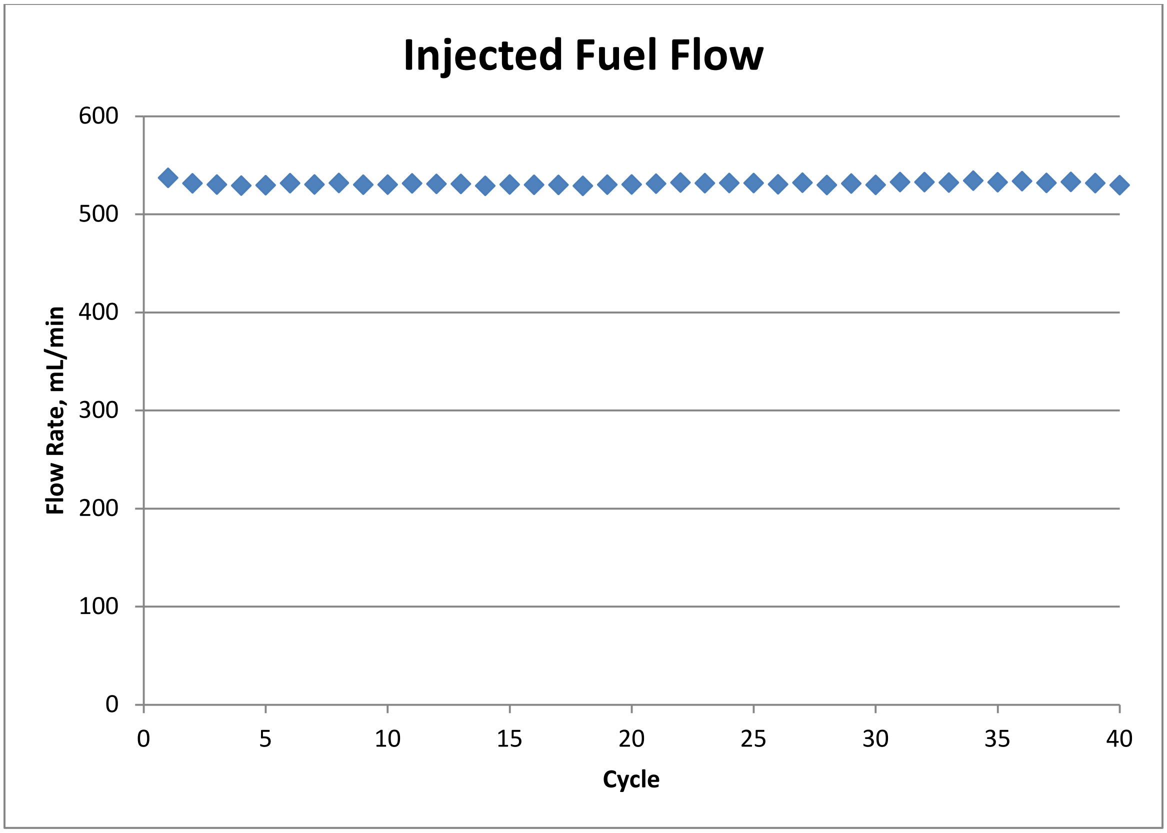

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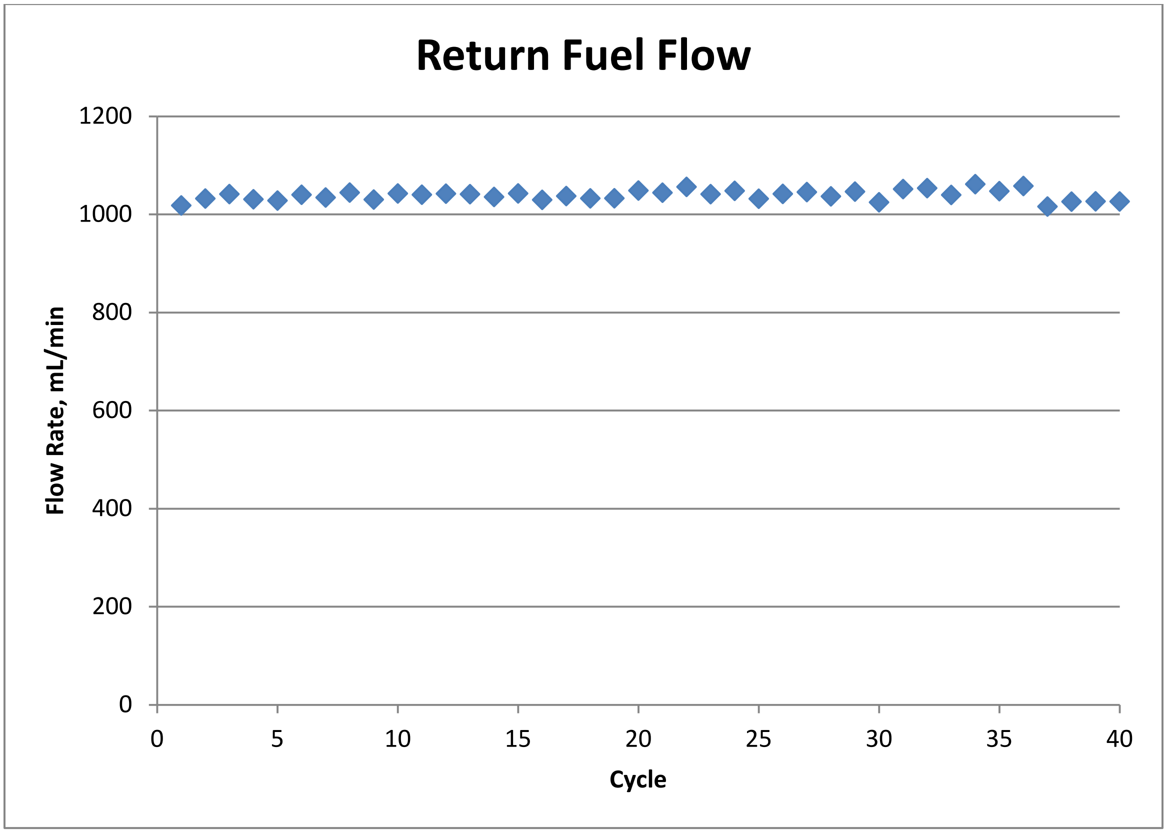

Figure C-4. Return Fuel Flow

Figure C-5 shows the system inlet temperature. This was controlled through a pulse-width modulated heater element. Temperature remained within proper control through the test.

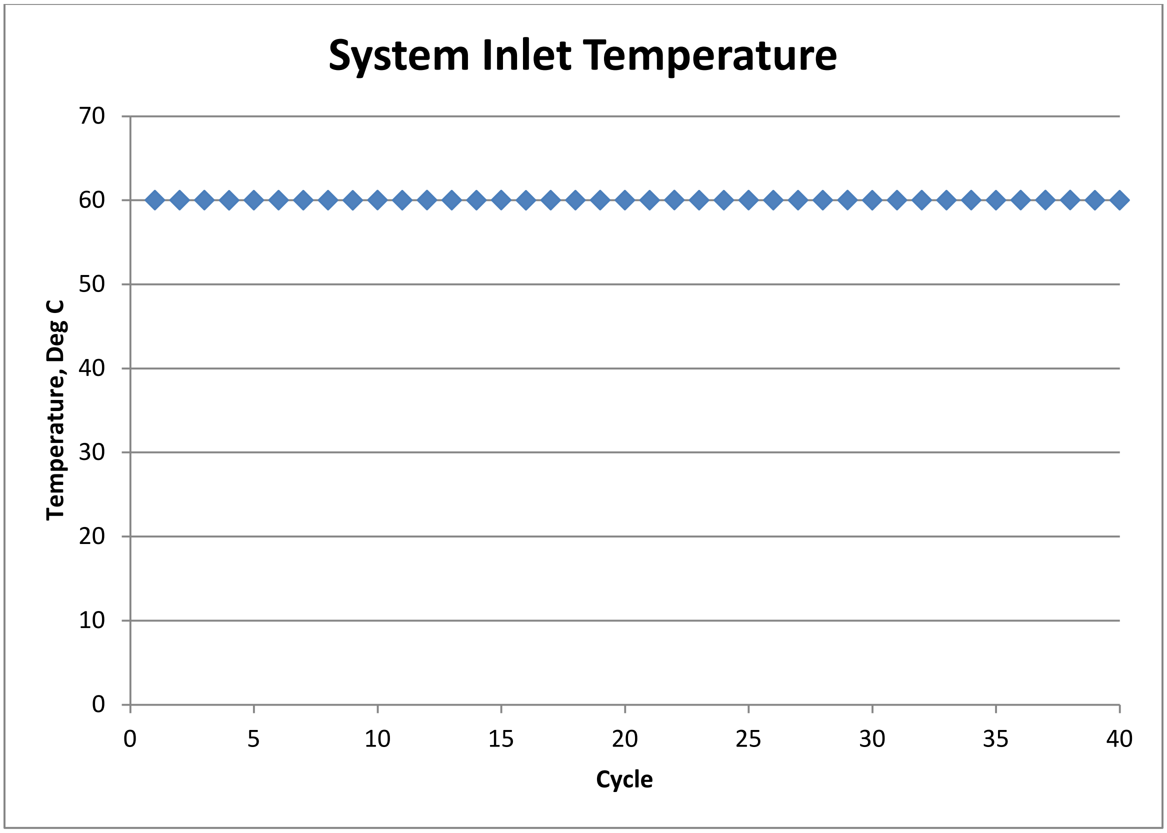

Figure C-5. System Inlet Fuel Temperature

Figure C-6 shows a measure of the fuel pressure as it was supplied to the final filter element by the electric lift pump.

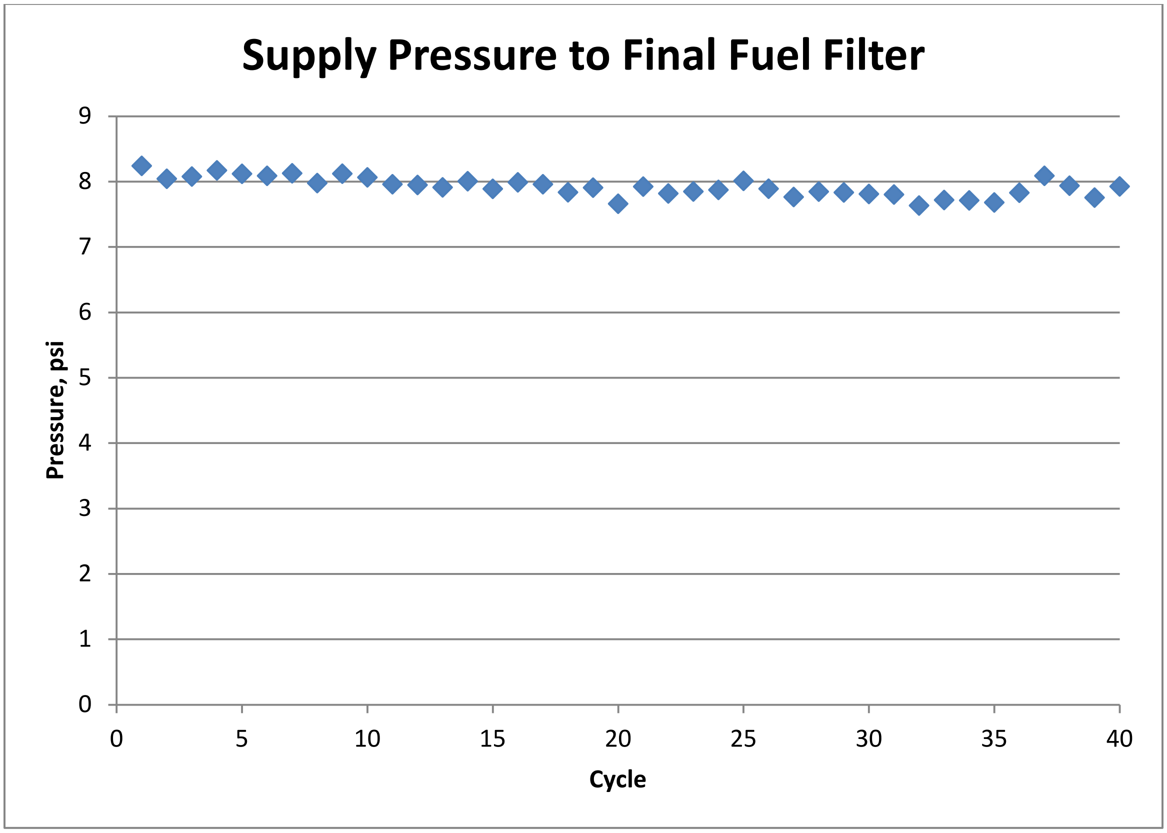

Figure C-6. Fuel Filter Pressure

A summary of the operating conditions for each 100 hour period are provided in Table C-2.

Table C-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.2	57.6	60.8
Bypass Fuel Temperature, deg C	104.6	2.6	85.9	107.7
Rail Pressure, psi	18811	28	18610	18911
Injected Flow Rate, mL/min	530.9	21.0	430.6	543.3
Return Fuel Flow Rate, mL/min	1033.2	16.5	915.4	1061.7
Fuel Filter Inlet Pressure, psi	8.1	0.1	7.8	8.9
Test Hours 100-200				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.2	57.7	60.9
Bypass Fuel Temperature, deg C	104.5	2.5	85.0	108.7
Rail Pressure, psi	18809	32	18456	18932
Injected Flow Rate, mL/min	529.9	22.4	414.1	542.4
Return Fuel Flow Rate, mL/min	1037.5	11.5	966.5	1062.8
Fuel Filter Inlet Pressure, psi	7.9	0.1	7.4	8.4
Test Hours 200-300				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.2	57.9	60.9
Bypass Fuel Temperature, deg C	105.7	3.1	58.0	108.9
Rail Pressure, psi	18807	30	18535	18969
Injected Flow Rate, mL/min	531.0	21.0	425.3	543.7
Return Fuel Flow Rate, mL/min	1040.9	16.1	853.8	1080.4
Fuel Filter Inlet Pressure, psi	7.9	0.1	7.5	9.0
Test Hours 300-400				
	Mean	**Std. Dev.**	**Min**	**Max**
System Inlet Temperature, deg C	60.0	0.2	57.8	62.3
Bypass Fuel Temperature, deg C	105.5	3.2	61.0	108.9
Rail Pressure, psi	18809	33	18628	18934
Injected Flow Rate, mL/min	532.2	16.7	436.6	542.2
Return Fuel Flow Rate, mL/min	1039.9	21.0	874.9	1082.8
Fuel Filter Inlet Pressure, psi	7.8	0.2	7.5	8.7

Lubricity Fuel Analysis

Fuel lubricity 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 Figure C-7 and Figure C-8.

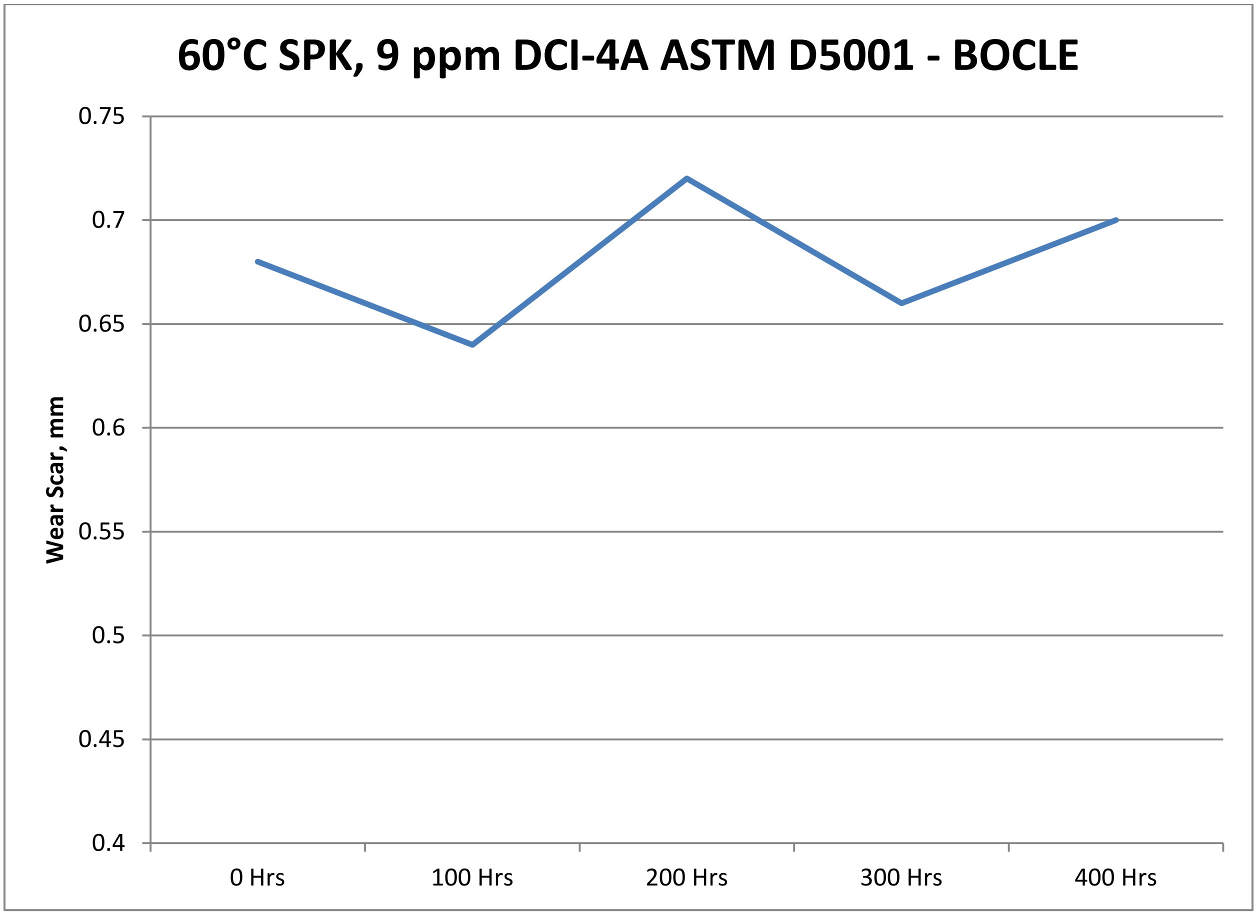

Figure C-7. ASTM D5001 BOCLE

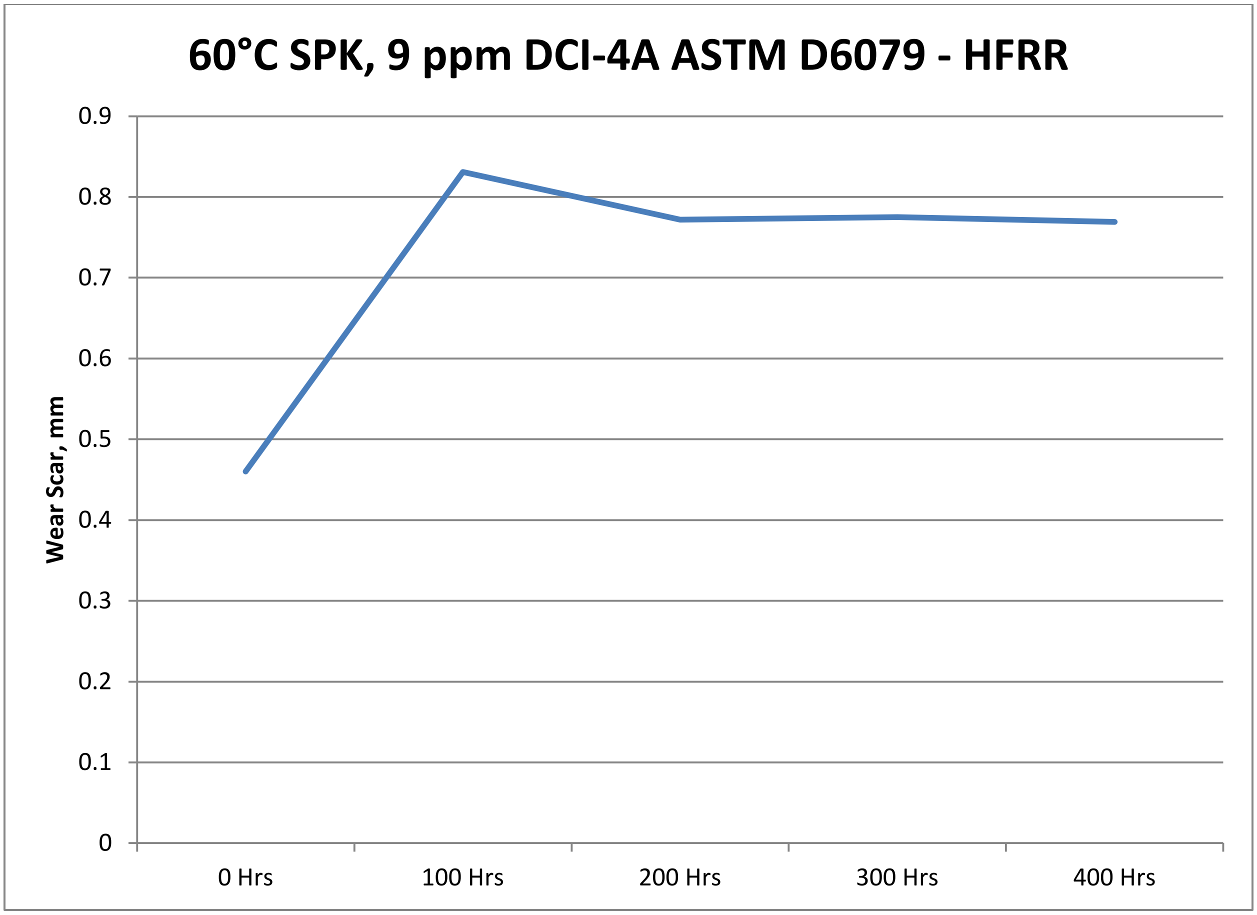

Figure C-8. ASTM D6079 HFRR

Component Wear

Post-test tear disassembly of the pump and injectors was performed to evaluate wear operating on SPK at 60°C inlet with 9 ppm DCI-4A. The following figures highlight various areas of the pump and injectors.

Fuel Pump

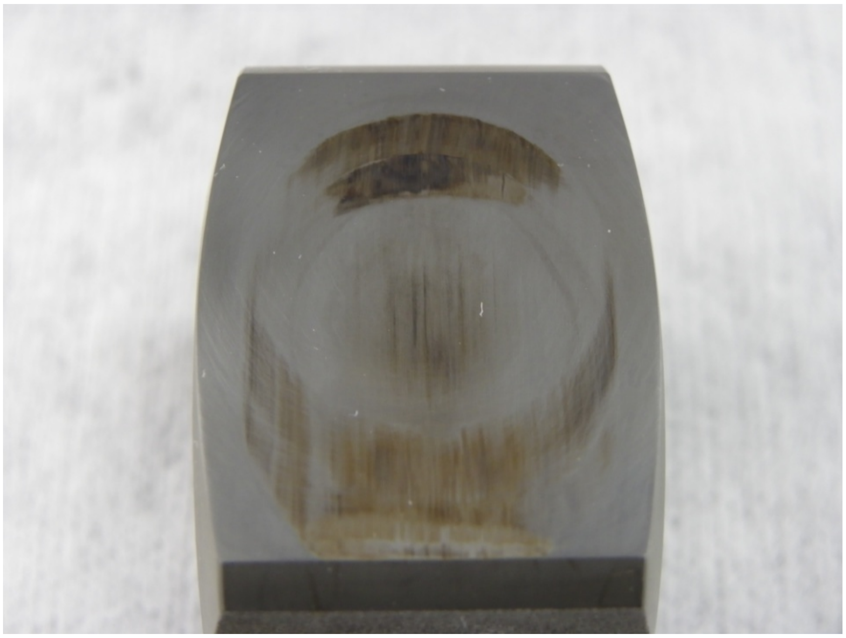

Figure C-9. Ring Cam - Top

Figure C-10. Plunger Face - Top

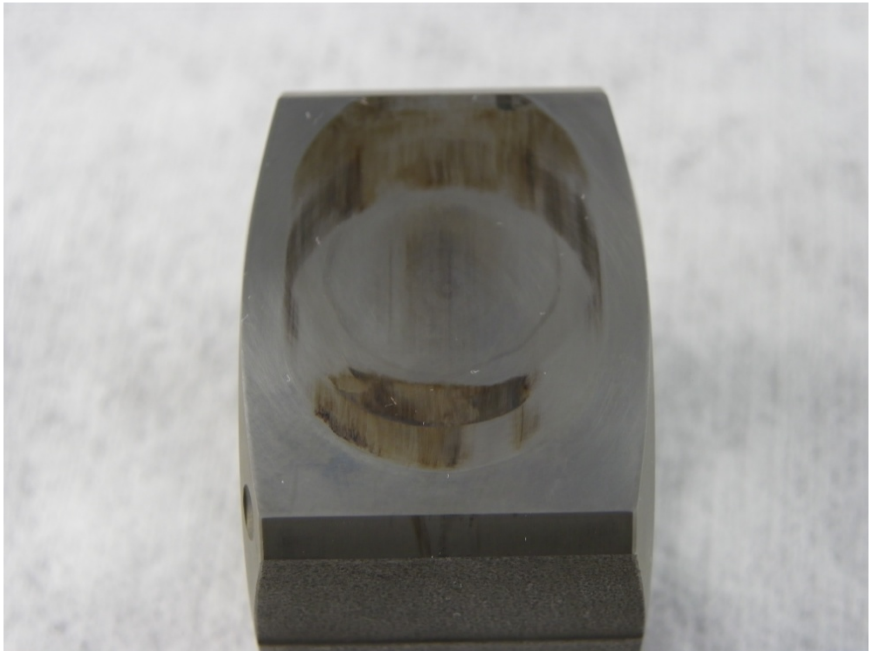

Figure C-11. Ring Cam - Bottom

Figure C-12. Plunger - Bottom

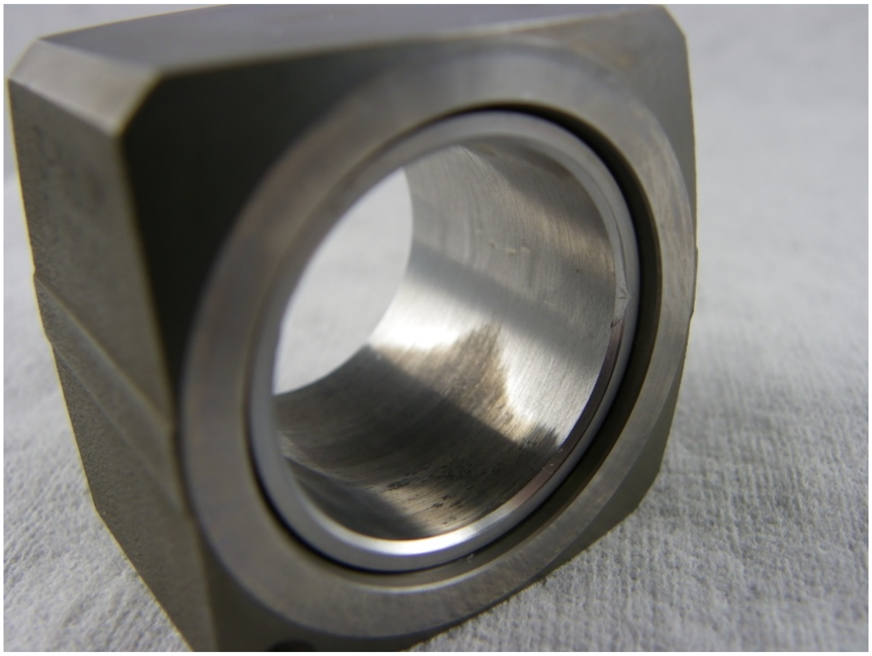

Figure C-13. Ring Cam – Front

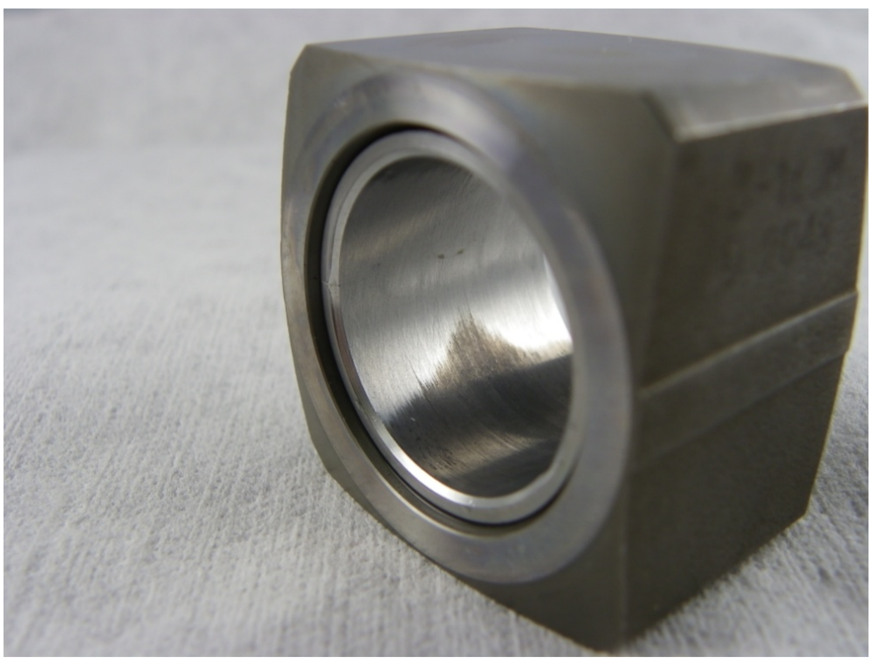

Figure C-14. Ring Cam - Rear

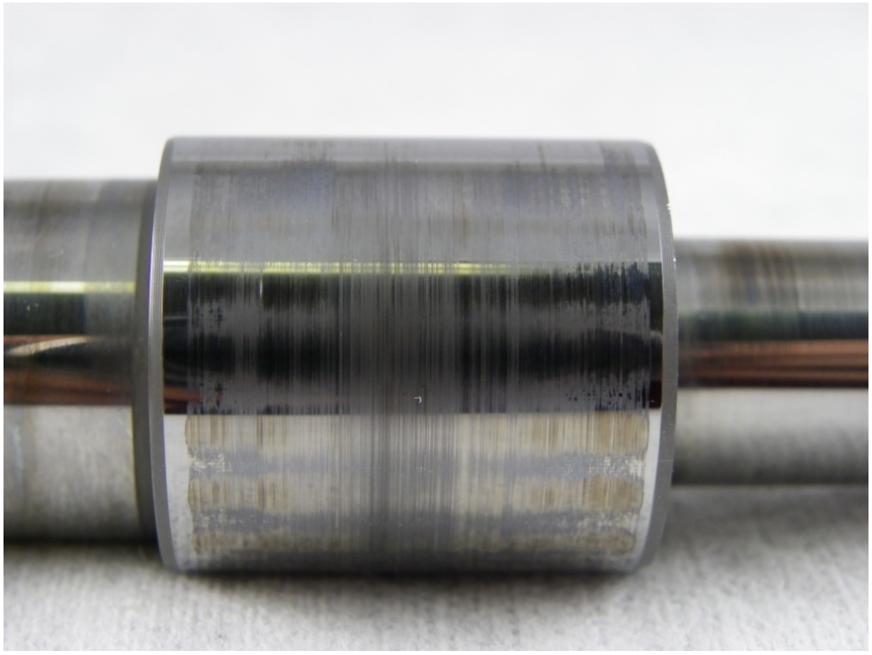

Figure C-15. Eccentric Cam Lobe

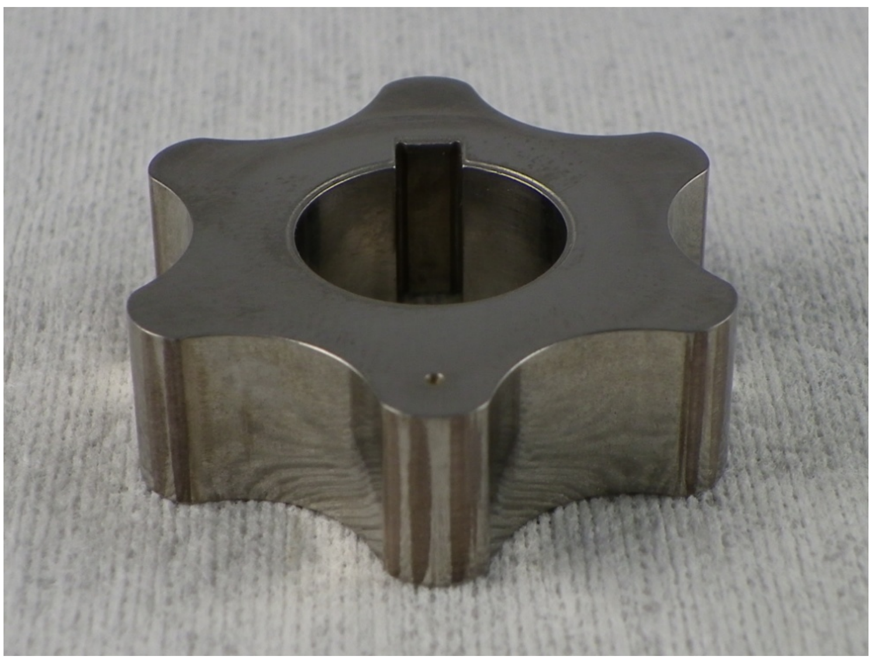

Figure C-16. Transfer Pump Gear

Fuel Injector

Figure C-17. Injector Needle

Figure C-18. Lower Injector Connecting Pin

Figure C-19. Upper Injector Connecting Pin

APPENDIX D

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: FT-SPK with 9 ppm DCI-4A
Test Number: SPK-9 ppm-93°C-JD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

John Deere 4.5L Powertech Plus

Test Fuel: FT-SPK with 9 ppm DCI-4A
Test Number: SPK-9 ppm-93°C-JD
Start of Test Date: July 9, 2012
End of Test Date: July 9, 2012
Test Duration: 4:20:48 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

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

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Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) performed a project for US Army TARDEC on synthetic and alternative fuels. The project goal was 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 and viscosity impact of various fuels. Using a test bench method was 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, Jet A, an FT SPK treated with corrosion inhibitor/lubricity improver (CI/LI), and a 1:1 blend of 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. The lower temperature ULSD test is considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the John Deere 4.5L Powertech Plus fuel system manufactured by Denso. The fuel-lubricated high pressure pump allows the system to reach rail pressures of up to 20,000 psi. It is operated at the same rotational speed as the engine crankshaft for a rated condition of 2400 rpm. Within the pump, the camshaft drives two plungers, in an opposed orientation, which pressurize the fuel entering the rail. Each plunger is driven by a single ring cam which rotates on an eccentric lobe of the pump shaft. The low pressure system consists of an external electric lift pump and filter combination to remove large particles and water along with a high efficiency final filter before entering the high pressure pump. An internal transfer pump pressurizes fuel prior to entry into the high pressure plunger bore. Injectors are solenoid driven and controlled by the ECM. For each fuel test a new high pressure pump, filters, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand modified for Powertech Plus 4.5L 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 an engine control module (ECM) modified by John Deere 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 pump consisted of two plungers which compressed fuel to reach the desired rail pressure. Fuel then flowed 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 under the cylinder head, cooled to a consistent temperature, 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.

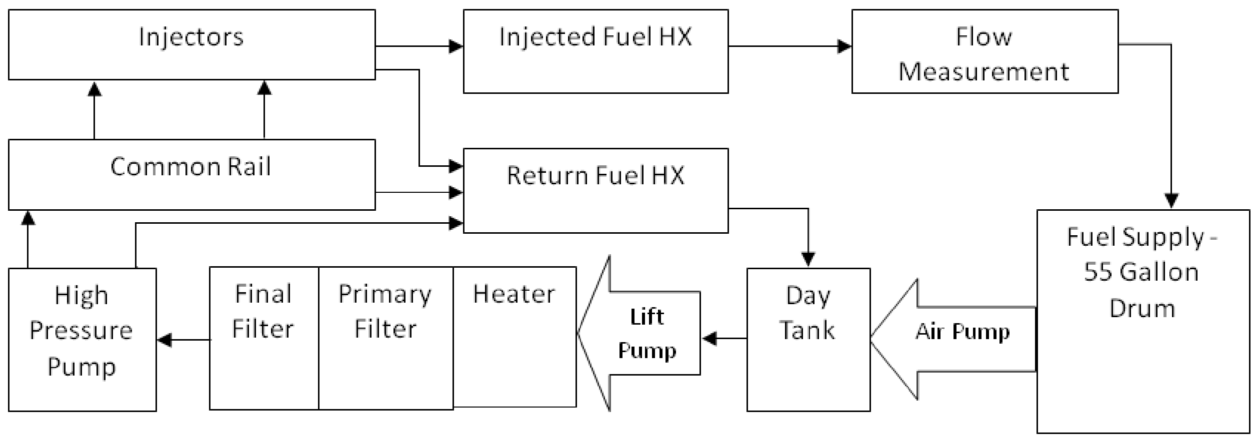

Figure D-1. Fuel System Layout

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 John Deere 4.5L Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	800	0	0.5
2	2400	100	2
3	2560	0	0.5
4	1800	100	1
5*	800 to 2400	0 to 100	2
6	1440	100	0.5
7	800	0	0.5
8	2500	70	0.5
9	1500	100	2
10	1440	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are for the entire test prior to failure. 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 Deere supplied ECM for monitoring purposes, shown in Figure D-2. Calibration of this channel was performed using the Deere service tool through the SAE J1939 CAN bus. The system did not experience any performance issues related to rail pressure during the course of the test.

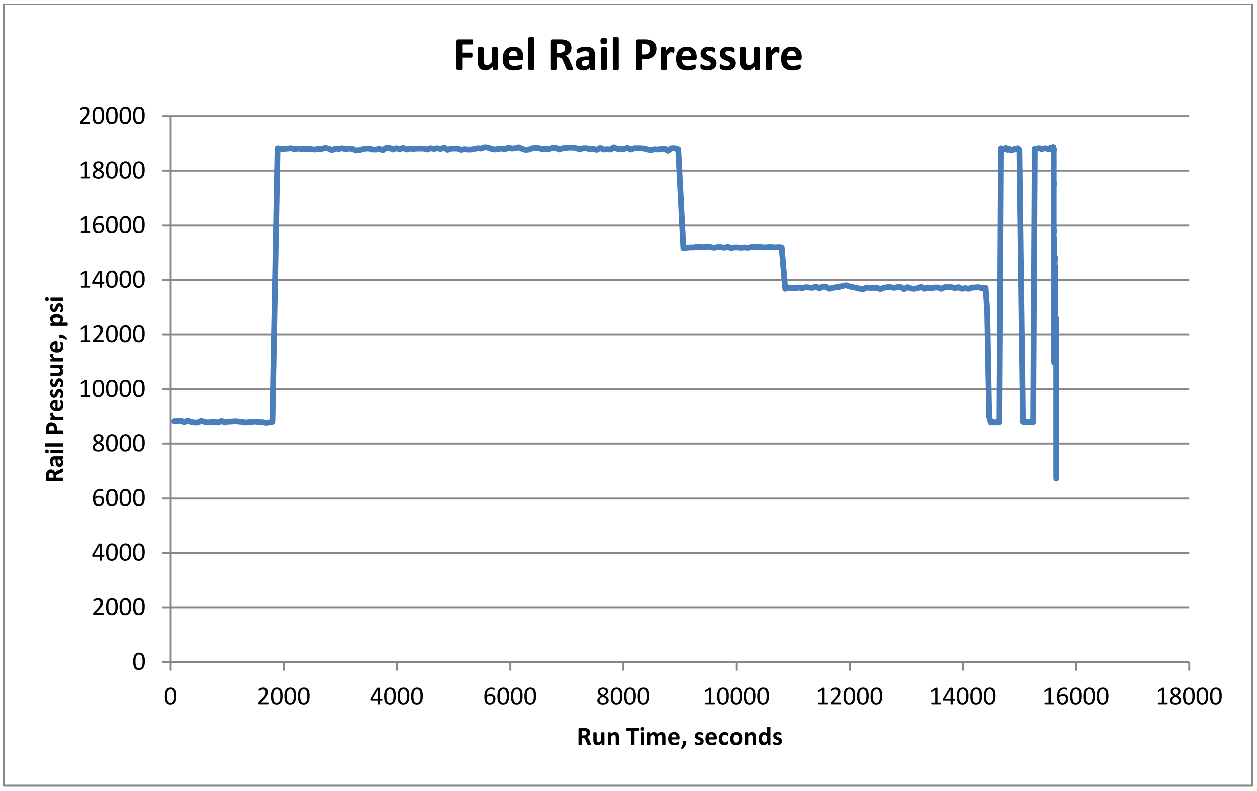

Figure D-2. Fuel Rail Pressure

The flow rate for injected fuel is shown in Figure D-3.

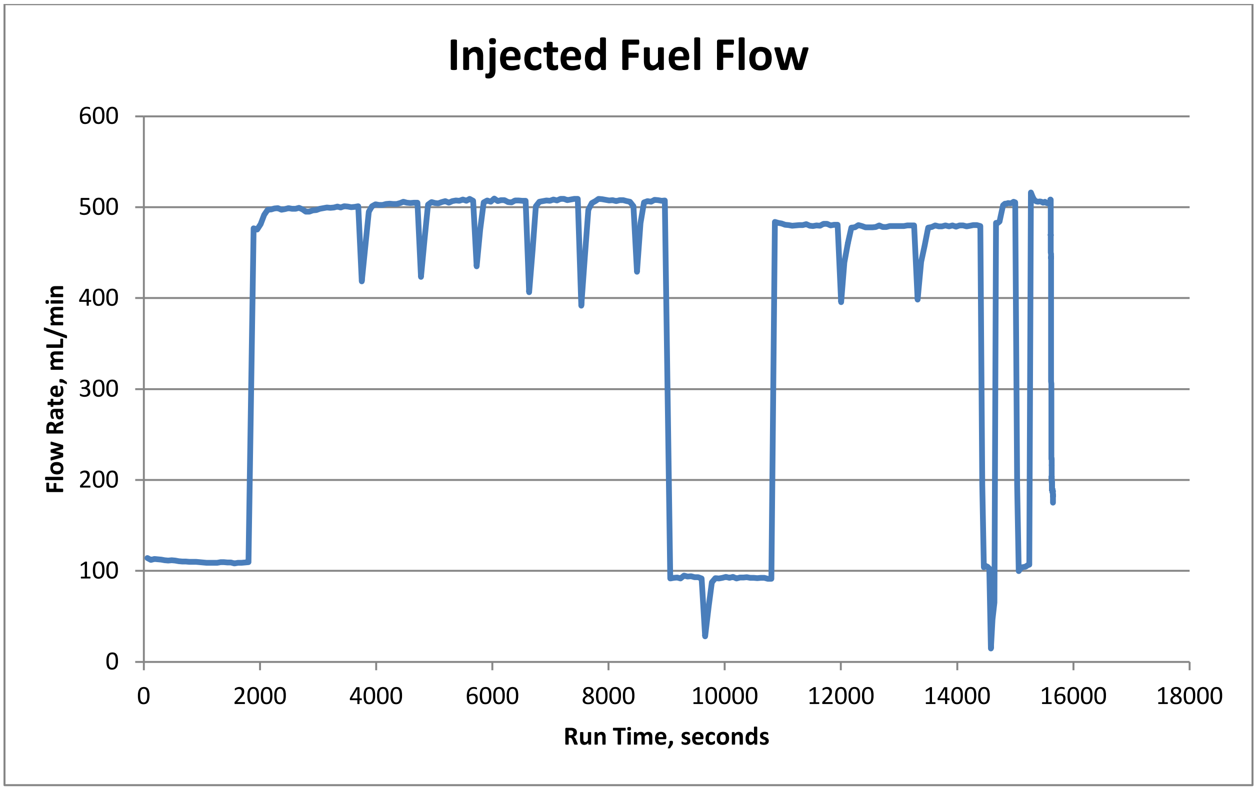

Figure D-3. Injected Fuel Flow

Figure D-4 shows the return fuel from the injectors, rail, and high pressure pump.

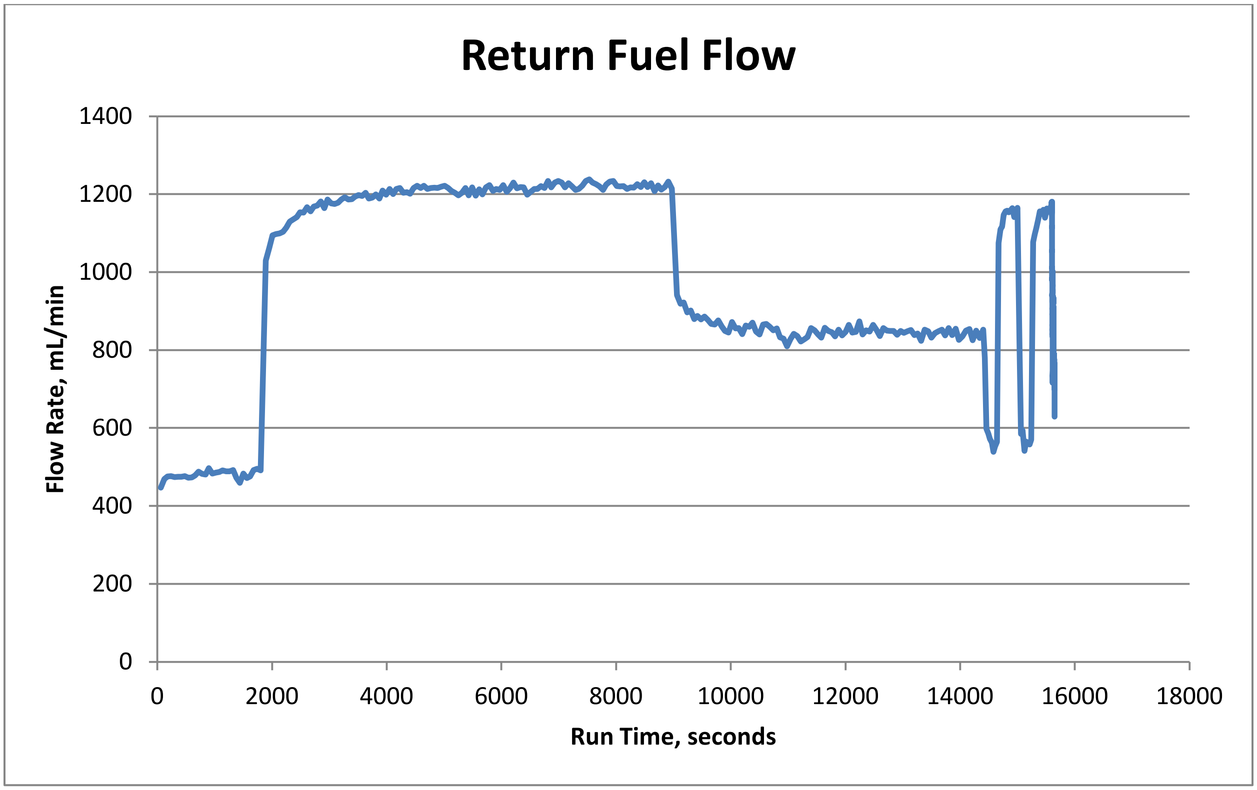

Figure D-4. Return Fuel Flow

Figure D-5 shows the system inlet temperature. This was controlled through a pulse-width modulated heater element. Some overshoot was experienced at flow rate changes.

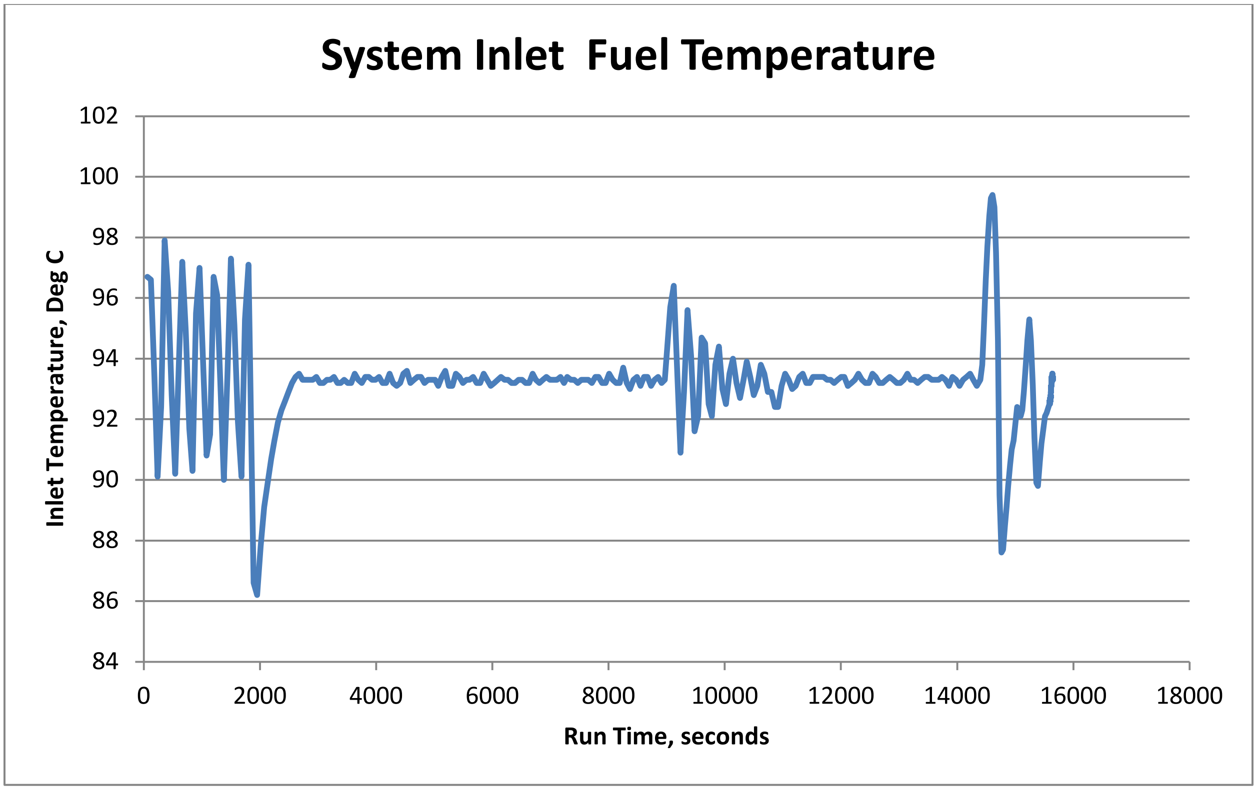

Figure D-5. System Inlet Fuel Temperature

Figure D-6 shows a measure of the fuel pressure as it was supplied to the final filter element by the electric lift pump.

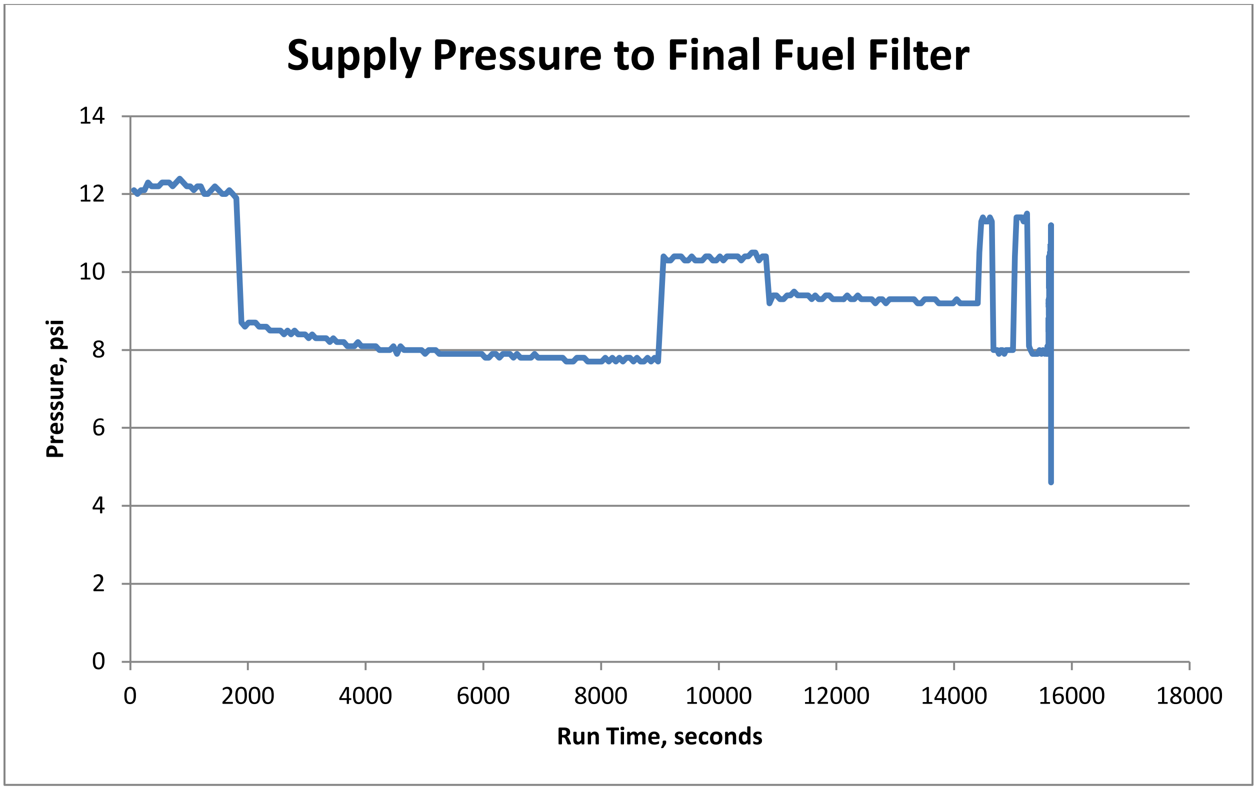

Figure D-6. Fuel Filter Pressure

Lubricity Fuel Analysis

Fuel lubricity was evaluated at the beginning of the test and after failure at 4 hours. Results are shown in Table D-2.

Table D-2. Fuel Lubricity

ASTM Test	Wear Scar Diameter, mm
D5001 BOCLE	0.64
D6079 HFRR	0.841

Component Wear

Post-test tear disassembly of the pump and injectors was performed to evaluate wear operating on SPK at 93.3°C inlet with 9 ppm DCI-4A. The following figures highlight various areas of the pump at the time of failure. Injectors were not removed due to use with a second pump at the same fuel conditions.

Fuel Pump

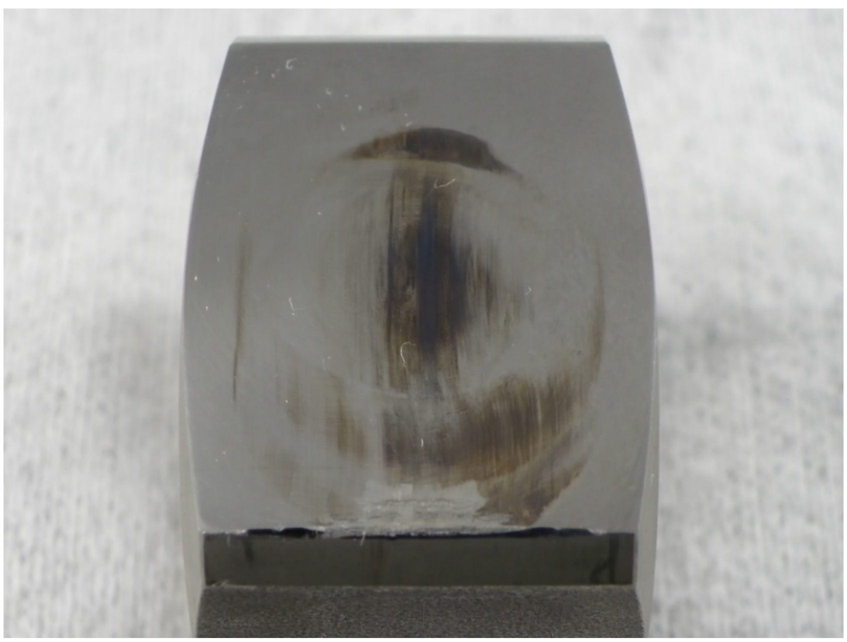

Figure D-7. Ring Cam - Top

Figure D-8. Plunger Face - Top

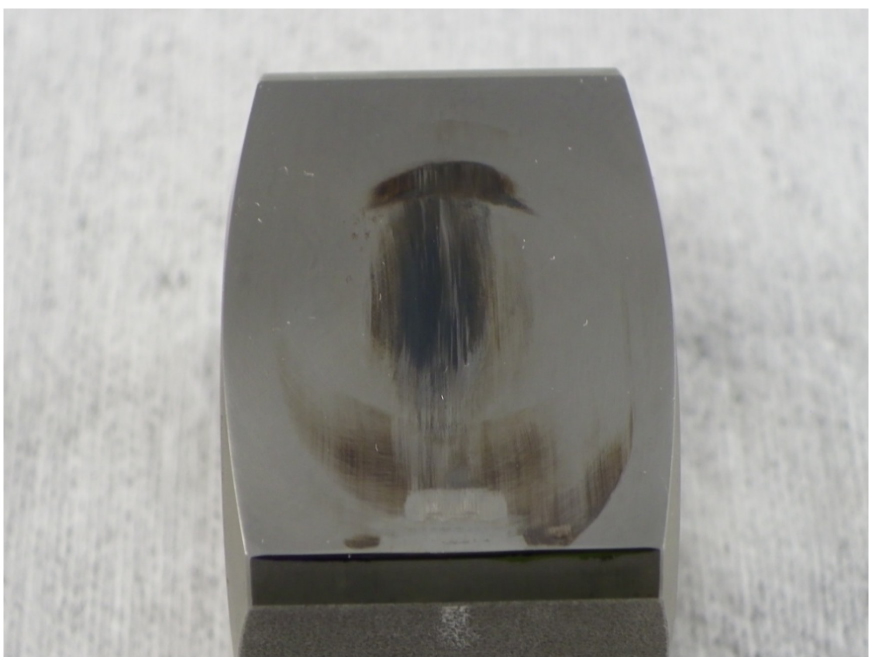

Figure D-9. Ring Cam - Bottom

Figure D-10. Plunger - Bottom

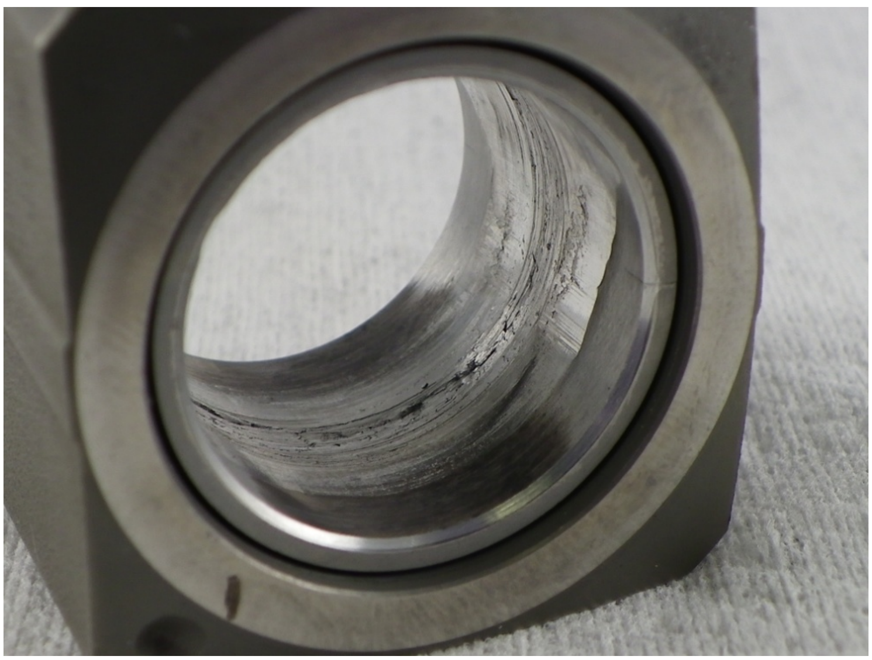

Figure D-11. Ring Cam – Front

Figure D-12. Eccentric Cam Lobe

Figure D-13. Transfer Pump Gear

Figure D-14. Cam Input

APPENDIX E

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: FT-SPK with 9 ppm DCI-4A
Test Number: SPK-9 ppm-93°C-JD2

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

John Deere 4.5L Powertech

Test Fuel: FT-SPK with 9 ppm DCI-4A

Test Number: SPK-9 ppm-93°C-JD2

Start of Test Date: July 11, 2012

End of Test Date: July 11, 2012

Test Duration: 4:04:11 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC

Force Projection Technologies

Warren, Michigan

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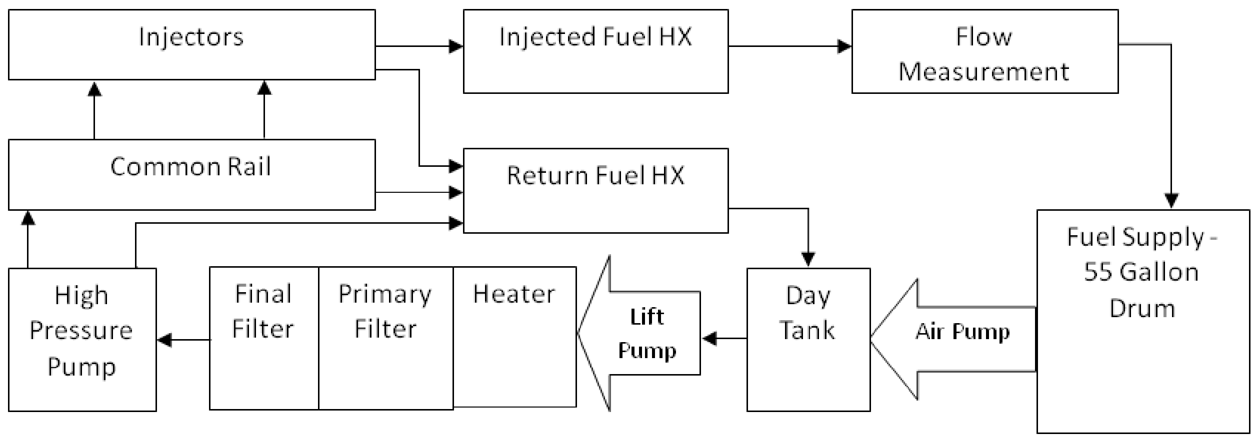

Figure E-1. Fuel System Layout

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 John Deere 4.5L Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	800	0	0.5
2	2400	100	2
3	2560	0	0.5
4	1800	100	1
5*	800 to 2400	0 to 100	2
6	1440	100	0.5
7	800	0	0.5
8	2500	70	0.5
9	1500	100	2
10	1440	50	0.5

*Step 5 cycles between idle and rated conditions

System Operating Conditions

Graphs shown for System Operating Conditions are for the entire test prior to failure. 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 Deere supplied ECM for monitoring purposes, shown in Figure E-2. Calibration of this channel was performed using the Deere service tool through the SAE J1939 CAN bus. The system did not experience any performance issues related to rail pressure during the course of the test.

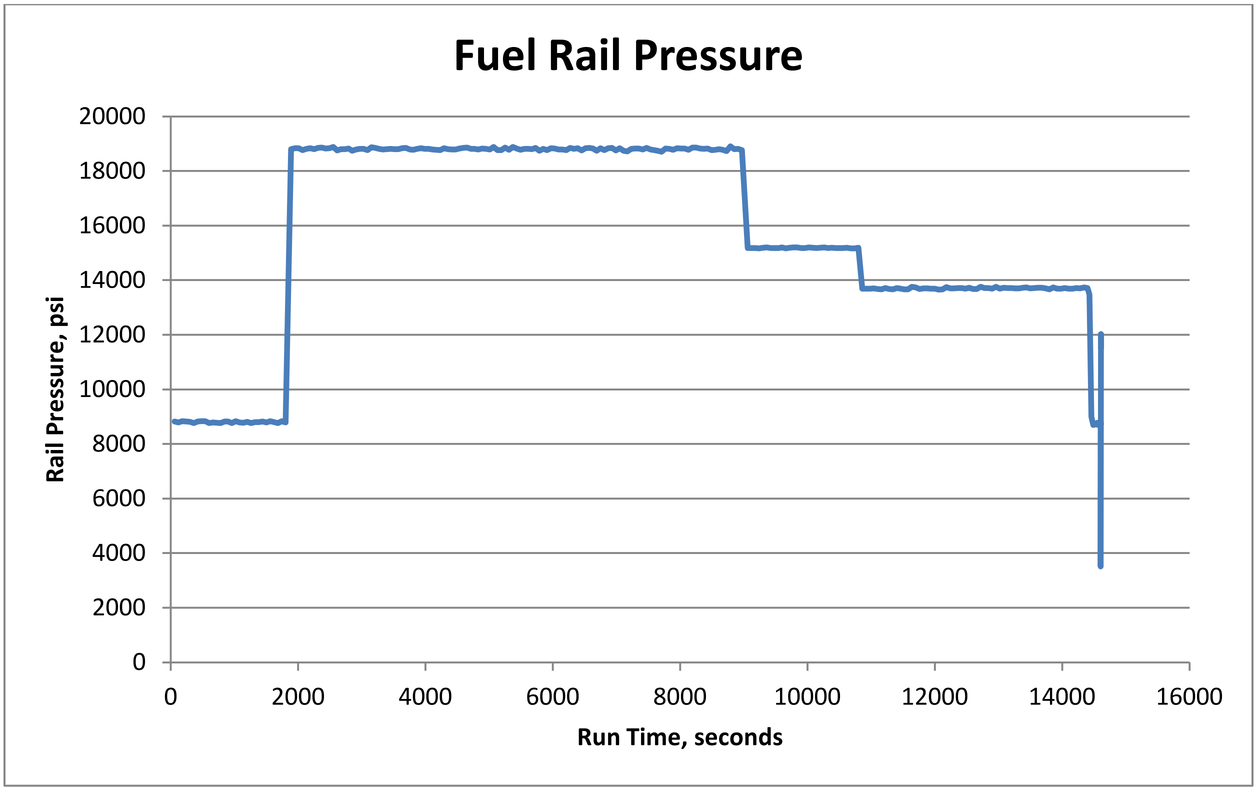

Figure E-2. Fuel Rail Pressure

The flow rate for injected fuel is shown in Figure E-3.

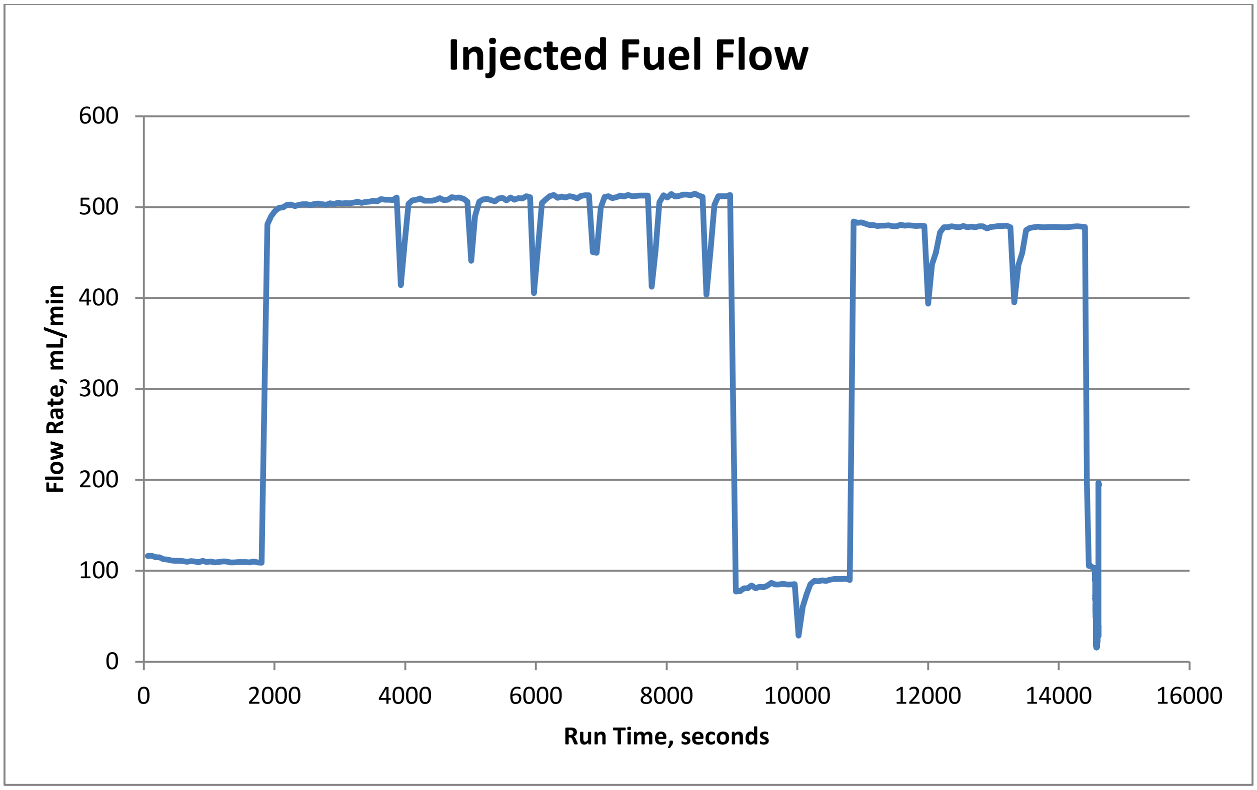

Figure E-3. Injected Fuel Flow

Figure E-4 shows the return fuel from the injectors, rail, and high pressure pump.

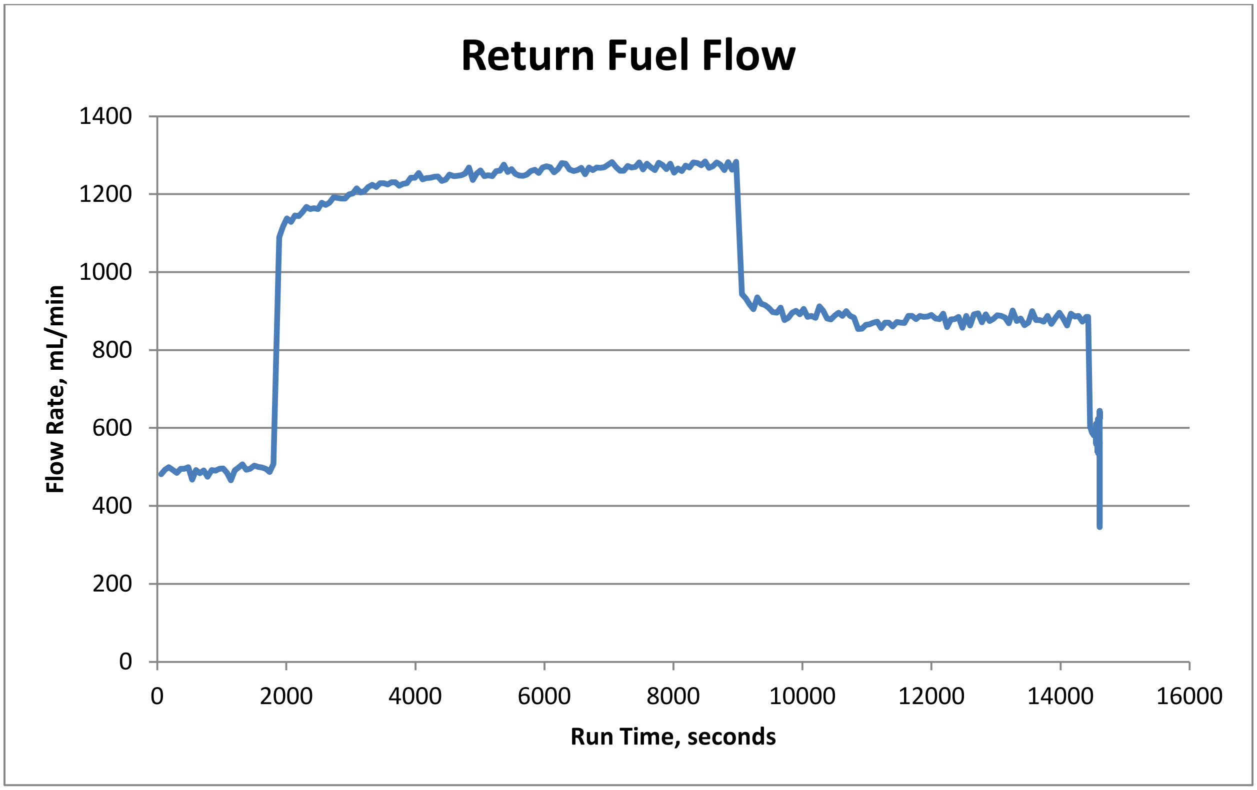

Figure E-4. Return Fuel Flow

Figure E-5 shows the system inlet temperature. This was controlled through a pulse-width modulated heater element. Some overshoot was experienced at flow rate changes.

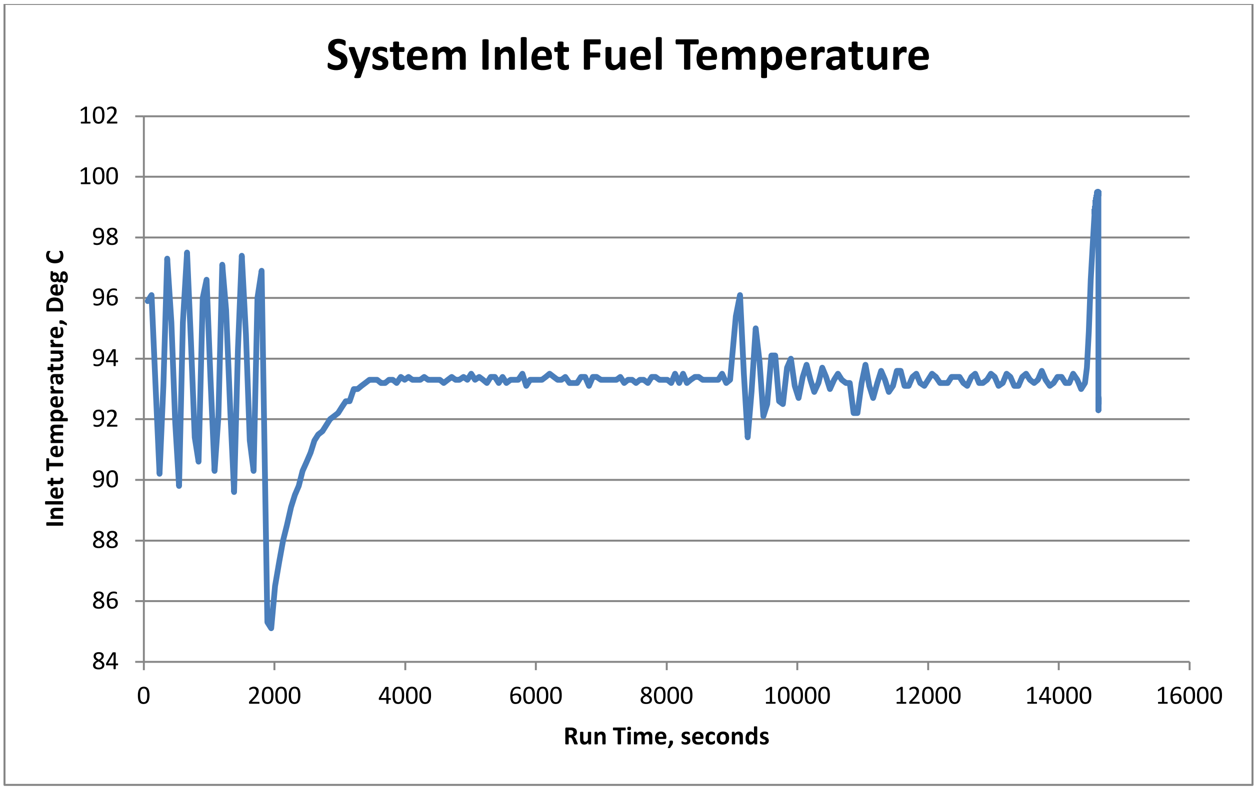

Figure E-5. System Inlet Fuel Temperature

Figure E-6 shows a measure of the fuel pressure as it was supplied to the final filter element by the electric lift pump.

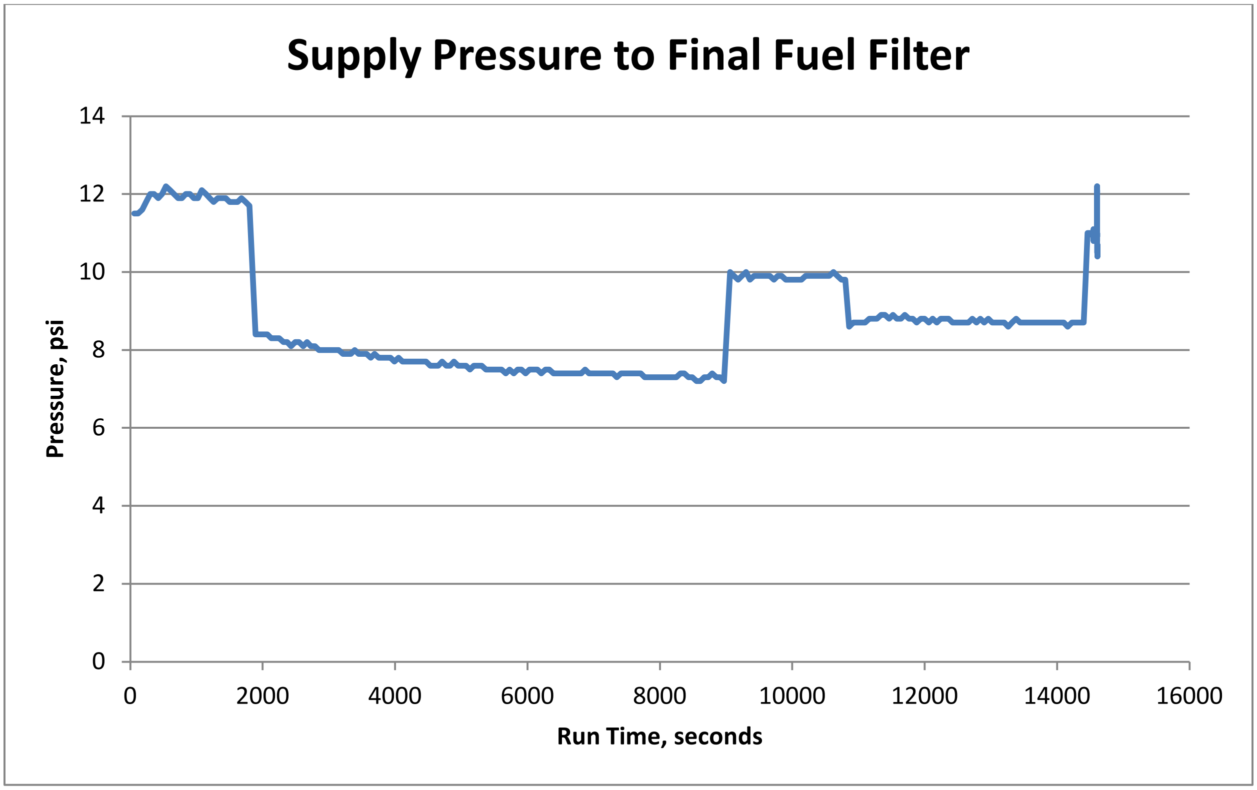

Figure E-6. Fuel Filter Pressure

Lubricity Fuel Analysis

Fuel lubricity was evaluated at the beginning of the test and after failure at 4 hours. Results are shown in Table E-2.

Table E-2. Fuel Lubricity

ASTM Test	Wear Scar Diameter, mm
D5001 BOCLE	0.64
D6079 HFRR	0.841

Component Wear

Post-test tear disassembly of the pump and injectors was performed to evaluate wear operating on SPK at 93.3°C inlet with 9 ppm DCI-4A. The following figures highlight various areas of the pump at the time of failure. Injectors were not removed due to use with a second pump at the same fuel conditions.

Fuel Pump

Figure E-7. Ring Cam - Top

Figure E-8. Plunger Face – Top

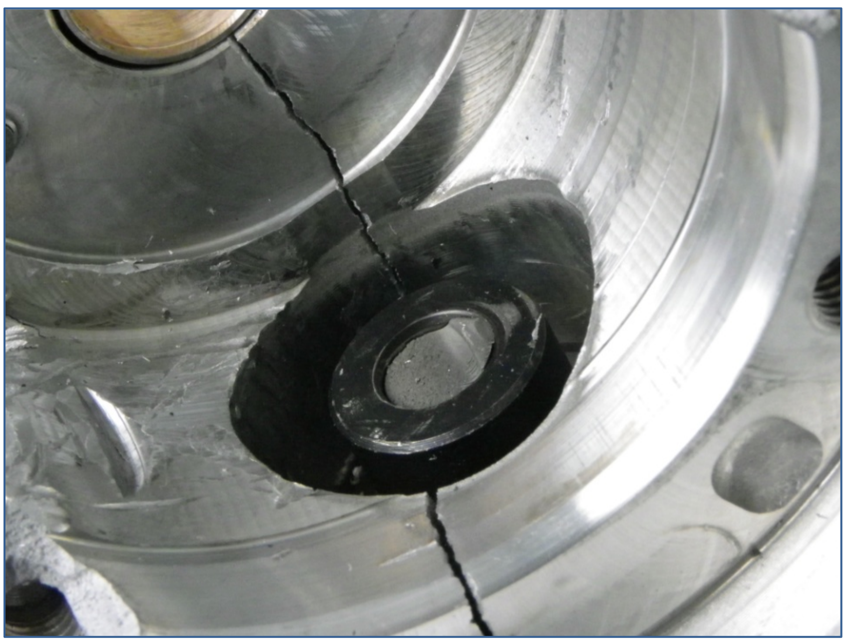

Figure E-9. Plunger Shaft - Top

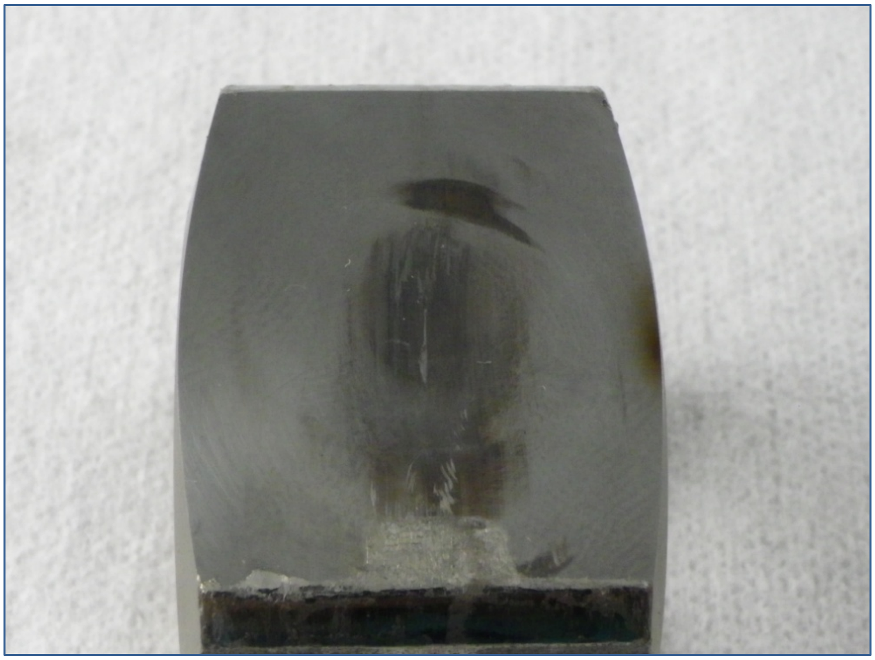

Figure E-10. Ring Cam - Bottom

Figure E-11. Plunger - Bottom

Figure E-12. Ring Cam – Front

Figure E-13. Eccentric Cam Lobe

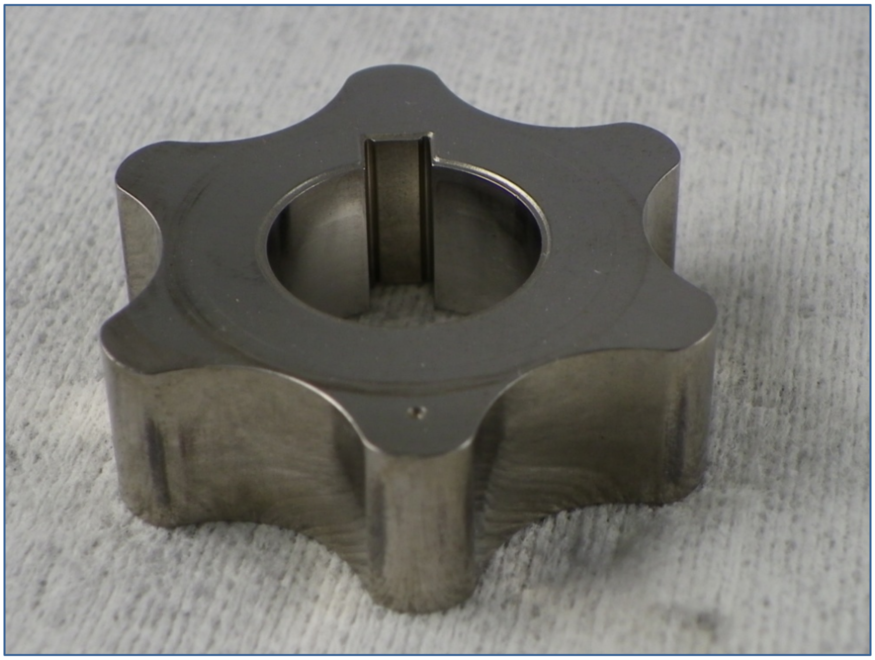

Figure E-14. Transfer Pump Gear

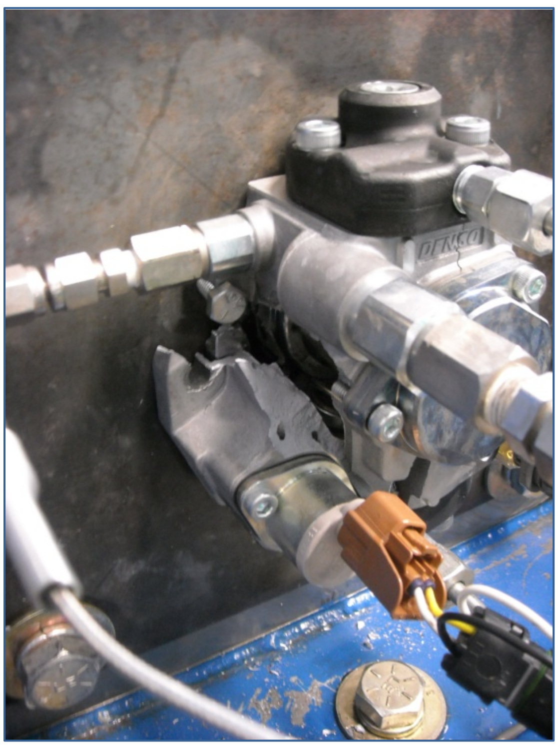

Figure E-15. Pump Body Failure

Figure E-16. Pump Body Failure 2

APPENDIX F

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: Jet A with 9 ppm DCI-4A
Test Number: Jet A-9 ppm-60°C-JD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

John Deere 4.5L Powertech Plus

Test Fuel: Jet A with 9 ppm DCI-4A
Test Number: Jet A-9 ppm-60°C-JD
Start of Test Date: April 12, 2012
End of Test Date: May 8, 2012
Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

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

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Introduction and Background

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute (SwRI) performed a project for US Army TARDEC on synthetic and alternative fuels. The project goal was 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 and viscosity impact of various fuels. Using a test bench method was 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, Jet A, an FT SPK treated with corrosion inhibitor/lubricity improver (CI/LI), and a 1:1 blend of 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. The lower temperature ULSD test is considered a baseline for comparison of other tests.

Test System

Test fuel was evaluated in the John Deere 4.5L Powertech Plus fuel system manufactured by Denso. The fuel-lubricated high pressure pump allows the system to reach rail pressures of up to 20,000 psi. It is operated at the same rotational speed as the engine crankshaft for a rated condition of 2400 rpm. Within the pump, the camshaft drives two plungers, in an opposed orientation, which pressurize the fuel entering the rail. Each plunger is driven by a single ring cam which rotates on an eccentric lobe of the pump shaft. The low pressure system consists of an external electric lift pump and filter combination to remove large particles and water along with a high efficiency final filter before entering the high pressure pump. An internal transfer pump pressurizes fuel prior to entry into the high pressure plunger bore. Injectors are solenoid driven and controlled by the ECM. For each fuel test a new high pressure pump, filters, and injector components were used.

Test Stand Configuration

The pump and hardware was mounted in a test stand modified for Powertech Plus 4.5L 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 an engine control module (ECM) modified by John Deere 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 pump consisted of two plungers which compressed fuel to reach the desired rail pressure. Fuel then flowed 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 under the cylinder head, cooled to a consistent temperature, 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.

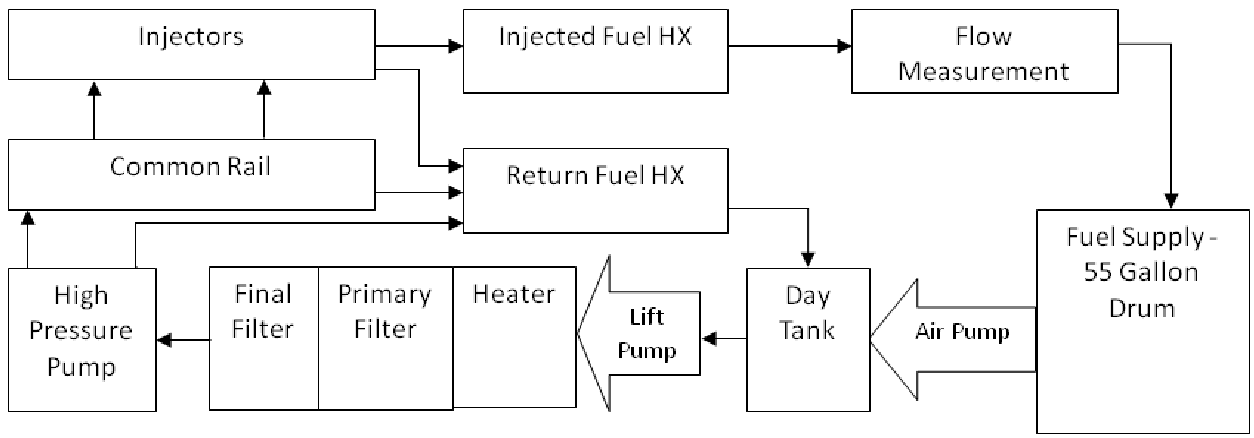

Figure F-1. Fuel System Layout

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 John Deere 4.5L Pump Stand

Step	Pump Speed, RPM	Throttle, %	Duration, hrs
1	800	0	0.5
2	2400	100	2
3	2560	0	0.5
4	1800	100	1
5*	800 to 2400	0 to 100	2
6	1440	100	0.5
7	800	0	0.5
8	2500	70	0.5
9	1500	100	2
10	1440	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 Deere supplied ECM for monitoring purposes, shown in Figure F-2. Calibration of this channel was performed using the Deere service tool through the SAE J1939 CAN bus. The system did not experience any performance issues related to rail pressure during the course of the test.

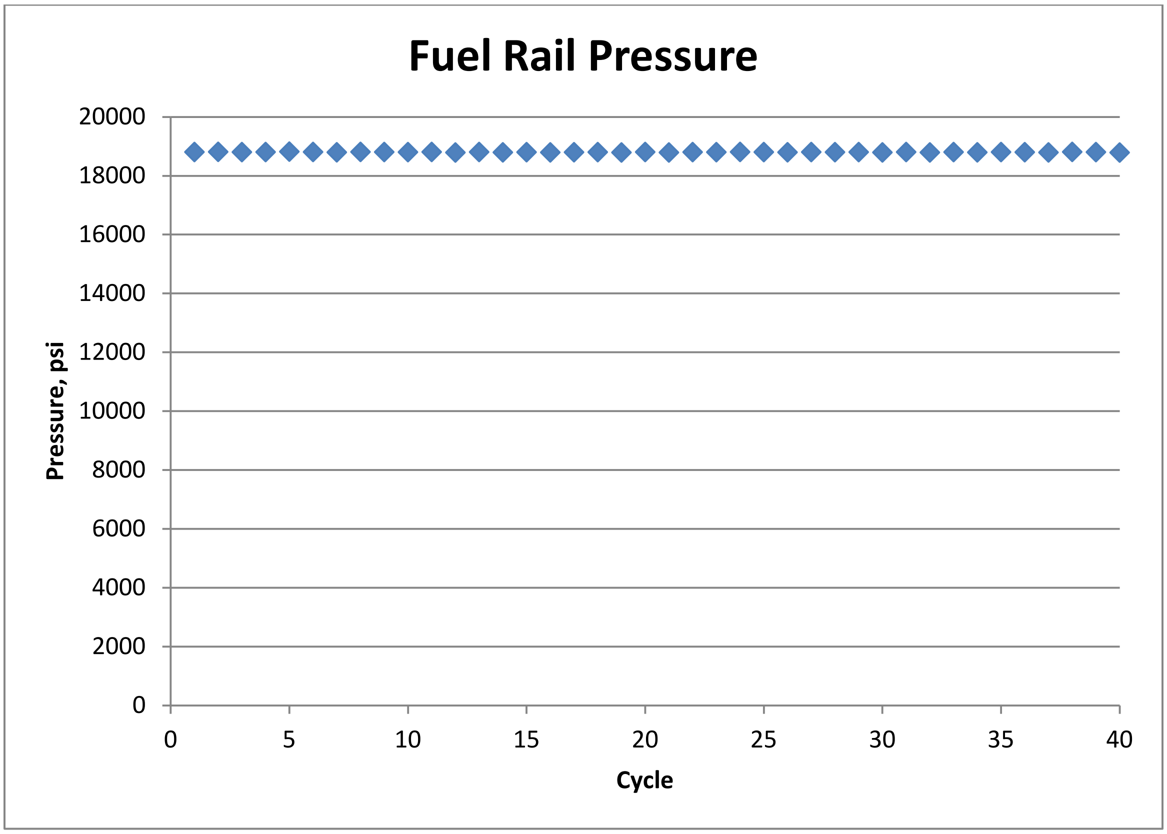

Figure F-2. Fuel Rail Pressure

The flow rate for injected fuel is shown in Figure F-3. There is no major change in fuel flow rate over the duration of the test.

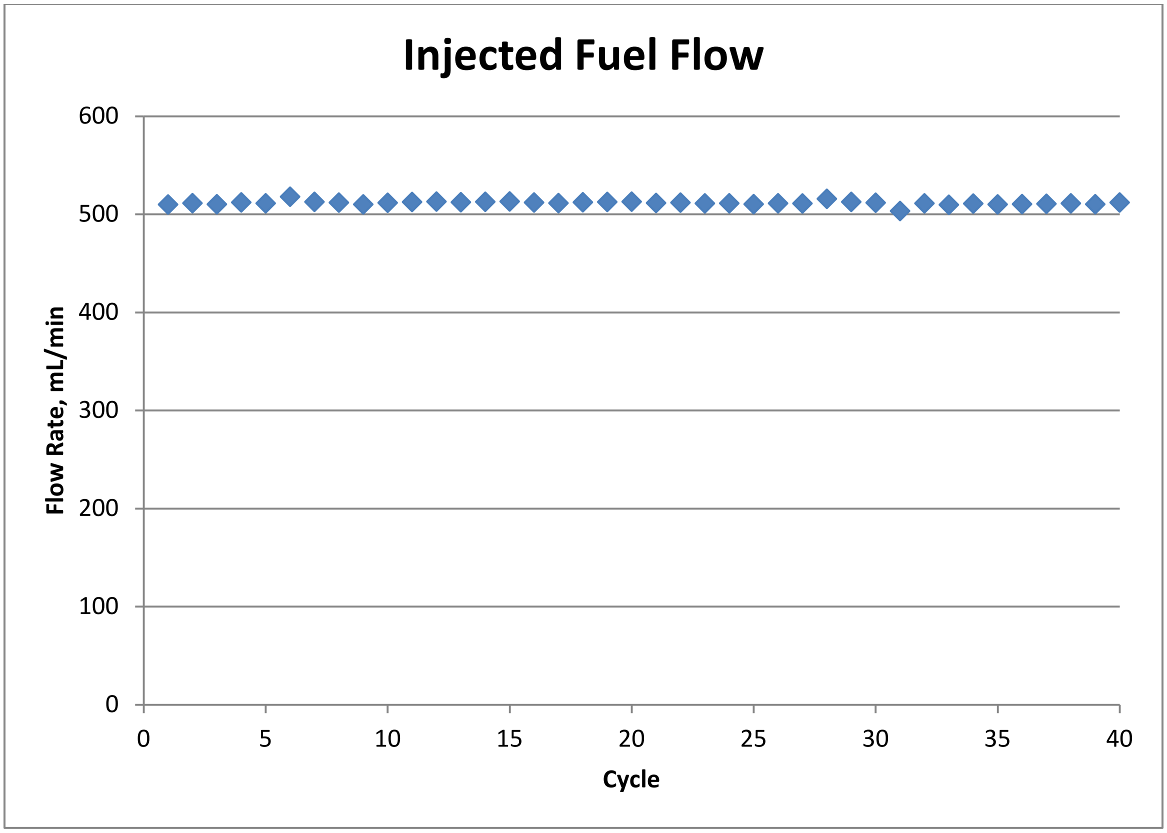

Figure F-3. Injected Fuel Flow

Figure F-4 shows the return fuel from the injectors, rail, and high pressure pump. The loss of flow rate in cycle six is due to an issue with the system inlet temperature.

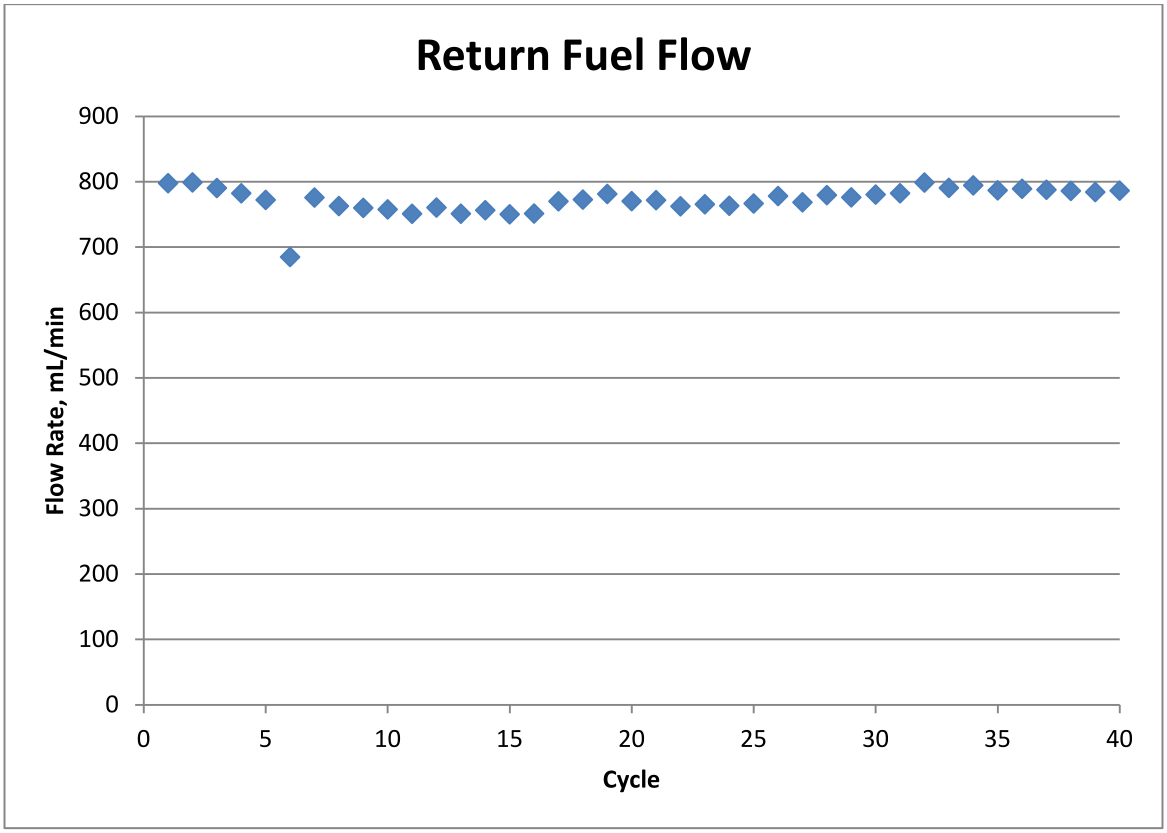

Figure F-4. Return Fuel Flow

Figure F-5 shows the system inlet temperature. This was controlled through a pulse-width modulated heater element. Temperature dropped during the 6th cycle due to a faulty pressure switch safety on the heater control loop. This was corrected prior to the next cycle

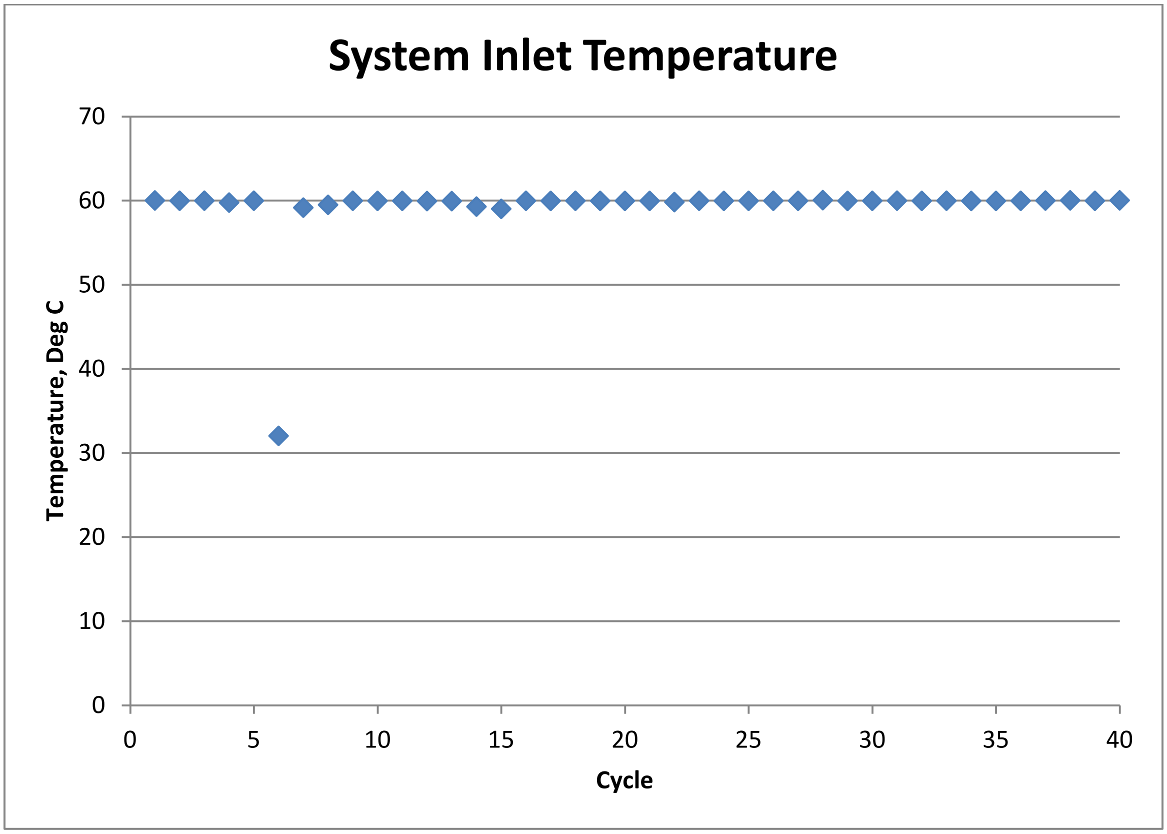

Figure F-5. System Inlet Fuel Temperature

Figure F-6 shows a measure of the fuel pressure as it was supplied to the final filter element by the electric lift pump.

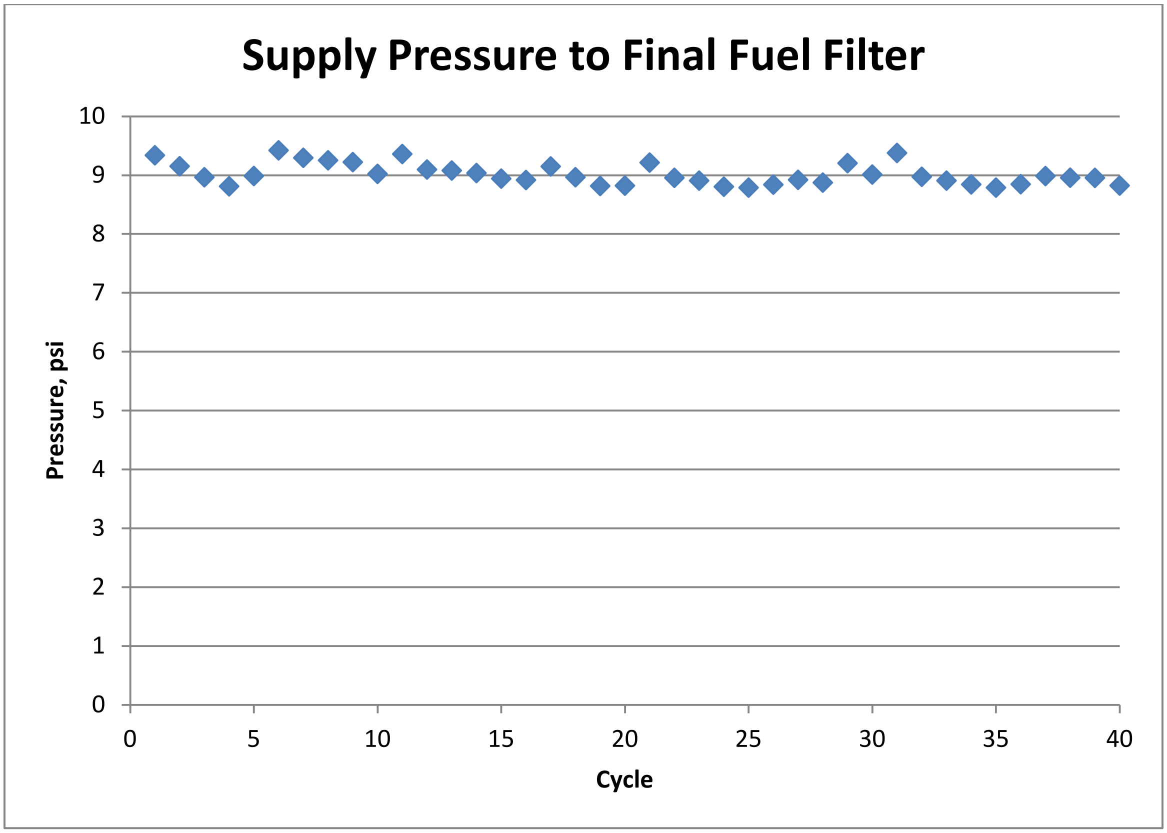

Figure F-6. Fuel Filter Pressure

A summary of the operating conditions for each 100 hour period are provided in Table F-2.

Table F-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	57.1	8.5	27.9	62.3
Bypass Fuel Temperature, deg C	94.8	5.3	71.9	106.3
Rail Pressure, psi	18810	28	18563	18969
Injected Flow Rate, mL/min	511.7	18.2	416.3	526.0
Return Fuel Flow Rate, mL/min	767.7	32.9	651.2	825.6
Fuel Filter Inlet Pressure, psi	9.1	0.2	8.6	9.8
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	59.8	0.8	53.5	62.0
Bypass Fuel Temperature, deg C	98.0	2.9	74.6	101.9
Rail Pressure, psi	18802	39	18546	19039
Injected Flow Rate, mL/min	512.4	18.3	426.9	523.3
Return Fuel Flow Rate, mL/min	761.3	15.0	678.8	799.2
Fuel Filter Inlet Pressure, psi	9.0	0.2	8.5	9.7
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	0.6	56.6	64.7
Bypass Fuel Temperature, deg C	98.0	3.2	76.0	102.1
Rail Pressure, psi	18804	43	18436	19056
Injected Flow Rate, mL/min	511.8	19.5	426.1	664.8
Return Fuel Flow Rate, mL/min	771.1	13.9	720.5	977.1
Fuel Filter Inlet Pressure, psi	9.0	0.2	6.5	9.5
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	60.0	0.5	57.7	64.2
Bypass Fuel Temperature, deg C	97.1	4.4	50.8	106.0
Rail Pressure, psi	18803	40	18481	19074
Injected Flow Rate, mL/min	509.9	18.1	424.1	528.5
Return Fuel Flow Rate, mL/min	788.5	11.6	725.2	838.5
Fuel Filter Inlet Pressure, psi	8.9	0.2	6.9	9.8

Lubricity Fuel Analysis

Fuel lubricity 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 Figure F-7 and Figure F-8.

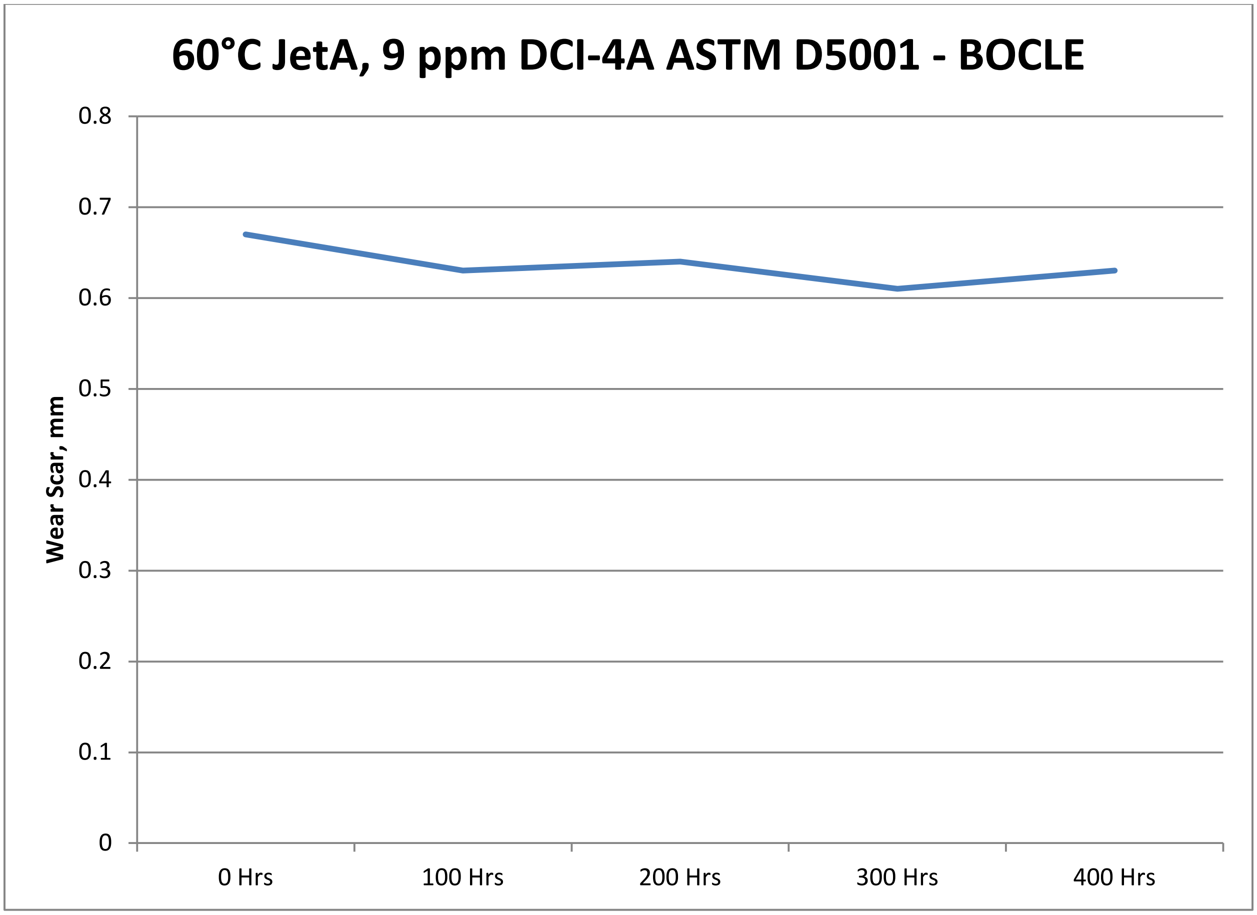

Figure F-7. ASTM D5001 BOCLE

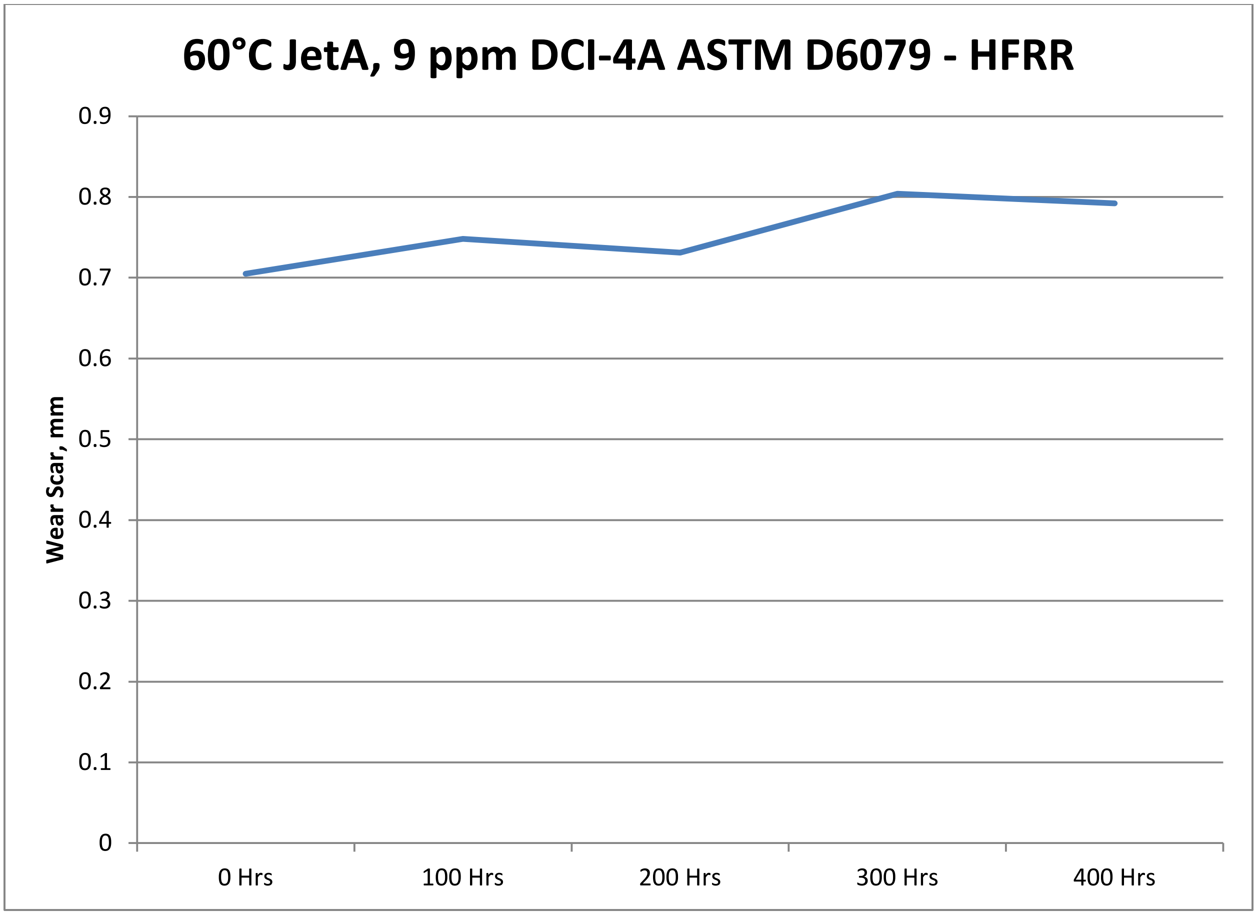

Figure F-8. ASTM D6079 HFRR

Component Wear

Post-test tear disassembly of the pump and injectors was performed to evaluate wear operating on SPK at 60°C inlet with 9 ppm DCI-4A. The following figures highlight various areas of the pump and injectors.

Fuel Pump

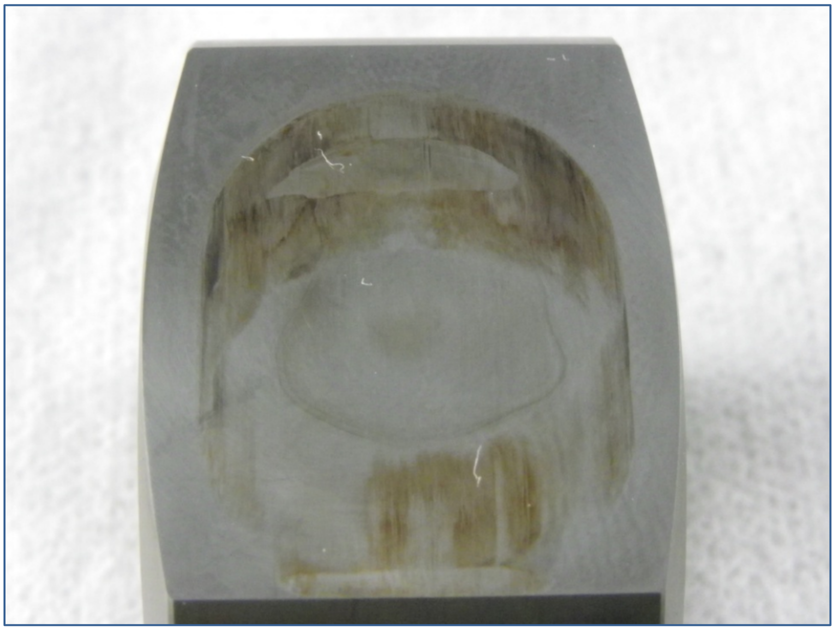

Figure F-9. Ring Cam - Top

Figure F-10. Plunger Face - Top

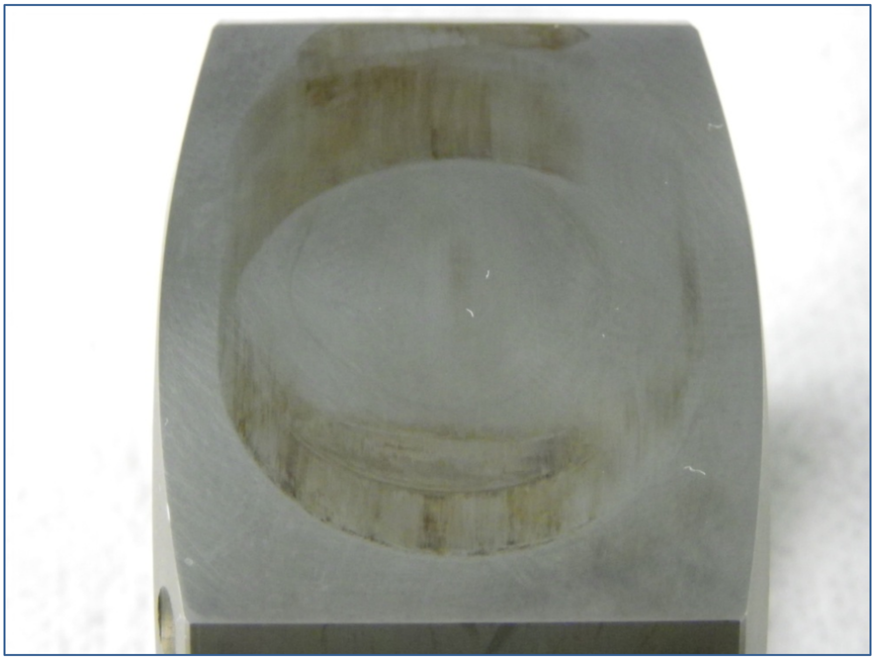

Figure F-11. Ring Cam - Bottom

Figure F-12. Plunger - Bottom

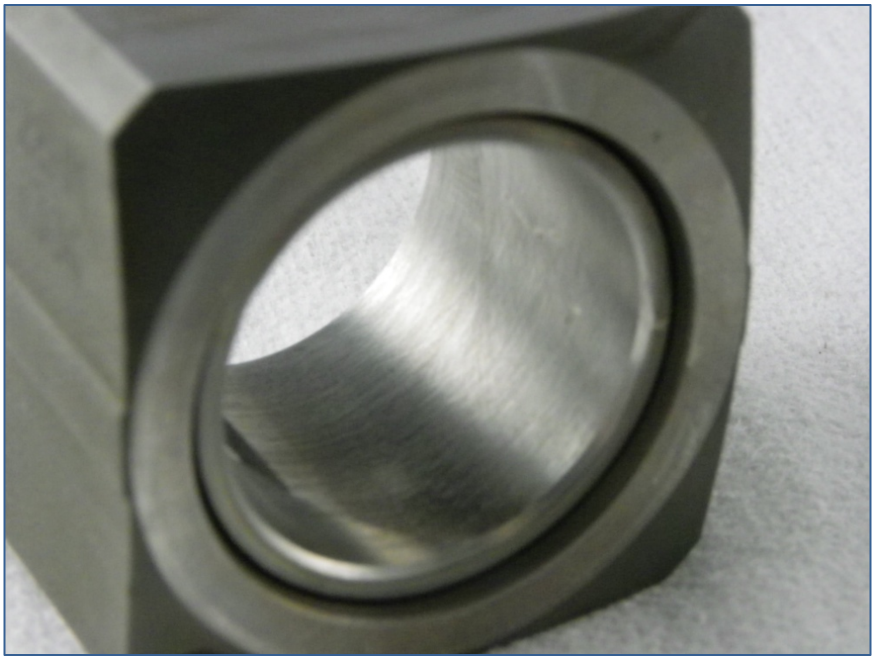

Figure F-13. Ring Cam – Front

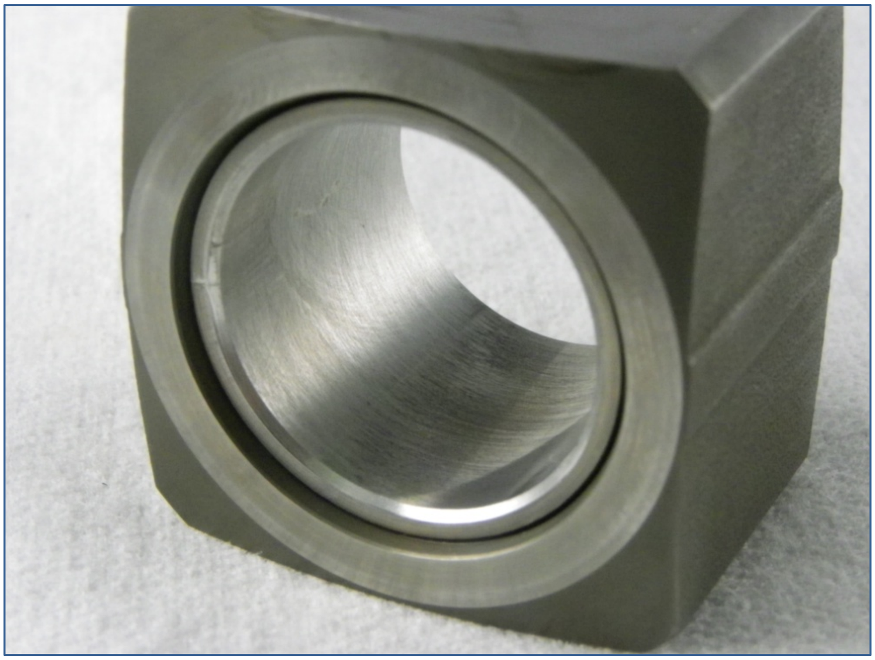

Figure F-14. Ring Cam - Rear

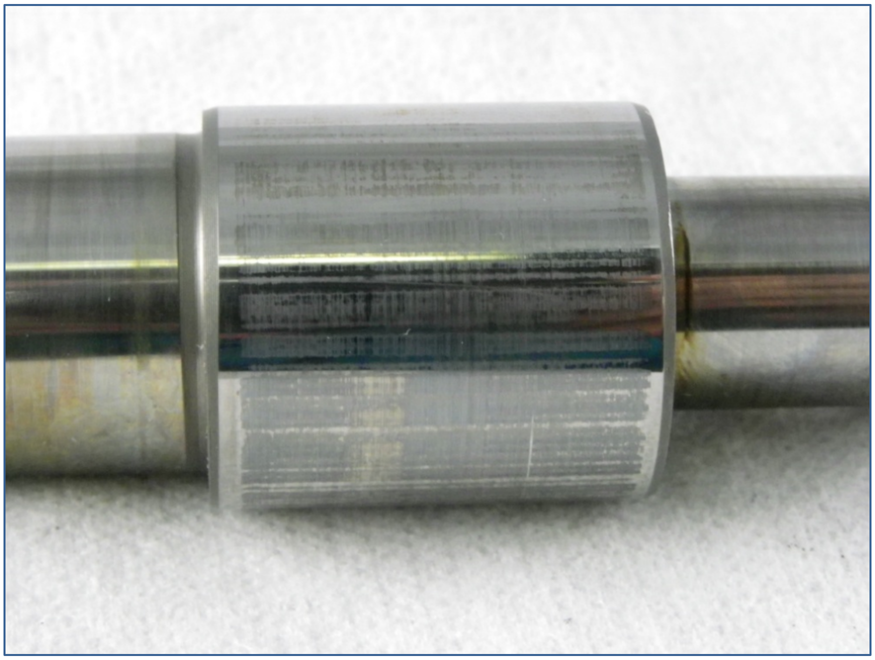

Figure F-15. Eccentric Cam Lobe

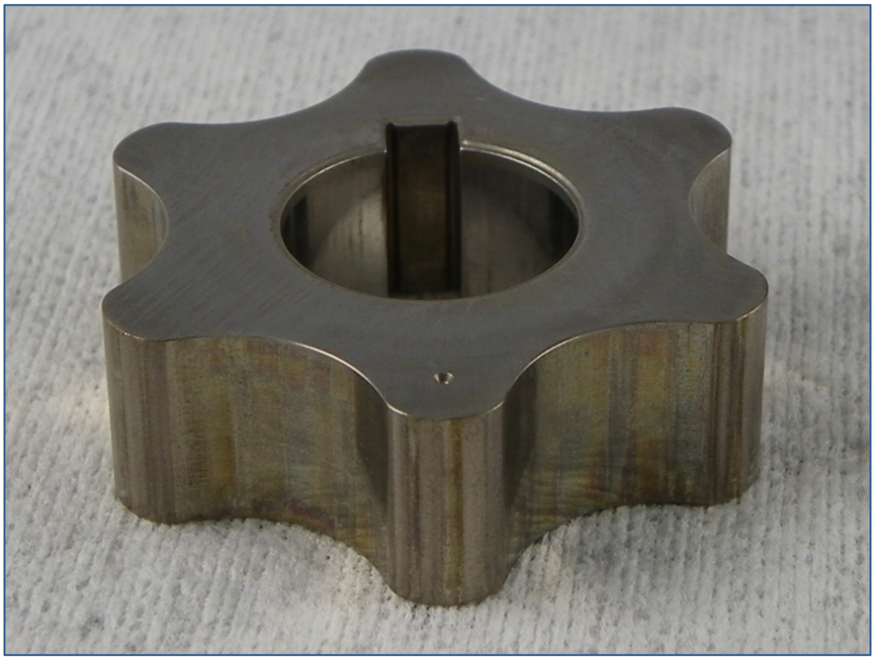

Figure F-16. Transfer Pump Gear

Fuel Injector

Figure F-17. Injector Needle

Figure F-18. Lower Injector Connecting Pin

Figure F-19. Upper Injector Connecting Pin

APPENDIX G

Evaluation of High Pressure Common Rail Fuel System

Test Fuel: Jet A with 9 ppm DCI-4A
Test Number: Jet A-9 ppm-93°C-JD

EVALUATION OF HIGH PRESSURE COMMON RAIL FUEL SYSTEM

Project 14734.04

John Deere 4.5L Powertech Plus

Test Fuel: Jet A with 9 ppm DCI-4A

Test Number: Jet A-9 ppm-93°C-JD

Start of Test Date: June 13, 2012

End of Test Date: July 6, 2012Test Duration: 400 Hours

Test Procedure: Simulated NATO Standard Engine Laboratory Test

Conducted for

U.S. Army TARDEC

Force Projection Technologies

Warren, Michigan

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Introduction and Background

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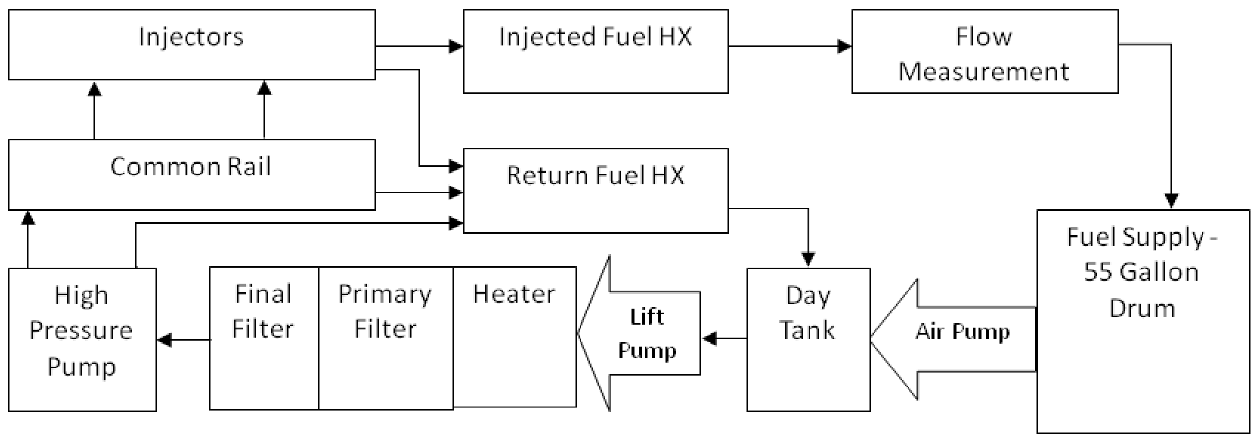

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7	800	0	0.5
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9	1500	100	2
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*Step 5 cycles between idle and rated conditions

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.

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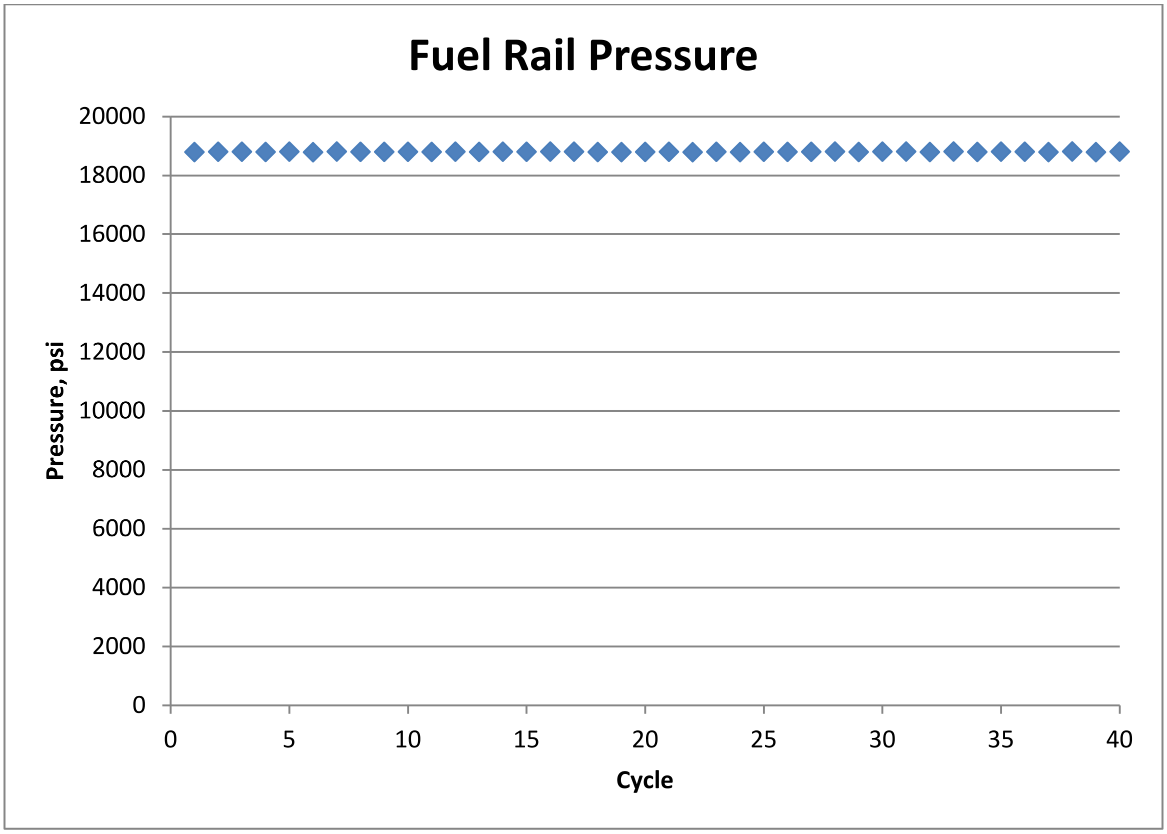


Figure G-2. Fuel Rail Pressure

The flow rate for injected fuel is shown in Figure G-3. There is no major change in fuel flow rate over the duration of the test.

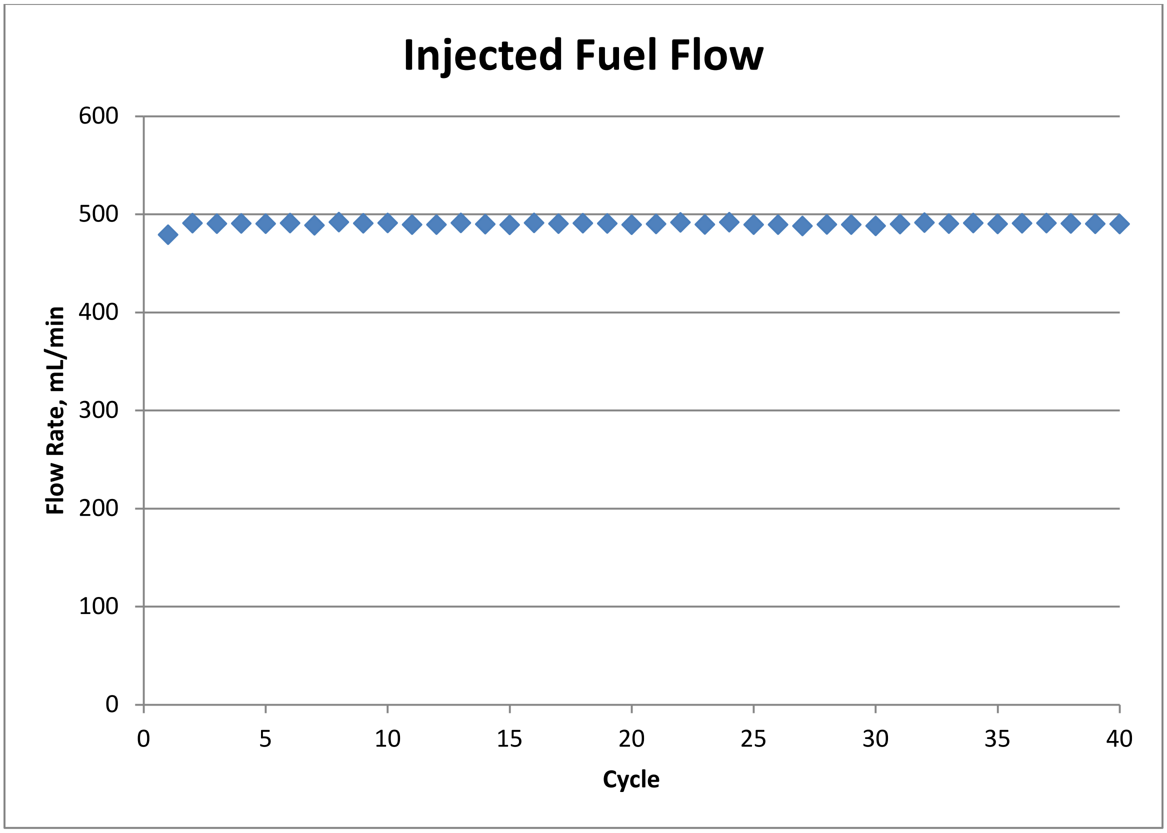


Figure G-3. Injected Fuel Flow

Figure G-4 shows the return fuel from the injectors, rail, and high pressure pump.

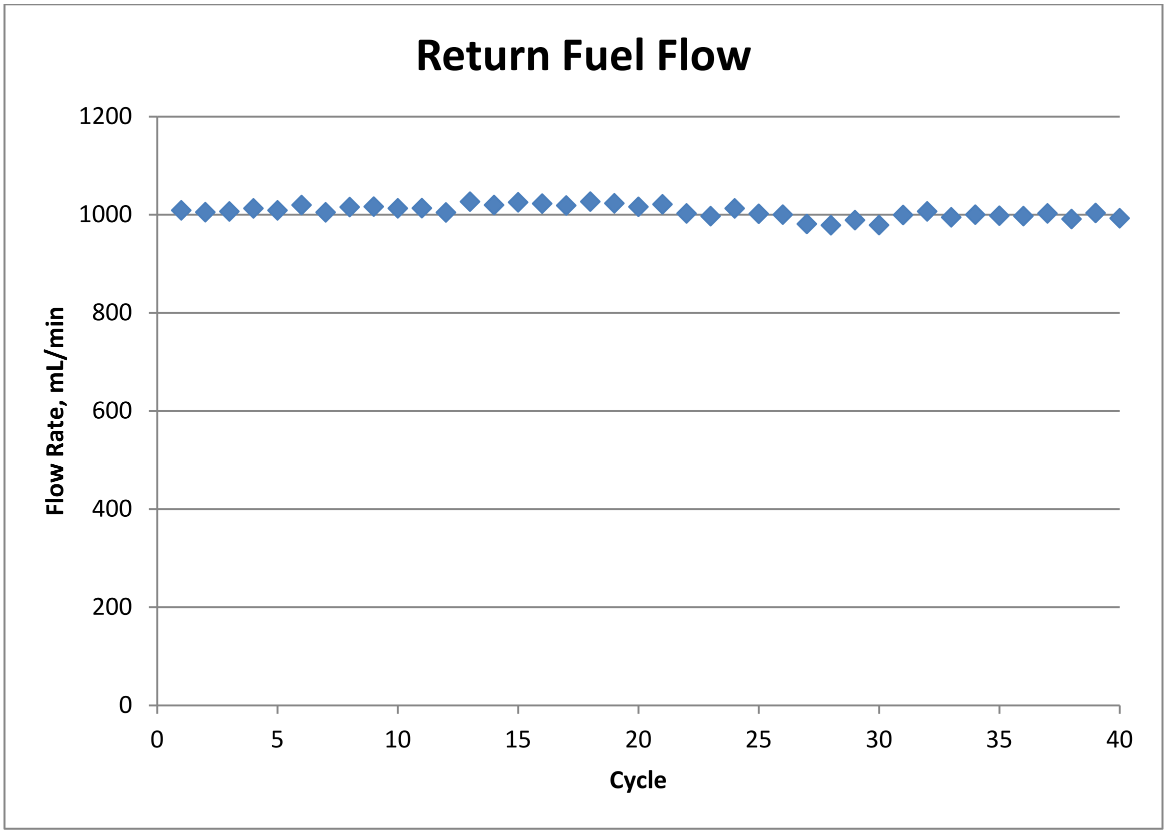
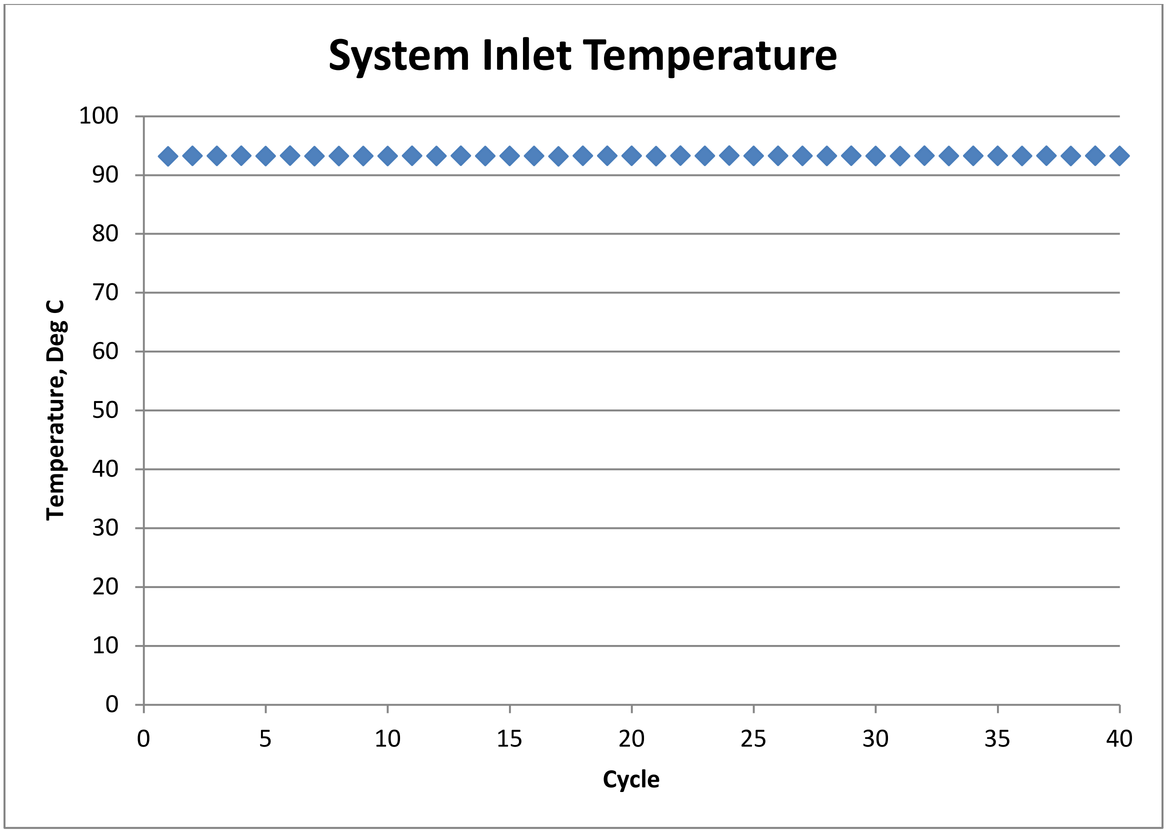


Figure G-4. Return Fuel Flow

Figure G-5 shows the system inlet temperature. This was controlled through a pulse-width modulated heater element. Inlet temperature remained stable throughout testing.



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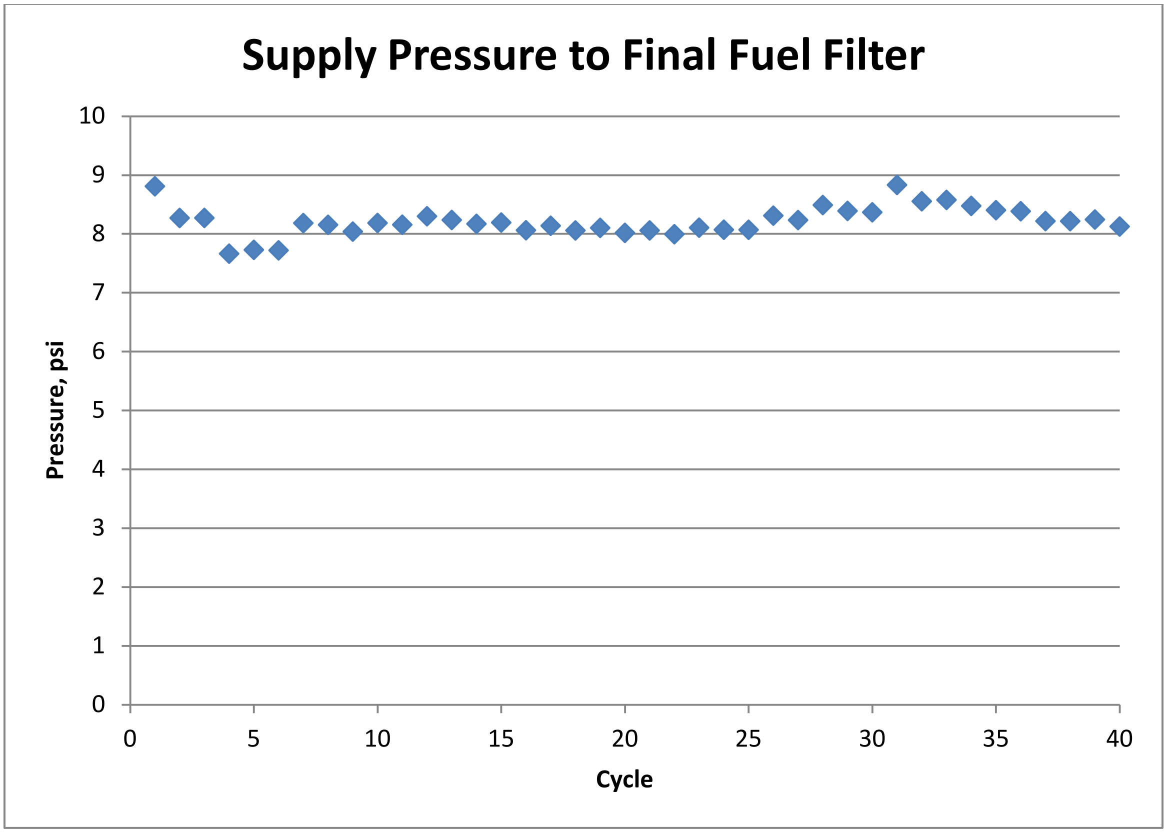

Figure G-6. Fuel Filter Pressure

A summary of the operating conditions for each 100 hour period are provided in Table G-2.

Table G-2. Summarized Operating Conditions

Test Hours 0-100				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	93.1	0.9	86.4	93.8
Bypass Fuel Temperature, deg C	130.7	3.3	106.9	134.5
Rail Pressure, psi	18801	27	18702	18912
Injected Flow Rate, mL/min	489.3	21.6	396.6	503.8
Return Fuel Flow Rate, mL/min	1010.0	16.8	911.9	1039.9
Fuel Filter Inlet Pressure, psi	8.1	0.4	7.4	9.3
Test Hours 100-200				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	93.1	0.9	86.3	93.8
Bypass Fuel Temperature, deg C	131.3	3.1	107.5	134.5
Rail Pressure, psi	18802	32	18669	18917
Injected Flow Rate, mL/min	489.9	21.0	394.1	501.8
Return Fuel Flow Rate, mL/min	1018.4	18.5	913.1	1058.1
Fuel Filter Inlet Pressure, psi	8.1	0.1	7.8	8.6
Test Hours 200-300				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	93.2	0.8	86.6	96.6
Bypass Fuel Temperature, deg C	129.1	4.0	93.9	134.4
Rail Pressure, psi	18801	26	18710	18877
Injected Flow Rate, mL/min	489.5	20.6	392.7	509.0
Return Fuel Flow Rate, mL/min	995.1	23.4	827.4	1043.5
Fuel Filter Inlet Pressure, psi	8.2	0.2	7.7	8.7
Test Hours 300-400				
	Mean	Std. Dev.	Min	Max
System Inlet Temperature, deg C	93.2	0.8	86.5	93.7
Bypass Fuel Temperature, deg C	130.0	3.2	107.0	133.1
Rail Pressure, psi	18803	28	18666	18889
Injected Flow Rate, mL/min	490.4	19.2	398.0	499.8
Return Fuel Flow Rate, mL/min	997.1	19.9	877.3	1029.4
Fuel Filter Inlet Pressure, psi	8.4	0.2	8.0	9.2

Lubricity Fuel Analysis

Fuel lubricity 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 Figure G-7 and Figure G-8.

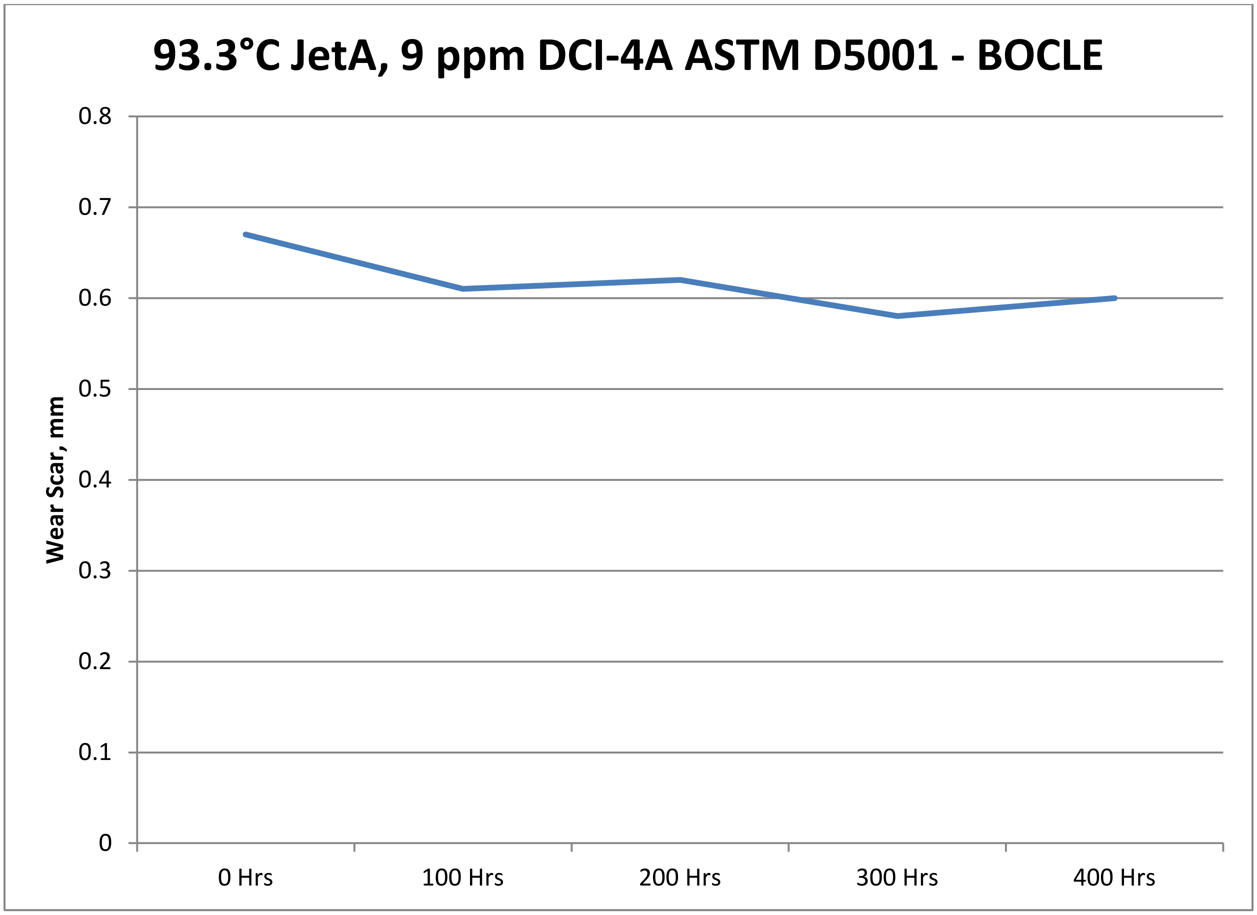

Figure G-7. ASTM D5001 BOCLE

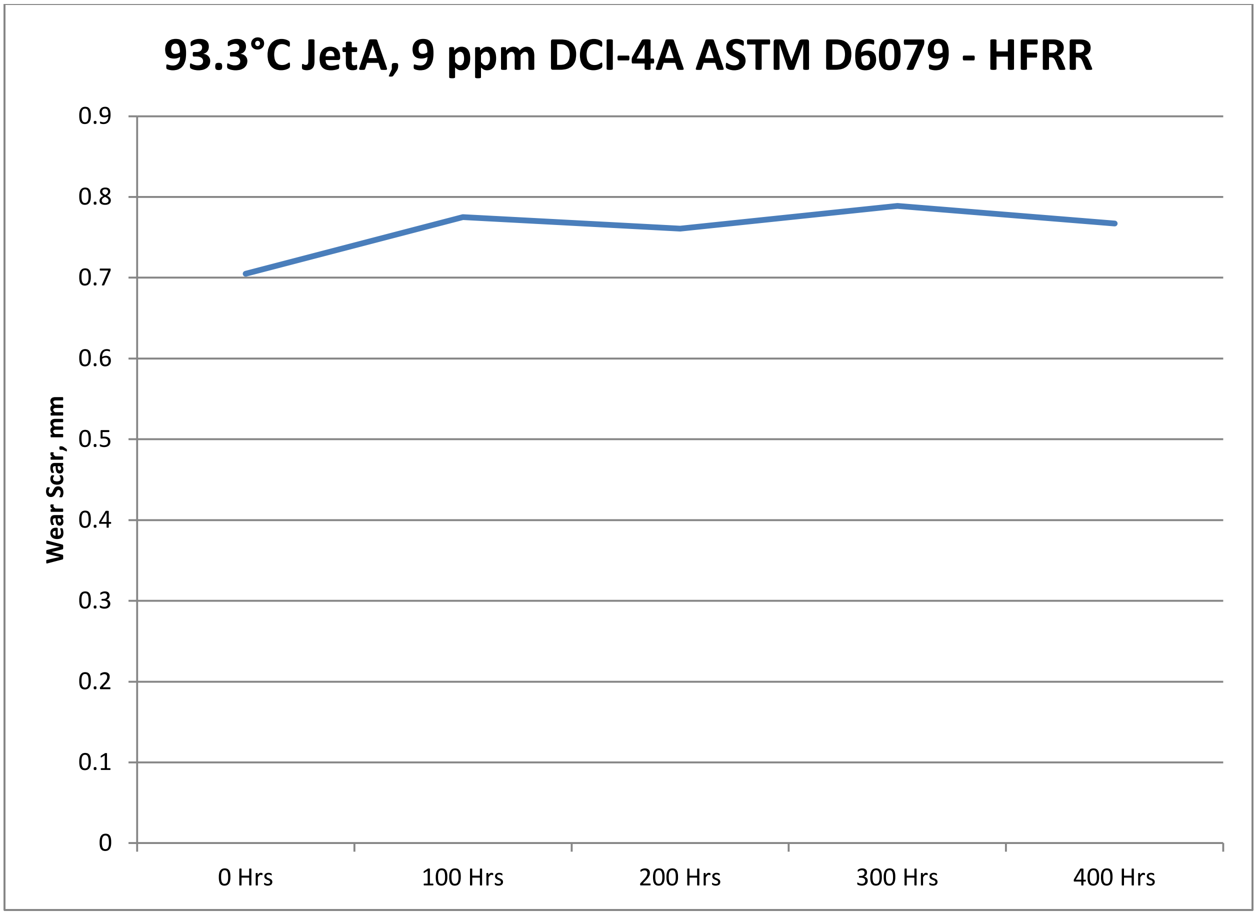

Figure G-8. ASTM D6079 HFRR

Component Wear

Post-test tear disassembly of the pump and injectors was performed to evaluate wear operating on SPK at 60°C inlet with 9 ppm DCI-4A. The following figures highlight various areas of the pump and injectors.

Fuel Pump

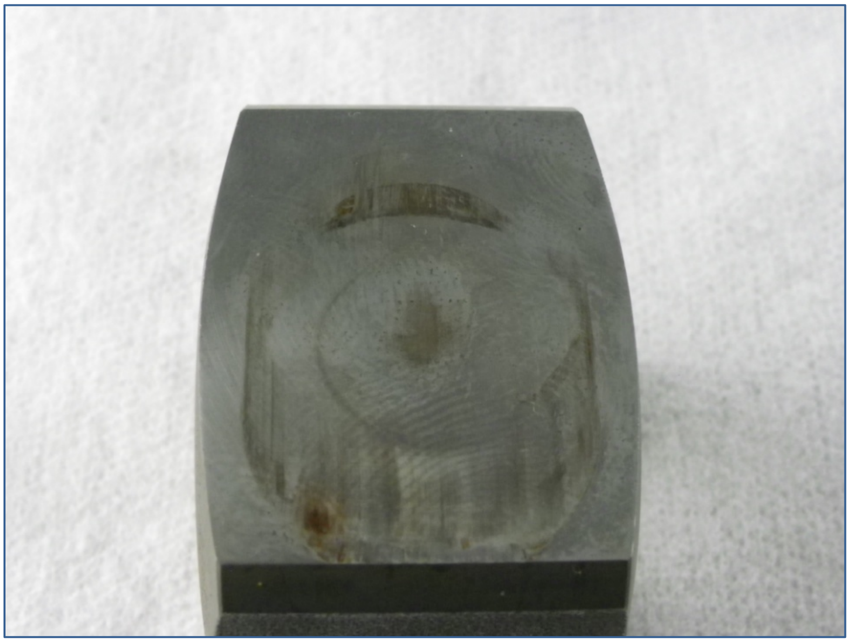

Figure G-9. Ring Cam - Top

Figure G-10. Plunger Face - Top

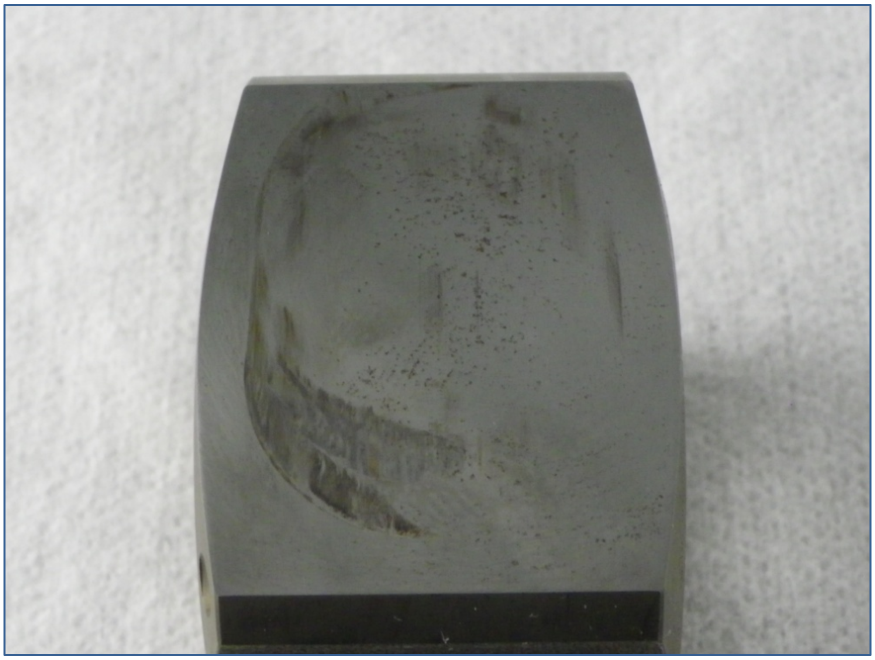

Figure G-11. Ring Cam - Bottom

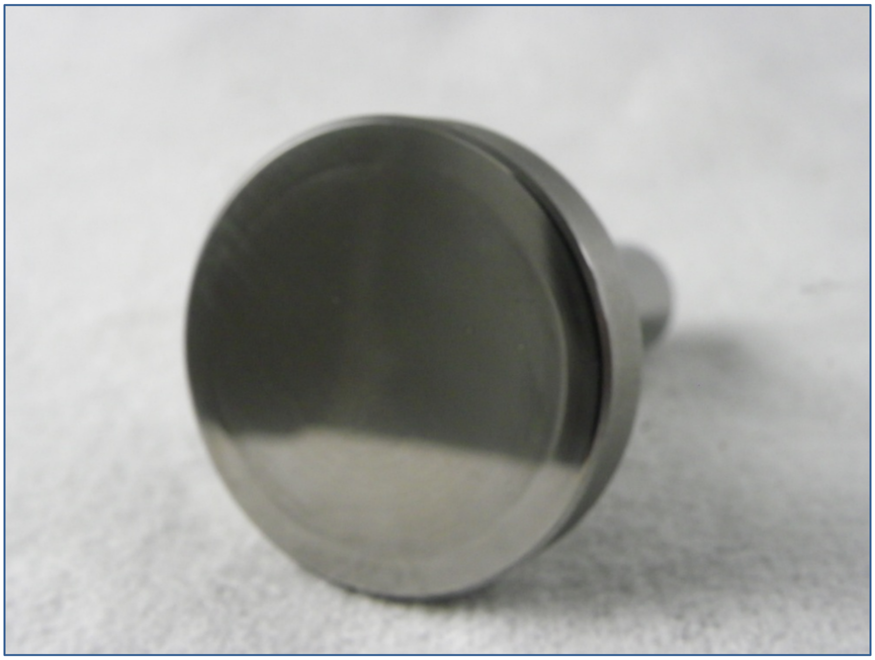

Figure G-12. Plunger - Bottom

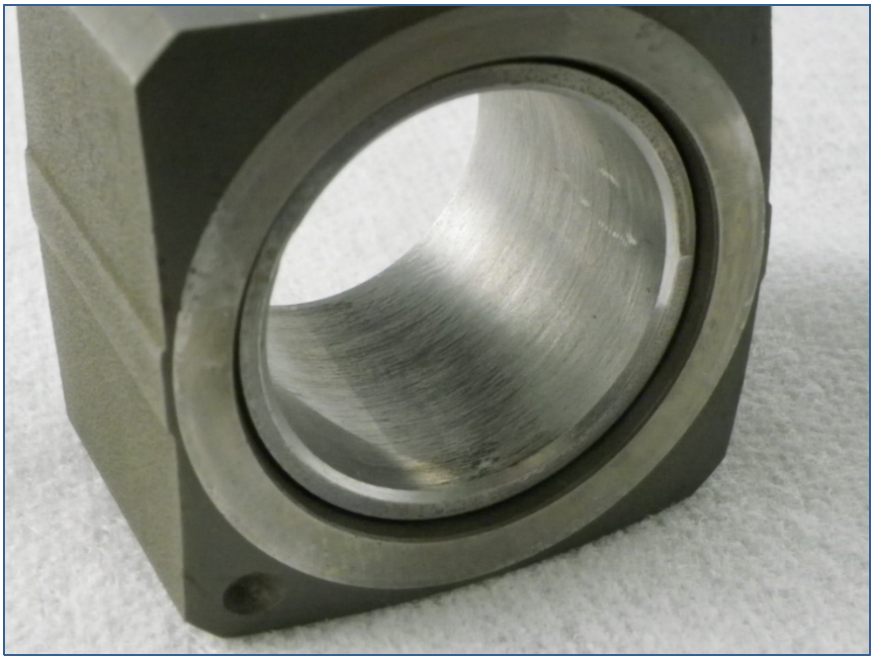

Figure G-13. Ring Cam – Front

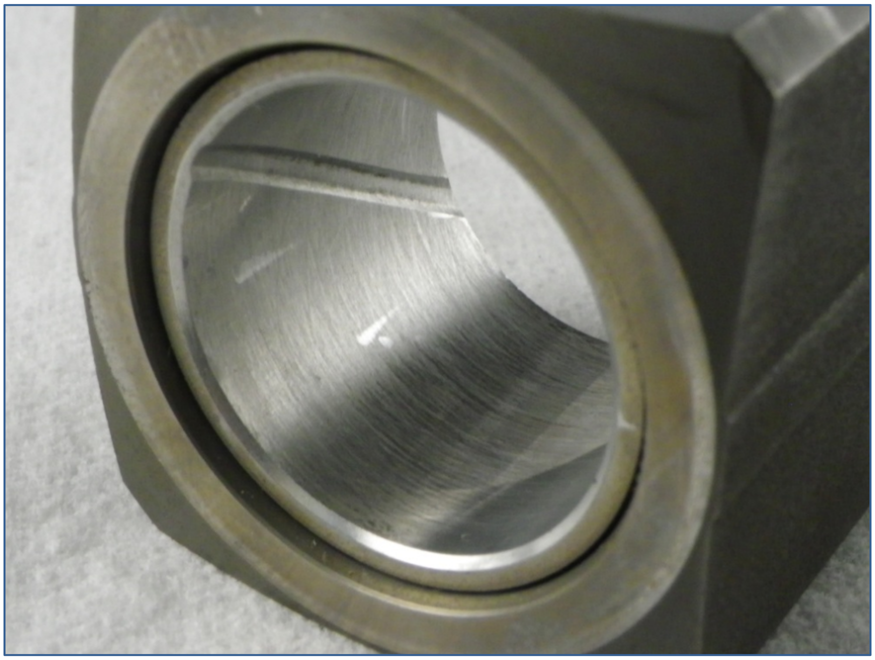

Figure G-14. Ring Cam - Rear

Figure G-15. Eccentric Cam Lobe

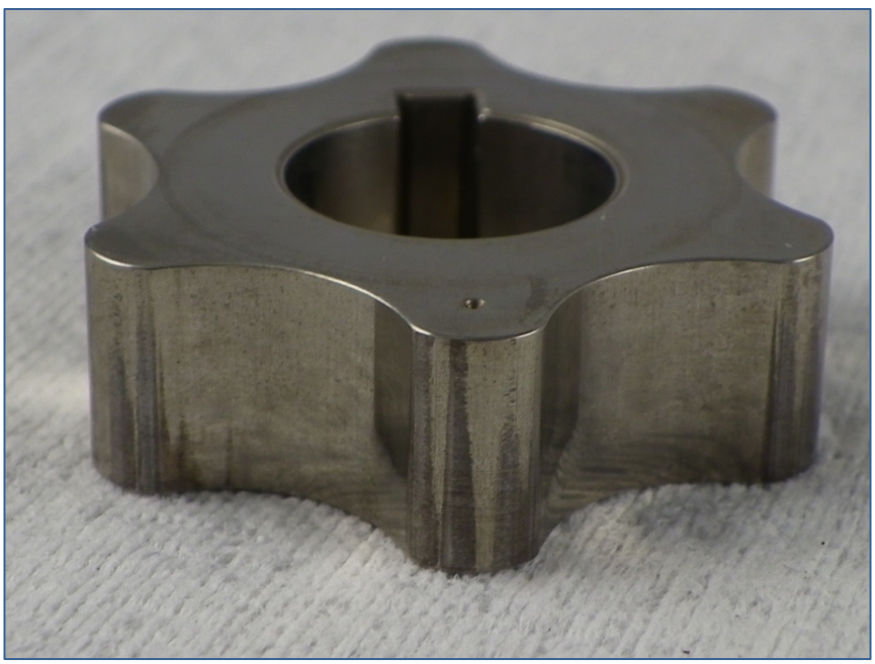

Figure G-16. Transfer Pump Gear

Fuel Injector

Figure G-17. Injector Needle

Figure G-18. Lower Injector Connecting Pin

Figure G-19. Upper Injector Connecting Pin