ENHANCED JET FUEL – PHASE 0

INTERIM REPORT
GVSC No. 494

By
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GVSC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

For
Angela Rymill

Force Projection Technology
U.S. Army CCDC Ground Vehicle Systems Center
FCDD-GVS-ES (M/S 110)
6501 E. 11 Mile Road
Warren, MI 48397-5000

Contract No. W56HZV-15-C-0030 (WD 028)

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July 2020

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14. ABSTRACT This task researched and reviewed previous work conducted by Southwest Research Institute with regards to fuel pump performance as it relates to fuel additives and test conditions. Raw data was extracted from previous testing and evaluated against pump performance and wear. These results were used to make recommendations for future pump testing, including the Phase 2 testing outline in WD031.						
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FOREWORD/ACKNOWLEDGMENTS

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The authors would like to acknowledge the contribution of the GFLRF technical and administrative support staff.

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ACRONYMS AND ABBREVIATIONS

°C	degrees Celsius
ASTM	ASTM International
ATJ	Alcohol to Jet Fuel
BOCLE	Ball-on-Cylinder Lubricity Evaluator
cc	Cubic Centimeter
CI/LI	Corrosion Inhibitor/Lubricity Improver
cm	Centimeter
ft	Foot
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
HFRR	High Frequency Reciprocating Rig
HPCR	High Pressure Common Rail
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
hr	Hour
in	Inch
JP-8	Jet Propellant 8
kW	Kilowatt
L	Liter
lb	Pound
m	Meter
mg	milligram
mg/L	milligrams per Liter concentration
MIL-PRF-25017	Military Performance Specification number 25017
mL	milliliter
mm	millimeter
ppm	parts per million
psi	pounds per square inch
QPL	Qualified Products List
RPM	rotation(s) per minute
SLBOCLE	Scuffing Load Ball on Cylinder Lubricity Evaluator
SwRI®	Southwest Research Institute®
SOW	Scope of Work
SPK	Synthetic Paraffinic Kerosene
TARDEC	Tank Automotive Research, Development, and Engineering Center
ULSD	Ultra Low Sulfur Diesel fuel
WOT	Wide Open Throttle
WD	Work Directive
WSD	Wear Scar Diameter

1.0 BACKGROUND

SwRI has been conducting dedicated fuel pump testing for the Army for more than 30 years. Many of these tests have utilized similar fuel system hardware to be representative of the Army ground vehicle fleet. Programs have focused on hardware differences, fuel differences, or fuel additive differences. The testing programs have operated on several different test cycles and at multiple environmental conditions.

In general, fuel pump wear ratings have been subjective, although some critical components have quantified wear data where it is easily measurable. In the past 10-15 years, the pump tests also have recorded analog data that has been reported. But no two testing programs were reported in exactly the same way. Contrast this with the ASTM lubricity tests, where the conditions and measurements are standardized, there leaves room for improvement in quantifying and comparing the results of the pump tests.

Additionally, fuel pump test results have been categorized as pass or fail. Either the pump was functional at the end of the test, or it was not. This pass/fail criteria does not take into account any incremental loss of performance due to normal (not catastrophic) wear. If the fuel pump has exhibited a loss of performance but still operates, the vehicle may continue to function but with reduced power and/or reduced speed.

An improved methodology of rating pump wear and performance needs to take into account practical limits on reduced vehicle function. This literature review and data correlation is an attempt to improve the rating system of fuel pump testing conducted at SwRI for the Army.

The literature review will roughly span the past 20 years of fuel pump tests. The data extracted includes fuel flow rates, fuel pressures, and fuel temperatures. Comprehensive fuel property tables for many tests are also included, along with physical examinations of pump components.

1.1 TEST RIG SETUP

1.1.1 High Pressure Common Rail Fuel Pump Setup

The high pressure common rail fuel pump (HPCR) tests were run on a test stand specifically configured for the fuel system being tested. Where possible, production parts were used to maintain a realistic evaluation of the fuel system. Each system was controlled by the production control module which was modified for bench use. A 55 gallon drum was used as a remote fuel source for the stand. Fuel temperatures were maintained using a liquid-to-liquid heat exchanger and heater. An electric lift pump provided fuel to the main fuel pump. The fuel system schematic of a typical test rig is shown in Figure 1.

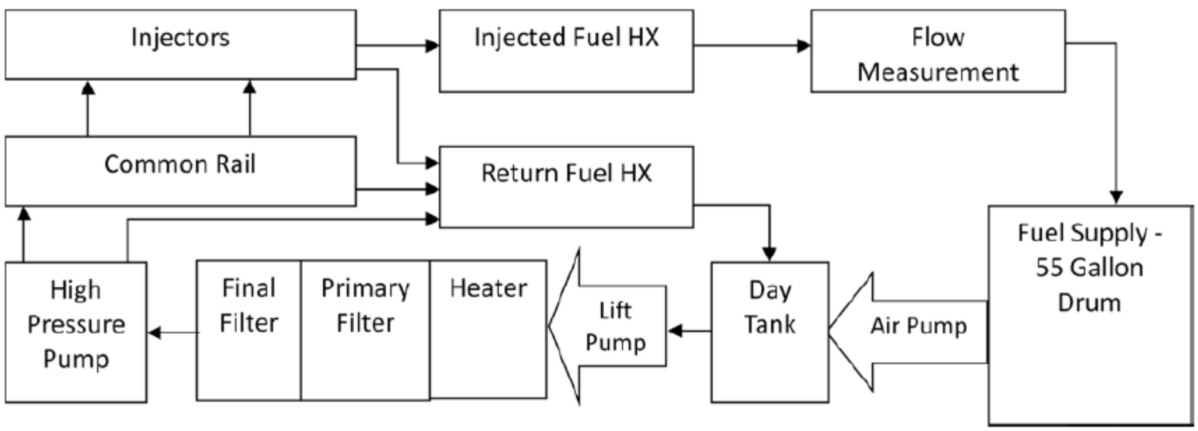

Figure 1. HPCR Test Rig Fuel System Schematic

Three HPCR setups were used for the testing covered in this report: Cummins XPI, John Deere 4.5L Powertech Plus, and a 2011 Ford 6.7L. A photo of a completed test stand is shown in Figure 2.

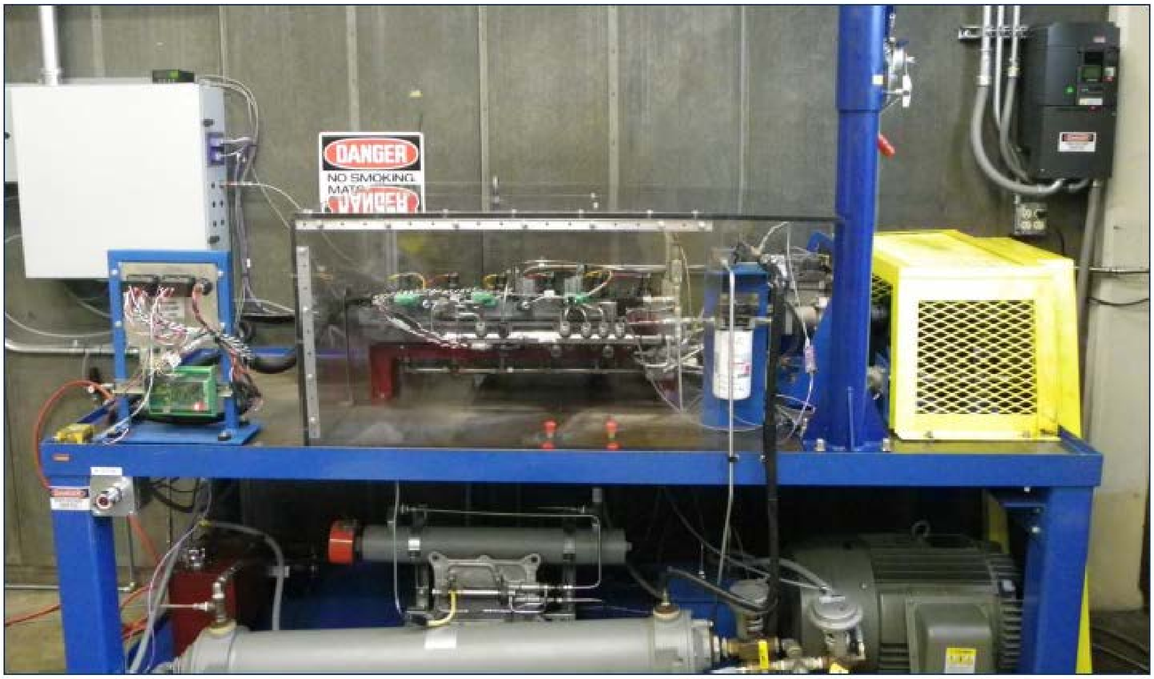

Figure 2. HPCR Completed Test Stand

All HPCR fuel pumps were tested using the NATO Standard Engine Laboratory Test AEP-5, Edition 3. The NATO Test is a 400 hour test consisting of repeated 10 hour cycles. Each cycle has 10 operating modes in which speed and load are controlled. The cycle is defined using normalized values, and speed and load are expressed as a percentage of rated speed and load. The normalized cycle is shown in Table 1.

Table 1. NATO 400-hour Test 10 Hour Cycle

Mode	% Rated Speed	% Load	Duration [hrs]
1	Idle	0	0.5
2	100	100	2.0
3	Governed Speed	0	0.5
4	75	100	1.0
5	Idle____100	0____100	2.0
6	60	100	0.5
7	Idle	0	0.5
8	Governed Speed	70	0.5
9	Max. Torque Speed	100	2.0
10	60	50	0.5

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. The engine speed is de-normalized to the specific engine calibration of the system being tested, and the pump speed is determined from the engine speed.

1.1.2 Rotary Fuel Pump Setup

The rotary fuel injection pump test rigs were configured to test pumps representative of current High Mobility Multi-Purpose Wheeled Vehicle (HMMWV) production engines at the time of testing. Duplicate pump rig tests were conducted simultaneously for each unique test fuel and fuel additive combination, and the pumps were tested with a common fuel supply. The fuel system schematic of a typical test rig is shown in Figure 3.

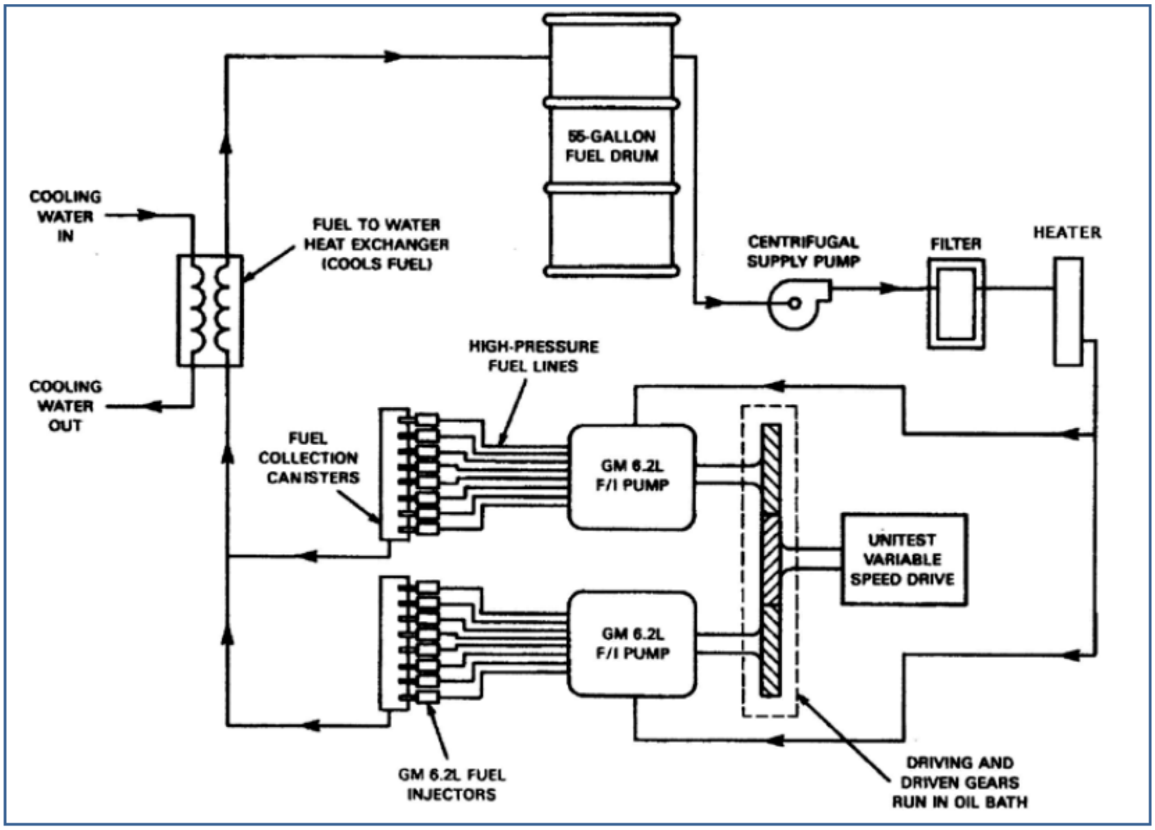

Figure 3. Rotary Pump Test Rig Fuel System Schematic

The test fuel was maintained in a 55 gallon drum and recirculated throughout the duration of each test. A centrifugal pump provided a positive pressure to the inlet of the test pump. Cartridge filters were utilized to remove wear debris and particulate contamination, and a heater was used to produce the required fuel inlet temperature. A photo of a pump test rig is shown in Figure 4.

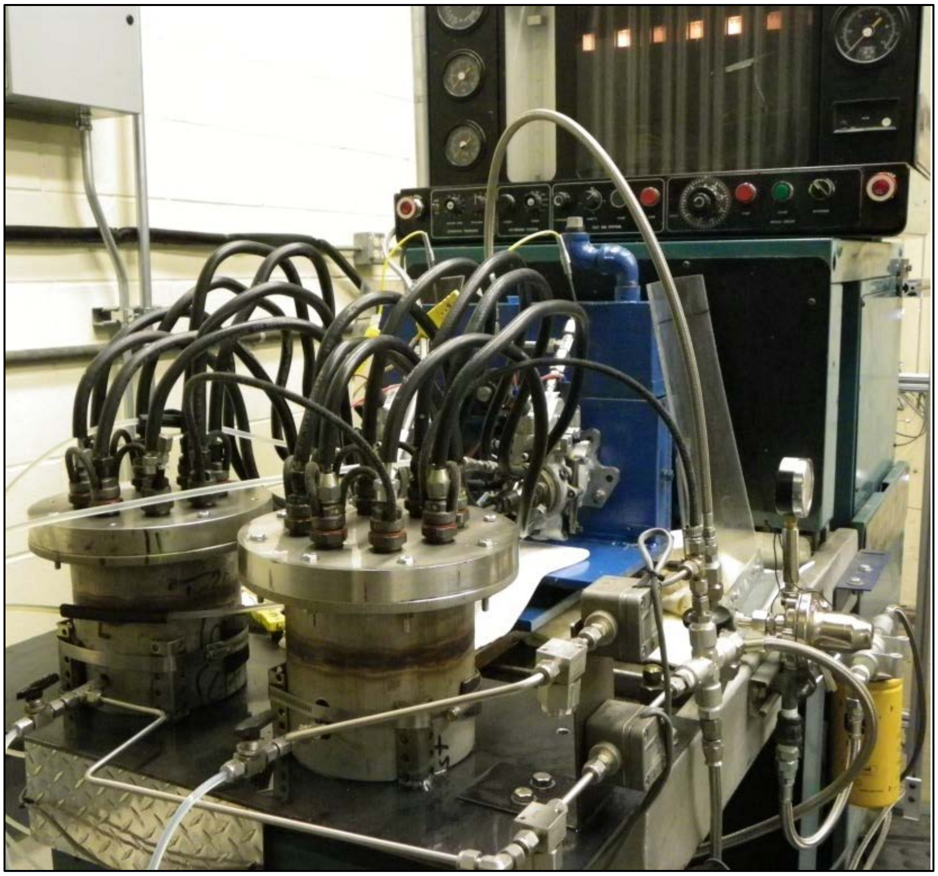

Figure 4. Cell 3 Pump Stand

Two different rotary pump setups were used for the testing covered in this report. The first was designed to mimic a General Motors (GM) 6.2L, and ran the fuel injection pumps at 1,800 rpm. The second was a General Engine Products (GEP) 6.5L and ran the pumps at 1,700 rpm. The hardware shift was reflective of a change of hardware in the field.

1.2 TEST PUMPS

1.2.1 HPCR Test Pumps

Three different HPCR fuel pumps were tested. The first was a Cummins XPI. The XPI system was developed jointly between Cummins, Inc. and Scania for Cummins midrange and Scania heavy duty applications. The pump is oil-lubricated which allows the system to reach rail and injection pressures of up to 30,000 psi. It is operated at half engine speed to reach a rated speed of 1,050 rpm. The XPI high pressure pump features a combination of a low pressure gear pump and a high pressure piston pump driven by a common shaft. The full pump is shown in Figure 5 and Figure 6.

Figure 5. Cummins XPI Pump – Drive Input

Figure 6. Cummins XPI Pump – Gear Pump Side

The John Deere 4.5L setup used a DENSO HPCR HP3 fuel pump. The high pressure pump consists of two opposing plunger assemblies and a transfer pump, all driven from a common camshaft. It is operated at a 1:1 speed ratio with the crankshaft. The DENSO pump is shown in Figure 7.

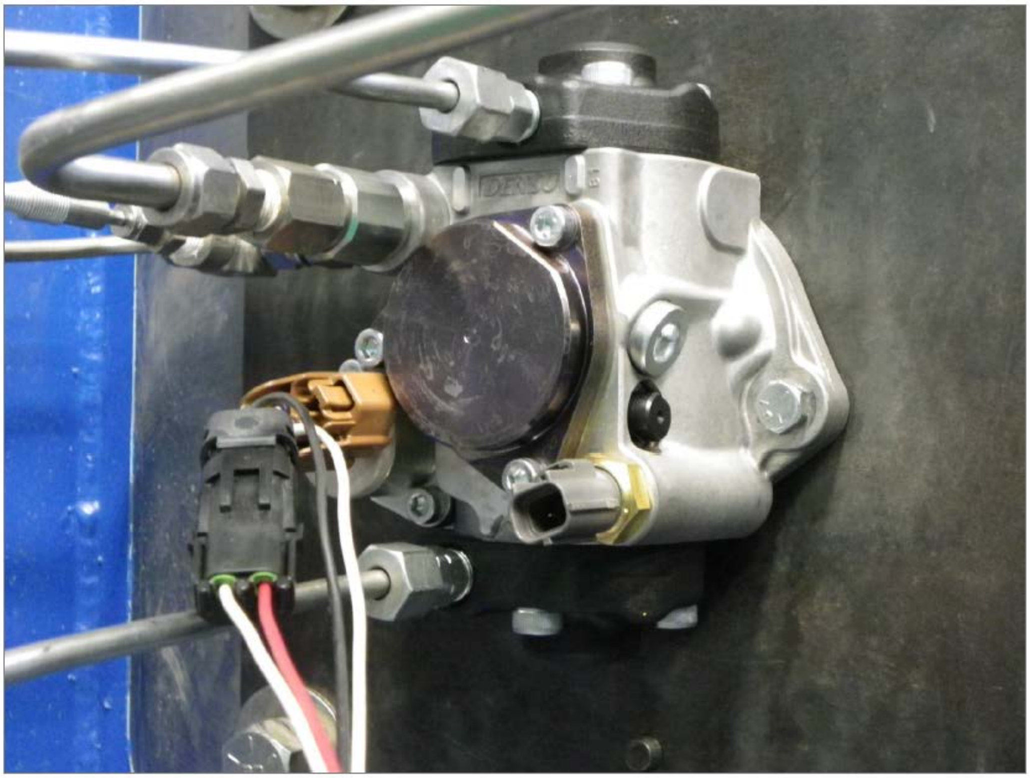

Figure 7. DENSO Pump

The Ford 6.7L engine HPCR fuel pump was a Bosch CR/CP4 design and was driven at a 1:1 speed ratio with the crankshaft. Pistons within the pump are oriented in a “V” configuration and driven off of common camshaft lobes. Photos of the pump housing can be seen in Figure 8 and Figure 9.

Figure 8. Ford 6.7L Pump Housing, Front

Figure 9. Ford 6.7L Pump Housing, Rear

1.2.2 Rotary Test Pumps

The test pumps used in the testing were Stanadyne Model DB2 pumps. They were opposed-piston, inlet-metered, positive-displacement, rotary-distributor, fuel-lubricated, and mechanically governed injection pumps. A cutaway diagram of the pump is shown in Figure 10, and Figure 11 shows the fuel distribution of the pump during use.

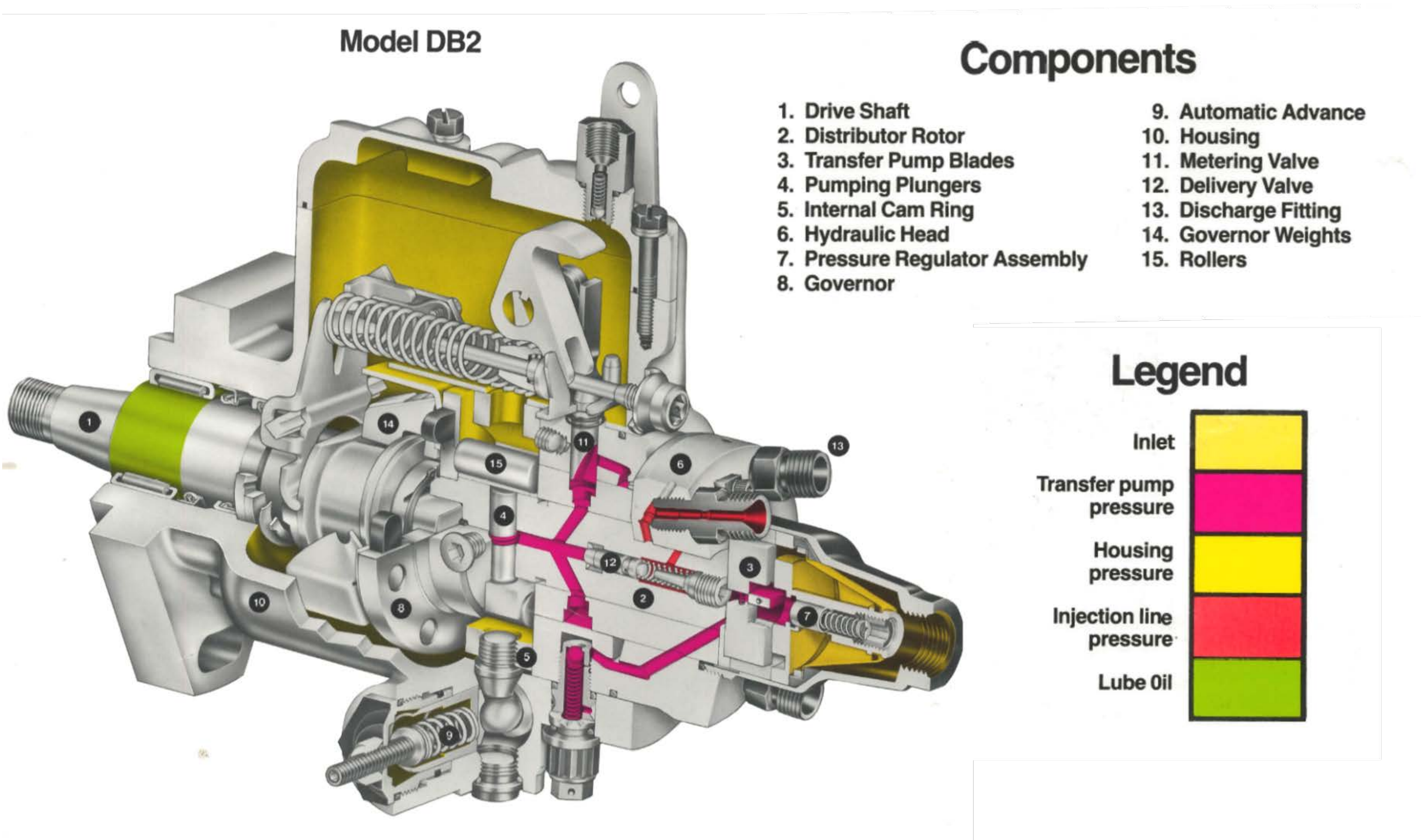

Figure 10. Cutaway Diagram of Model DB2 Pump

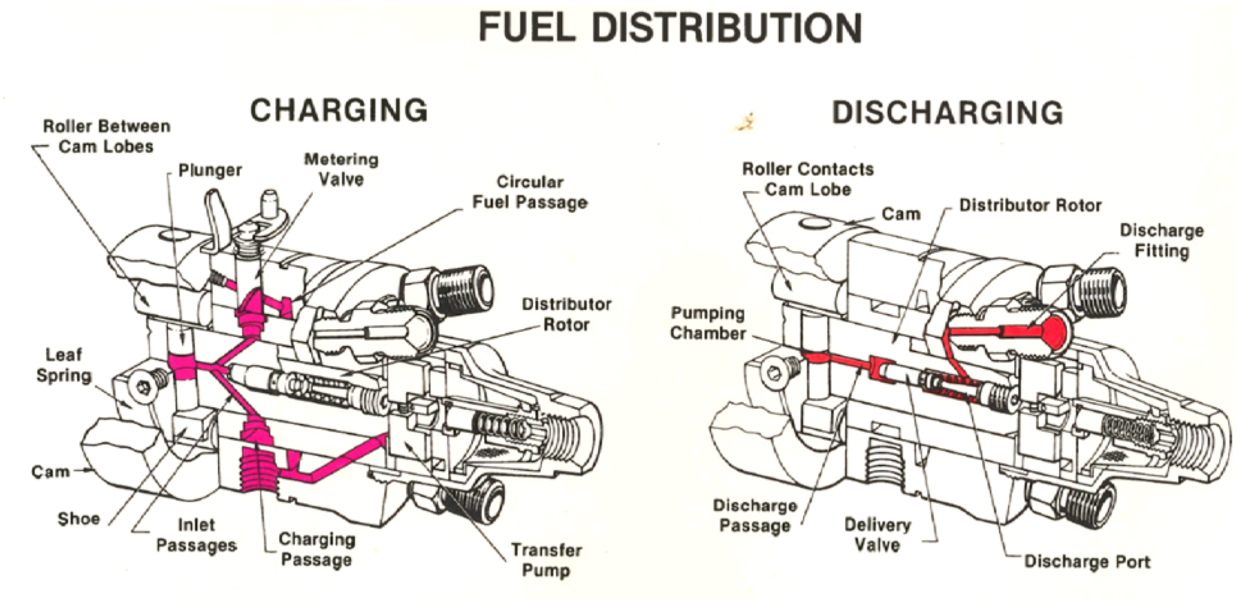

Figure 11. Fuel Distribution Diagram of Model DB2 Pump

Two versions of the DB2 pump were used in testing: standard and arctic. The arctic pump was equipped with hardened transfer pump blades, transfer pump liner, governor thrust washer, and drive shaft tang. Figure 12 shows an exploded view of some of these critical pump components.

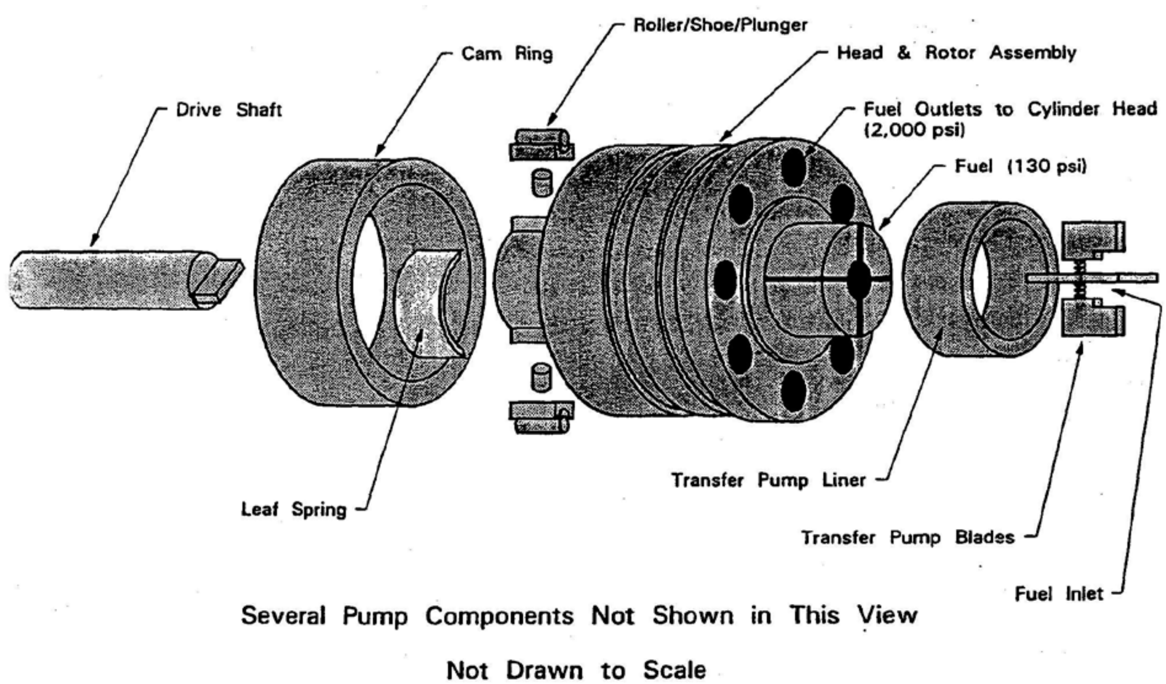

Figure 12. Schematic Diagram of Principal Pump Components

1.3 POST-TEST ANALYSIS, STANADYNE PUMPS

Prior to and after testing, each Stanadyne pump was evaluated using a calibration test stand. The pump characteristics were measured using conditions specified by the manufacturer, repeating those made prior to testing. The objective of the calibration stand evaluation was to determine the effects of testing on pump performance. Each calibration stand evaluation was performed at an authorized pump distributor, and no adjustments were made to any of the pumps prior to evaluation.

Over time, the parameters evaluated changed due to changes in the pump model tested and the manufacturer's specifications. An example of the pump calibration is shown below in Table 2.

Table 2. Stanadyne Pump Calibration Example (IR488, 30%ATJ/70%F-24 w/ 24 ppm DCI-4)

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-6282 (arctic)	SN : 17200858
Test condition : 1000 hours @ FIT 40°C and 1700 RPM	Test : AF9625-24-C3ATJ4-40-1000
Fuel : 30% ATJ, AF9625 with 24ppm DCI-4A	

PUMP RPM	Description	Specification		Pump Duration: 1000 Hours		
		min.	max.	Before	After	Change
1000	Transfer pump psi.	60 psi	62 psi	62 psi	62 psi	psi
	Return Fuel	225 cc	375 cc	305 cc	227 cc	78 cc
350	Low Idle	12 cc	16 cc	13.8 cc	5.3 cc	8.5 cc
	Housing psi.	8 psi	12 psi	10.3 psi	10.4 psi	-.1 psi
	Advance	3.5°		6.5°	6.3°	.3°
	Cold Advance Solenoid	0 psi	1 psi	.4 psi	.7 psi	-.3 psi
750	Shut-Off		4 cc	0 cc	0 cc	0 cc
900	Fuel Delivery	64.5 cc	67.5 cc	66.6 cc	64.8 cc	1.8 cc
1600	WOT Fuel delivery	58.5 cc		60.2 cc	59.1 cc	1.1 cc
	WOT Advance	2.5°	3.5°	3.5°	3.5°	.0°
	Face Cam Fuel delivery	21.5 cc	23.5 cc	22.5 cc	22.5 cc	.0 cc
	Face Cam Advance	5.25°	7.25°	6.0°	6.0°	.0°
	Low Idle	11.0°	12.0°	11.0°	11.0°	.0°
1700	WOT Fuel Delivery	58 cc		58.10 cc	58.40 cc	-.3 cc
1850	Fuel Delivery	33 cc		43.3 cc	57.5 cc	-14.2 cc
1975	High Idle		15 cc	4 cc	54 cc	50 cc
	Transfer pump psi.		125 psi	102 psi	98 psi	3.5 psi
200	WOT Fuel Delivery	58 cc		58.2 cc	55.8 cc	2.4 cc
	WOT Shut-Off		4 cc	0 cc	0 cc	0 cc
75	Low Idle Fuel Delivery	37 cc		45.9 cc	42.7 cc	3.2 cc
	Transfer pump psi.	16 psi		17.1 psi	17.8 psi	-.7 psi
	Housing psi.	0 psi	12 psi	9.7 psi	6.1 psi	3.6 psi
	Air Timing	-1.0°	0°	-.5°	-1.0°	.5°
	Fluid Temp. Deg. C :			45.5°	45.4°	
	Date :			2/20/2017	7/18/2017	

Notes :

2.0 INTRODUCTION AND OBJECTIVES

The Army is interested in conducting a literature search of previous work conducted by SwRI with regards to fuel pump wear and performance as it relates to fuel additives and test conditions. The results of this search will be used as a basis for determining the test matrix for the Phase 2 pump testing effort to follow.

3.0 HISTORICAL REVIEW

3.1 LITERATURE REVIEW

A literature review of all fuel pump test rig final technical reports was conducted. Work directives performed by Southwest Research Institute were reviewed for relevance to fuel pump performance. The literature search included reports dating back to Fiscal Year 1995. Reports that covered testing on Stanadyne rotary fuel pumps, DENSO fuel pumps, and Bosch CP-3 fuel pumps were of particular interest.

The literature search yielded nine reports of interest. The list of reports including report number, title, and date published is shown in Table 3. Each pump test covered in the literature search was reviewed for performance, wear results, and other applicable criteria. Raw data from the testing was evaluated where available, including pump pressures, temperatures, and fuel flow. A summary of pertinent data for each test is shown in Appendix A

Due to the unique results of reports 429, 433, and 434, this pump data was not included in the bulk analysis. In those tests, either the pump performed well and suffered no wear or lack of performance or it failed catastrophically. A pass/fail test does not serve as a good objective metric.

Table 3. Reports of Interest

Report No.	Title	Date
323	Fuel Lubricity Additive Evaluation	Jun-97
367	Synthetic Fuel Lubricity Evaluation	Sep-03
429	Evaluation of Future Fuels in a High Pressure Common Rail System Part 1 – Cummins XPI	Oct-12
433	Evaluation of Future Fuels in a High Pressure Common Rail System – Part 3 John Deere 4.5L Powertech Plus	Jan-13
434	Evaluation of Future Fuels in a High Pressure Common Rail System - Part 2 2011 Ford 6.7L Diesel Engine	Jan-13
437	Effectiveness of Additives in Improving Fuel Lubricity and Preventing Pump Failure at High Temperature	Jan-13
468	Using 25%/75% ATJ/JP-8 Blend Rotary Fuel Injection Pump Wear Testing At Elevated Temperature	Sep-15
482	Using 20% / 80% DSHJP-8 Blend Rotary Fuel Injection Pump Wear Testing At Elevated Temperature	Oct-16
488	Rotary Fuel Injection Pump Wear Testing Using A 30% / 70% ATJ/F-24 Fuel Blend	Nov-17

3.2 Common Rail Performance Summaries

3.2.1 Report 429: Evaluation of Future Fuels in a High Pressure Common Rail System Part 1 – Cummins XPI

This report covered the testing of a series of fuels on a full scale pump test using a Cummins XPI High Pressure Common Rail Fuel System setup. Fuels tested included ULSD, JP-8, FT-SPK, and Jet A-1, and testing occurred at 60 and 93.3 °C. Laboratory tests BOCLE and HFRR were also conducted on each fuel. A summary of the fuels tested is shown in Table 4.

Table 4. IR429 Test Fuels

Test	Fuel	Additive	Test Temp. [°C]	Viscosity at Temp. [mm^2/s]	BOCLE [mm]	HFRR [mm]
1	ULSD	none	60.0	1.90	0.54	0.382
2	JP-8	as received	60.0	0.89	0.67	0.647
3	JP-8	as received	93.3	0.65	0.67	0.647
4	FT-SPK	22.5 ppm DCI-4A	60.0	0.99	0.59	0.681
5	50% JP-8/50% FT-SPK	22.5 ppm DCI-4A	60.0	0.94	0.67	0.670
6	50% JP-8/50% FT-SPK	22.5 ppm DCI-4A	93.3	0.67	0.67	0.670
7	Jet A-1	as received	60.0	0.81	0.81	0.750
8	FT-SPK	none	60.0	0.95	1.01	0.663

The tests were run using a NATO Standard Engine Laboratory Test AEP-5, Edition 3, which is a 400 hour test consisting of repeated 10 hour cycles. The de-normalized NATO Cycle is shown in Table 5.

Table 5. IR429 NATO Cycle

Step	Pump Speed [rpm]	Throttle [%]	Duration [hr]
1	400	0	0.50
2	1050	100	2.00
3	1155	0	0.50
4	788	100	1.00
5*	400 to 1050	0 to 100	2.00
6	630	100	0.50
7	400	0	0.50
8	1081	70	0.50
9	650	100	2.00
10	650	50	0.50

**Step 5 cycles between idle and rated conditions*

The full scale pump test used a Cummins XPI HPCR setup. The initial test plan called for testing four fuels at two temperatures each: neat ULSD, neat JP-8, FT-SPK with 22.5 ppm DCI-4A, and 50%/50% JP-8/FT-SPK with 22.5 ppm DCI-4A. As testing progressed, the results indicated a lower sensitivity to low viscosity fuels than expected. Therefore, the high temperature ULSD and additized FT-SPK test were replaced with neat Jet A-1 and neat FT-SPK tests at 60 °C.

All fuels tested completed the 400 hour test. Over the 400 hour test, no major indicators of decreased system health or performance were noted. Fuel rail pressure, gear pump outlet pressure, injected fuel flow rate, return fuel flow rate, and drive motor power output were compared over the life of the test. None of these parameters showed fuel based performance issues for any test fuel.

At the conclusion of the 400 hour test, the pump components were evaluated for wear. These components included the low pressure gear pump housing, gear teeth, low pressure relief valve, and injector needles. The most severe tests, Tests 7 and 8, showed visual indications of wear within the injectors. The injector needles for both tests showed dark spots of heavy wear not present in any of the other tests. The wear was not severe enough to cause performance degradation over 400 hours, but over time could cause an injector needle to seize when fired.

The XPI HPCR system, overall, was found to be robust with regards to fuel lubricity and viscosity. While little was seen based on performance data and wear analysis, it should be noted that an electronically controlled engine may make adjustments and compensations without operator awareness. Additionally, the 400 hour test duration was a fraction of the expected useful life of a vehicle, and it is unknown what might have occurred if tested longer.

3.2.2 Report 433: Evaluation of Future Fuels in a High Pressure Common Rail System – Part 3 John Deere 4.5L Powertech Plus

This report covered the testing of a series of fuels on a full scale pump test using a John Deere 4.5L Powertech Plus High Pressure Common Rail Fuel System setup. The pump used in testing was a DENSO HPCR HP3 high pressure fuel pump. Fuels tested included ULSD, Jet A-1, FT-SPK, and 50%/50% Jet A-1/FT-SPK at various temperatures. Laboratory tests BOCLE and HFRR were also conducted on each fuel. A summary of the fuels tested is shown in Table 6.

Table 6. IR433 Test Fuels

Test	Fuel	Additive	Test Temp. [°C]	Test Hours [hrs]	Viscosity at Temp. [mm^2/s]	BOCLE [mm]	HFRR [mm]
1	ULSD	none	60.0	400	1.90	0.54	0.47
2	Jet A-1	9 ppm DCI-4A	60.0	400	0.95	0.68	0.72
3	Jet A-1	9 ppm DCI-4A	93.3	400	0.68	0.67	0.72
4	FT-SPK	9 ppm DCI-4A	60.0	400	0.78	0.67	0.84
5	FT-SPK	9 ppm DCI-4A	93.3	4.35	0.57	0.67	0.84
6	50% Jet A-1/50% FT-SPK	9 ppm DCI-4A	60.0	400	0.85	0.67	0.75
7	50% Jet A-1/50% FT-SPK	9 ppm DCI-4A	93.3	4.40	0.61	0.67	0.75
8	50% Jet A-1/50% FT-SPK	22.5 ppm DCI-4A	82.8	400	0.68	0.63	0.74
9	50% Jet A-1/50% FT-SPK	22.5 ppm DCI-4A	93.3	4.07	0.61	0.63	0.74

The tests were run using a NATO Standard Engine Laboratory Test AEP-5, Edition 3, which is a 400 hour test consisting of repeated 10 hour cycles. The de-normalized NATO Cycle is shown in Table 7.

Table 7. IR433 NATO Cycle

Step	Pump Speed [rpm]	Throttle [%]	Duration [hr]
1	800	0	0.5
2	2400	100	2.0
3	2560	0	0.5
4	1800	100	1.0
5	800 to 2400	0 to 100	2.0
6	1440	100	0.5
7	800	0	0.5
8	2500	70	0.5
9	1500	100	2.0
10	1440	50	0.5

The initial test plan included four fuels operated at two temperatures each: neat ULSD, Jet A-1 with 9 ppm DCI-4A, FT-SPK with 9 ppm DCI-4A, and 50%/50% Jet A-1/FT-SPK with 9 ppm DCI-4A. As testing progressed, the results indicated a higher sensitivity to low viscosity fuels than previously tested systems. Therefore, changes to the test plan were made, resulting in the test matrix shown in Table 6.

Of the nine tests, three failed to complete the 400 hour test. At the 93.3 °C test temperature, neat FT-SPK, 50%/50% Jet A-1/FT-SPK with 9 ppm DCI-4A, and 50%/50% Jet A-1/FT-SPK with 22.5 ppm DCI-4A all resulted in catastrophic pump failure between four and five test hours. All other evaluations completed the full 400 hour test. Results from the system evaluated indicated a high sensitivity to the fuel viscosity at the test temperature. The minimum value for fuel viscosity which resulted in a completed test was 0.68 mm^2/s.

At the conclusion of testing, the pump components were evaluated for wear. Post-test component analysis indicated the critical area for system failure was the interaction between the ring cam and camshaft within the high pressure pump.

Results from the system evaluated indicated a sensitivity to synthetic aviation fuels not seen in other modern HPCR equipment. This fuel system was found to be catastrophically sensitive to fuel inlet temperature and viscosity. The minimum value for fuel viscosity which resulted in a completed test was 0.68 mm^2/s. Operation of this system in high ambient temperature applications may require the use of solely petroleum based fuels.

3.2.3 Report 434: Evaluation of Future Fuels in a High Pressure Common Rail System - Part 2 2011 Ford 6.7L Diesel Engine

A series of fuels were tested in the fuel system for the 2011 Ford 6.7L “Scorpion” Diesel Engine which used a Bosch CR/CP4 high pressure fuel pump. The fuels tested were ULSD, FT-SPK, Jet A-1, and 50%/50% FT-SPK/Jet A-1. Testing occurred at 60 and 80 °C over a 400 hour NATO cycle. Laboratory tests BOCLE and HFRR were also conducted on each fuel. A summary of the fuels tested is shown in Table 8.

Table 8. IR434 Test Fuels

Test	Fuel	Additive	Test Temp. [°C]	Viscosity at Temp. [mm^2/s]	BOCLE [mm]	HFRR [mm]
1	ULSD	none	60.0	1.90	0.47	0.48
2	Jet A-1	none	60.0	0.91	0.61	0.74
3	Jet A-1	none	80.0	0.74	0.61	0.74
4	FT-SPK	9 ppm DCI-4A	60.0	0.75	0.82	0.83
5	FT-SPK	9 ppm DCI-4A	80.0	0.62	0.82	0.83
6	50% Jet A-1/50% FT-SPK	9 ppm DCI-4A	60.0	0.83	0.66	0.71
7	50% Jet A-1/50% FT-SPK	22.5 ppm DCI-4A	60.0	0.83	0.56	0.76
8	Jet A-1, Clay Treated	none	60.0	0.91	0.81	N/A
8	FT-SPK, Clay Treated	none	60.0	0.75	0.96	N/A

The tests were run using a NATO Standard Engine Laboratory Test AEP-5, Edition 3, which is a 400 hour test consisting of repeated 10 hour cycles. The de-normalized NATO Cycle is shown in Table 9.

Table 9. IR434 NATO Cycle

Step	Pump Speed [rpm]	Throttle [%]	Duration [hr]
1	600	0	0.5
2	2800	100	2.0
3	2940	0	0.5
4	2100	100	1.0
5	600 to 2800	0 to 100	2.0
6	1680	100	0.5
7	600	0	0.5
8	2884	70	0.5
9	1600	100	2.0
10	1600	50	0.5

The initial test plan included four fuels operated at two temperatures each: neat ULSD, neat Jet A-1, FT-SPK with 9 ppm DCI-4A, and 50%/50% Jet A-1/FT-SPK with 9 ppm DCI-4A. As testing progressed, the results indicated a lower sensitivity to low viscosity fuels than previously tested systems. Rather than increasing the temperature of the blended fuel for the second test, additional DCI-4A was added to determine wear sensitivity. Additionally, a final evaluation of the system was performed using a combination of two fuels, neat Jet A-1 and FT-SPK, both clay treated. The resulting test matrix is shown in Table 8.

All fuels tested completed the 400 hour test. Fuel rail pressure, gear pump outlet pressure, lift pump pressure, injected fuel flow rate, return fuel flow rate, and drive motor power output were compared over the life of the test. The tests run utilizing FT-SPK as well as the 50%/50% Jet A-1/FT-SPK blend (Tests 4-7) experienced a drop in lift pump pressure over the course of the test. Tests 6 and 7 also experienced variations in return fuel flow rate over the life of the test. Both the drop in lift pump pressure and flow rate variations were attributed to degradation of the front bushing of the pump. Fuel rail pressure, gear pump outlet pressure, injected fuel rate, and drive motor power showed no fuel based performance issues for any test fuel.

At the conclusion of testing, the pump components were evaluated for wear. Degradation of the pump shaft bushings was present for all tests utilizing FT-SPK (Tests 4-7). Test 8 was conducted as an investigation into the source of the bushing degradation, and showed that the root cause was not likely fuel related but was due to physical installation variability

The Ford 6.7L system performed well from a durability standpoint and post-test component evaluations showed no signs of imminent failure. Results showed that the system had little sensitivity with regards to fuel lubricity and viscosity with even low levels of lubricity improver additive. No negative impacts should be expected from the use of current military fuels with the 6.7L injection system, or even future blended fuels with the minimum level of lubricity improver (9 ppm).

3.3 STANADYNE PERFORMANCE SUMMARIES

3.3.1 Report 323: Fuel Lubricity Additive Evaluation

For this work directive, 18 lubricity additives were evaluated using laboratory scale wear tests including SLBOCLE and HFRR. The additives were commercially available, and their composition proprietary. Each additive was given a distinct code; the most effective lubricity additive was labeled E-2. Using these results, the most effective additive was identified and subsequently evaluated using the full scale pump test for a duration of 200 hours. The pumps used in the testing were three standard Stanadyne pumps, model DB2829-4524 and three arctic Stanadyne pumps, model DB2829-4523.

The full scale pump test used a GM 6.2L engine setup. This included the mounting arrangement, drive gear, fuel injectors (Bosch NA52X), and primary and cartridge fuel filters of a GM 6.2L engine. This engine, as well as the arctic fuel pump, were used in the HMMWV at the time of testing. The tests were run at a pump speed of 1800 rpm and wide open throttle, with a target fuel inlet temperature of 40.0 °C.

The additive selected for use in the pump test was identified as E-2. At the time of this report, the identity of E-2 is unavailable. Three pump tests were performed using neat Jet A-1, Jet A-1 with 80 mg/L E-2, and Jet A-1 with 200 mg/L E-2. Each test ran two pumps (one arctic and one standard) simultaneously on the same test stand with a common fuel supply. All tests completed the 200 hour test with no significant deterioration in pump performance. Fuel pump delivery was consistent during all tests, with the exception of a significant increase in flow rate observed with neat Jet A-1 at 175 hours of testing.

After testing, the pumps were evaluated on a calibration stand for various measurements including pump delivery, transfer pump pressure, and injection advance. Both pumps run on neat Jet A-1 had low post-test transfer pump pressure. All other post-test measurements for all pumps were found to be within the manufacturer’s specifications. Next, each pump was disassembled and evaluated for wear. A subjective grade of 0 to 10 was given to wear-prone components of each pump, with 0 being no wear, 10 being severe wear, and a 5 considered a fail.

A summary of the results of the work directive is shown in Table 10.

Table 10. IR323 Data Summary

Pump No.	Pump	S/N	Fuel	Additive	Test Temp. [°C]	Post Test Calibration Failures (Out of 14)	Average Wear Rating	SLBOCLE [g]	HFRR [mm]
1	DB2829-4524 (standard)	8239197	Jet A-1	As Received	40.0	1	6.59	1300	0.645
2	DB2829-4523 (arctic)	8164640	Jet A-1	As Received	40.0	1	4.47	1300	0.645
3	DB2829-4524 (standard)	8239198	Jet A-1	80 mg/L E-2	40.0	1	4.00	2450	0.230
4	DB2829-4523 (arctic)	8164642	Jet A-1	80 mg/L E-2	40.0	0	3.76	2450	0.230
5	DB2829-4524 (standard)	8239209	Jet A-1	200 mg/L E-2	40.0	0	3.53	2550	0.215
6	DB2829-4523 (arctic)	8066006	Jet A-1	200 mg/L E-2	40.0	0	3.18	2550	0.215

The testing confirmed unacceptably severe fuel-injection system wear produced by the use of neat Jet A-1. The wear rate was significantly reduced using fuel-lubricity additives at concentrations below 100 mg/L, with a slight improvement in wear at 200 mg/L.

3.3.2 Report 367: Synthetic Fuel Lubricity Evaluation

The purpose of the testing conducted in this program was to evaluate the fuel lubricity properties of synthetic JP-5 fuel (S-5) using laboratory bench top scale and full scale pump tests. Laboratory bench top test results are shown in Appendix A

In addition to the neat S-5 fuel, two additized blends were tested: S-5 with 12 mg/L NALCO 5403, and S-5 with 22.5 mg/L NALCO 5403. Laboratory tests BOCLE, SLBOCLE, and HFRR were conducted on each of the three fuels. Full scale pump tests were also run on each fuel, with a target duration of 500 hours. In previous testing, the test length of 200 hours produced mostly mild wear and degradation results. The increase in test length to 500 hours reflects this result. The pumps used in the testing were Stanadyne arctic pumps (model DB2829-4879).

The full scale pump test for this testing used a GM 6.2L engine setup. This included the mounting arrangement, drive gear, fuel injectors (Bosch NA52X), and primary and cartridge fuel filters of a GM 6.2L engine. This engine, as well as the arctic fuel pump, were used in the HMMWV at the time of testing. The tests were run at a pump speed of 1800 rpm with the fuel levers in wide open throttle position, with a target fuel inlet temperature of 40.0 °C.

Each test ran two pumps simultaneously on the same fuel. During the test with neat S-5, both tests failed to complete the 500 hour test. One pump was shut down and removed from the stand at 96 hours due to impending seizure of the head and rotor. The second pump continued to run but the test was aborted at 151 hours due to high fuel return temperature which is also an indication of imminent failure. All four pumps run on additized S-5 completed the 500 hour testing.

After the completion of the pump tests, the pumps were evaluated for post-test performance on a calibration stand. Although both pumps run on neat S-5 were indicating severe wear, they were operational and post-test performance checks were possible. The pumps were then disassembled to evaluate individual components for wear, but no subjective grade was assigned to these components. Therefore, the Average Wear Rating for each pump is not applicable for this testing. The results of both the pump and laboratory tests are summarized in Table 11.

Table 11. IR367 Data Summary

Pump No.	Pump S/N	Fuel	Additive	Test Hours [hrs]	Test Temp. [°C]	Cal Points Failed (Out of 20)	HFRR [mm]	BOCLE [mm]	SLBOCLE [g]
1	10523925	S-5	As Received	95.6	40.0	9	0.609	0.95	967
2	10523926	S-5	As Received	151	40.0	3	0.609	0.95	967
3	10523924	S-5	12 mg/L NALCO 5403	500	40.0	4	0.662	0.76	1450
4	10524467	S-5	12 mg/L NALCO 5403	500	40.0	3	0.662	0.76	1450
5	10524469	S-5	22 mg/L NALCO 5403	500	40.0	1	0.668	0.68	1333
6	10524470	S-5	22 mg/L NALCO 5403	500	40.0	1	0.668	0.68	1333

3.3.3 Report 437: Effectiveness of Additives in Improving Fuel Lubricity and Preventing Pump Failure at High Temperature

The objective of this testing was to perform full scale pump tests to evaluate the effects of selected fuels and fuel blends, both neat and additized, on fuel injection pumps. Additionally, the effectiveness of lubricity additives was assessed in several fuels at fuel inlet temperatures of 40.0 °C, 57.0 °C, and 77.0 °C. The fuels selected for evaluation were: ultra-low sulfur diesel (ULSD), Jet A-1, Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), and a 50/50 Jet A-1/FT-SPK blend. The test duration was increased from 500 hours to 1,000 hours. This was due to the move to arctic pumps, which were outfitted with improved hardened and coated parts. The pumps tested were Stanadyne arctic pumps (DB2831-5079).

The full scale pump test used a GEP 6.5L engine setup. This included the mounting arrangement, drive gear, fuel injectors (Bosch Model O432217276), and cartridge fuel filter that corresponded to those used in the GEP 6.5L engine. This engine, as well as the arctic fuel pump, were used in the HMMWV at the time of testing. The tests were run at a pump speed of 1,700 rpm and with the fuel levers in wide open throttle position.

A total of 21 tests were performed in duplicate, simultaneously. The test matrix is shown in Table 12. Each test ran two pumps simultaneously on the same fuel. Seven pumps failed to reach the target test time: both pumps that ran on neat Jet A-1, neat FT-SPK, and 50/50 Jet A-1/FT-SPK with DCI-4A at 9 g/m³, and one pump that ran on Jet A-1 with INNOSPEC OLI-9070X at 50 g/m³. The remaining pumps were all operational at the end of testing.

Table 12. IR437 Test Matrix

Test No.	Test Fuel	40.0 °C	57.0 °C	77.0 °C
1,2,3	No.2 Diesel	X	X	X
4	No.2 Diesel, Clay Treated	X		
5	Jet A-1, neat	X		
6,8,10	Jet A-1 with DCI-4A @ 22.5 g/m³	X	X	X
7,9,11	Jet A-1 with Nalco 5403 @ 22.5 g/m³	X	X	X
12,13,14	Jet A-1 with INNOSPEC OLI-9070X @ 50 g/m³	X	X	X
15	FT-SPK, neat	X		
16,17,18	FT-SPK, DCI-4A @ 22.5 g/m³	X	X	X
19,20,21	50%/50% FT-SPK/Jet A-1, DCI-4A @ 9 g/m³	X	X	X

After testing, the pumps were evaluated on a calibration stand and checked for 22 parameters. The post-test calibration checks revealed that a large number of the pumps had compromised low idle delivery characteristics for all fuels, including ULSD. Each pump was then disassembled and evaluated for wear. A subjective grade was given to each component, with 0=new, and 5=failed.

BOCLE, SLBOCLE, and HFRR laboratory tests were performed on each test fuel/additive combination and target temperature in the pump test matrix. Table 13 shows the full test matrix and summarized results of the laboratory and full scale testing. The test hours, post-test calibration failures, and wear ratings shown are averages of the two pumps run in each test.

Table 13. IR437 Data Summary

Test	Fuel	Additive	Fuel Temperature	Test Hours	Post Test Calibration Failures (Out of 21)	Wear Rating	BOCLE	SLBOCLE	HFRR
-	-	-	[°C]	[hrs]	-	-	[mm]	[g]	[mm]
1	No.2 Diesel	none	40.0	1,000	4	1.11	0.53	5500	0.257
2	No.2 Diesel	none	57.0	1,000	4	1.14	0.55	5400	0.310
3	No.2 Diesel	none	77.0	1,000	4	1.10	0.49	6000	0.294
4	No.2 Diesel, clay treated	none	40.0	1,000	3	1.55	0.55	4400	0.640
5	Jet A-1, neat	As Received	40.0	125	6	2.22	0.78	1800	0.603
6	Jet A-1	DCI-4A @ 22.5 g/m^3	40.0	1,000	4	1.48	0.64	2500	0.653
8	Jet A-1	DCI-4A @ 22.5 g/m^3	57.0	1,000	3	1.40	0.60	1950	0.680
10	Jet A-1	DCI-4A @ 22.5 g/m^3	77.0	1,000	3	1.27	0.60	2650	0.720
7	Jet A-1	Nalco 5403 @ 25 g/m^3	40.0	1,000	4	1.53	0.53	2200	0.664
9	Jet A-1	Nalco 5403 @ 25 g/m^3	57.0	1,000	3	1.42	0.58	2650	0.701
11	Jet A-1	Nalco 5403 @ 25 g/m^3	77.0	1,000	7	1.69	0.59	2600	0.710
12	Jet A-1	INNOSPEC OLI-9070X @ 50 g/m^3	40.0	1,000	2	1.68	0.64	2450	0.710
13	Jet A-1	INNOSPEC OLI-9070X @ 50 g/m^3	57.0	1,000	5	1.93	0.63	1850	0.720
14	Jet A-1	INNOSPEC OLI-9070X @ 50 g/m^3	77.0	875	3	1.92	0.65	1600	0.730
15	FT-SPK	none	40.0	24	n/a	1.83	1.01	1200	0.840
16	FT-SPK	DCI-4A @ 22.5 g/m^3	40.0	1,000	2	1.79	0.65	1850	0.800
17	FT-SPK	DCI-4A @ 22.5 g/m^3	57.0	1,000	2	1.95	0.65	1850	0.800
18	FT-SPK	DCI-4A @ 22.5 g/m^3	77.0	1,000	2	1.63	0.56	1800	0.784
19	50%/50% FT-SPK/Jet A-1	DCI-4A @ 9 g/m^3	40.0	1,000	2	1.77	0.73	2100	0.681
20	50%/50% FT-SPK/Jet A-1	DCI-4A @ 9 g/m^3	57.0	1,000	5	2.13	0.78	1700	0.719
21	50%/50% FT-SPK/Jet A-1	DCI-4A @ 9 g/m^3	77.0	395	8	2.37	0.75	1700	0.719

The testing showed that clay treated diesel fuel caused greater wear than ULSD. It also confirmed unacceptably severe fuel-injection system wear produced by the use of neat Jet A-1, and showed that the same holds true for neat FT-SPK. The lubricity additives improved the durability of both Jet A-1 and FT-SPK at even low concentrations.

3.3.4 Report 468: Using 25%/75% ATJ/JP-8 Blend Rotary Fuel Injection Pump Wear Testing At Elevated Temperature

This work directive evaluated the durability of a fuel injection system with an alcohol-to-jet (ATJ) synthetic fuel blended with petroleum F-24 with lubricity additive treatments. Two full scale pump tests were run with an elevated fuel inlet temperature of 70 °C, for a target test duration of 1,000 hours. The fuel used for the first test was 25/75 ATJ/JP-8 with 9 ppm DCI-4A, and the second test used 25/75 ATJ/JP-8 with 24 ppm DCI-4A. The pumps used in this testing were Stanadyne arctic pumps, model DB2831-5079.

The full scale pump test used a GEP 6.5L engine setup. This included the mounting arrangement, drive gear, fuel injectors (Bosch Model O432217276), and cartridge fuel filter that corresponded to those used in the GEP 6.5L engine. This combination was used in the HMMWV at the time of testing. The tests were run at a pump speed of 1,700 rpm with the fuel levers in the wide open throttle position.

Each of the tests were performed in duplicate by running two pumps simultaneously with the same fuel and the same conditions. Neither of the pumps that ran with 25/75 ATJ/JP-8 with 9 ppm DCI-4A completed the 1,000 hour test. Pump SN16756534 seized at 251 hours and fractured the driveshaft. Excessive wear on the drive tang was found, as well as internal debris. This pump was removed and the test continued.

A phenomena that has been seen in pump test stand evaluations is that when the governor mechanism lessens the fuel quantity, the electric motor does not respond and reduce pump speed as an engine would. With low viscosity fuels at elevated temperatures, this can cause the fuel injection pumps to rattle and produce increase fretting wear on the drive tang. Usually the pump rattle can be reduced by lowering the testing speed below the governor interaction point. As wear occurs in the pump, this interaction sometimes also occurs at the lower speed and the test speed is subsequently reduced again. The reduction in test speed on the stand is used as a measure of test fuel pump performance degradation.

The test speed was lowered and Pump SN16756535 was placed back on test. The speed was eventually lowered enough that the injection quantity dropped, but rattling was still present. At 389 hours, the test was aborted after an inspection revealed wear debris in the housing. Both pumps tested with ATJ/JP-8 fuel with 24 ppm DCI-4A completed the 1,000 hours as operational.

After test completion, the pumps were to be evaluated on a calibration stand to check delivery performance. Of the four pumps, only SN16756536 was able to be evaluated. In addition to the seized pump which was non-operational, SN16756535 and SN16756538 had excessive backlash due to drive tang wear which rendered them non-operational on the calibration stand. Backlash is the relative clearance between thickness of the drive tang on the driveshaft and the width of the driven slot on the rotor. An increase in backlash is a consequence of increased wear between the drive tang and driven slot. The fourth pump, SN16756536, was evaluated and failed 4 of the 21 performance specifications. They were subsequently disassembled and select parts were evaluated for wear. A subjective grade was given to each component, with 0=new, and 5=failed. Table 14 shows the summary of the laboratory scale wear tests and full scale post-test evaluations.

Table 14. IR468 Data Summary

Pump S/N	Fuel	Additive	Test Hours [hrs]	Test Temp. [°C]	Post Test Calibration Failures (Out of 21)	Average Wear Rating	BOCLE [mm]	HFRR [mm]
16756534	25/75 ATJ/JP-8	9 ppm DCI-4A	251	40.0	n/a	2.59	0.563	0.670
16756535	25/75 ATJ/JP-8	9 ppm DCI-4A	389	40.0	n/a	2.24	0.563	0.670
16756536	25/75 ATJ/JP-8	24 ppm DCI-4A	1,000	40.0	n/a	2.09	0.504	0.729
16756538	25/75 ATJ/JP-8	24 ppm DCI-4A	1,000	40.0	4	2.33	0.504	0.729

This testing showed that 25/75 ATJ/JP-8 treated with 9 ppm DCI-4A was inadequate at preventing wear. Additionally, while the 25/75 ATJ/JP-8 treated with 24 ppm DCI-4A allowed for 1,000 hours of pump operation, there was evidence of excessive wear and the resulting performance degradation would impact engine operation.

3.3.5 Report 482: Using 20% / 80% DSH/JP-8 Blend Rotary Fuel Injection Pump Wear Testing At Elevated Temperature

The objective of this work directive was to evaluate the durability of a fuel injection system with a 20% DSH8/80% JP-8 fuel blend at an elevated fuel inlet temperature of 77.0 °C. This was accomplished by running a full scale pump test for 500 hours. The fuel was treated with a CI/LI additive, DCI-4A, at a 9 ppm treat rate.

The full scale pump test used a GEP 6.5L engine setup. This included the mounting arrangement, drive gear, fuel injectors (Bosch Model O432217276), and cartridge fuel filter that corresponded to those used in the GEP 6.5L engine. This combination was used in the HMMWV at the time of testing. The tests were run at a pump speed of 1,700 rpm with the fuel levers in the wide open throttle position.

The pump test ran two pumps simultaneously at the same conditions. Both pumps completed 500 hours of testing and remained operational. To determine the pump delivery performance post-test, the pumps were evaluated using a calibration stand. Both pumps failed 4 of the 21 performance specifications. The pumps were then disassembled and select parts were rated for wear. A subjective grade was given to each component, with 0=new, and 5=failed. Table 15 shows the summary of the laboratory scale wear tests and full scale post-test evaluations.

Table 15. IR468 Data Summary

SN	Fuel	Additive	Test Temp. [°C]	Post Test Calibration Failures (Out of 21)	Average Wear Rating	BOCLE [mm]	HFRR [mm]
17102937	20/80 DSH8/JP-8	9 ppm DCI-4A	77.0	4	1.80	0.529	0.670
17102938	20/80 DSH8/JP-8	9 ppm DCI-4A	77.0	4	2.13	0.529	0.670

Based on the testing and results, a 20/80 blend of DSH8/JP-8 with 9 ppm DCI-4A operated at 77.0 °C fuel inlet temperature will allow 500 hours of pump operation. However, the performance degradation of the fuel injection pumps at 500 hours could impact engine governor operation, and component inspections suggested excessive transfer pump liner wear.

3.3.6 Report 488: Rotary Fuel Injection Pump Wear Testing Using A 30% / 70% ATJ/F-24 Fuel Blend

This work directive evaluated the durability of a fuel injection system with an alcohol-to-jet (ATJ) synthetic fuel blended with petroleum F-24 with lubricity additive treatments. Two full scale pump tests were run for a target test duration of 1,000 hours, the first test with a fuel inlet temperature of 40.0 °C and the second test with a fuel inlet temperature of 70 °C. The fuel used for both tests was a 30% ATJ and 70% F-24 blend with 24 ppm of DCI-4A lubricity additive. The pumps evaluated for this program were Stanadyne arctic pumps, model DB2831-6282.

The full scale pump test used a GEP 6.5L engine setup. This included the mounting arrangement, drive gear, fuel injectors (Bosch Model O432217276), and cartridge fuel filter that corresponded to those used in the GEP 6.5L engine. This combination was used in the HMMWV at the time of testing. The tests were run at a pump speed of 1,700 rpm with the fuel levers in the wide open throttle position.

Each of the tests ran two pumps simultaneously with the same fuel and at the same conditions. Both tests finished the 1,000 hour tests with the pumps operational. After test completion, the pumps were evaluated on a calibration stand to check delivery performance. They were subsequently disassembled and select parts were evaluated for wear. A subjective grade was given to each component, with 0=new, and 5=failed. Table 16 shows the summary of the laboratory scale wear tests and full scale post-test evaluations.

Table 16. IR488 Data Summary

Pump S/N	Fuel	Additive	Test Temp. [°C]	Post Test Calibration Failures (Out of 21)	Average Wear Rating	BOCLE [mm]	HFRR [mm]
17200043	30 ATJ/70 F-24	24 ppm DCI-4A	40.0	3	2.24	0.540	0.723
17200045	30 ATJ/70 F-24	24 ppm DCI-4A	40.0	2	2.41	0.540	0.723
17200072	30 ATJ/70 F-24	24 ppm DCI-4A	77.0	3	2.24	0.555	0.718
17200858	30 ATJ/70 F-24	24 ppm DCI-4A	77.0	3	2.24	0.555	0.718

The results of this testing showed moderate wear and performance degradation of the fuel injection pumps in both tests. The 30/70 blend of ATJ/F-24 with 24 ppm CI/LI operated at both 77.0 °C and at 40.0 °C fuel inlet temperature over 1,000 hours resulted in an impact on the pump delivery performance which could translate to poor idle control and governor operation.

3.4 PUMP EVALUATION DISCUSSION

3.4.1 Subjective Wear Rating

All tests examined in this study reported an average wear rating with the exception of tests conducted in IR367. This rating is a subjective measurement, based on a visual inspection of the fuel lubricated wear contacts after pump disassembly. Over time, the list of parts examined has increased. Additionally, the person who rates the components occasionally changes from program to program. This introduces variations that make correlating the wear rating over decades and multiple programs difficult. For pumps that experienced catastrophic failure or near failure, there may be severe wear on one or a few of the parts evaluated while the other components remained relatively unaffected. This can cause the Average Wear Rating for the pump as a whole to be misleading and can mask major wear. An example of the wear evaluation and assigned ratings is shown below in Table 17.

Table 17. Pump Parts Wear Evaluation Example

Pump Type DB2831-5079 (arctic):		SN: 15396931
Test Condition : Jet A-1 No Additive @ 105°F		Pump Duration : 124.5-hrs.
Part Name	**Condition of Part**	**Rating 0 = New 5 = Failed**
BLADES	Polishing wear-rotor slots and liner contact	1
BLADE SPRINGS	Rubbing wear	3
LINER	Rubbing wear	1.5
TRANSFER PUMP REGULATOR	Polishing wear from rotor contact	1
REGULATOR PISTON	Light polishing wear	1
ROTOR	Normal	1
ROTOR RETAINERS	Wear marks from rotor contacts	1.5
DELIVERY VALVE	Polishing wear	2
PLUNGERS	Polishing wear from shoe contact	2
SHOES	wear from rollers, plunger, and leaf spring	4.5
ROLLERS	Scarring and pitting wear	4.5
LEAF SPRING	Wear from shoe contact	2
CAM RING	Scarred on lobes from contact with rollers	4
THRUST WASHER	Polishing wear from weights	1
THRUST SLEEVE	Polishing from linkage hook fingers	1
GOVORNER WEIGHTS	Light wear from T washer	1
LINK HOOK	Worn at pivot spot - polishing on fingers	2
METERING VAVLE	Polishing wear - stained brown	1.5
DRIVE SHAFT TANG	Some wear from rotor contact	1
DRIVE SHAFT SEALS	Normal	1
CAM PIN	0.002 inches out of round	3.5
ADVANCE PISTON	Fretting wear on top side	2.5
HOUSING	Bowl stained gold inside	1
	AVERAGE DEMERIT RATINGS	1.935

In this test, the pump failed at 124.5 hours out of a 1,000 hour test. The shoes, rollers, and cam rings had severe damage, but the Average Wear Rating for the pump was a 2. Out of 58 pumps evaluated using this wear rating reviewed in this report, 9 failed. The maximum Average Wear Rating was 3.3, and the average rating of the failed pumps was 2.2.

There exists a desire to move away from the subjective ratings and identify an objective and quantitative rating for fuel pump performance.

3.4.2 Quantitative Wear Measurements

Throughout the history of pump testing at Southwest Research Institute, a variety of different quantitative wear measurements have been used to evaluate wear. These include surface profilometry, measuring weight loss/gain, and measuring dimensions on wear-prone components. In IR323, surface profilometry and optical microscopy were used to determine wear volume on select pump components. The wear volume is plotted against the wear rating in Figure 13. There is a strong correlation between the average wear volume and the average wear rating. However, this was the only program that used this metric. More data points would improve the understanding of the correlation.

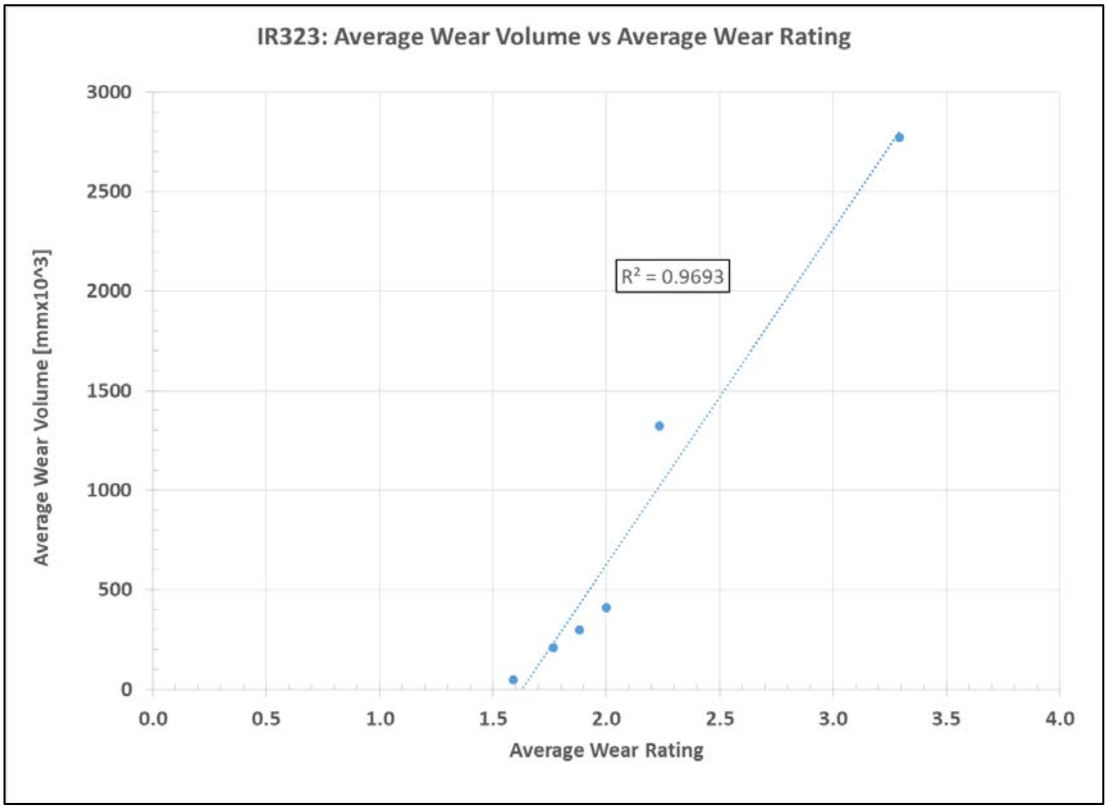

Figure 13. IR323: Average Wear Volume vs Wear Rating

Comparing the SLBOCLE results against the average wear volume suggests that the increased SLBOCLE numbers result in reduced wear of the pump components, as shown in Figure 14.

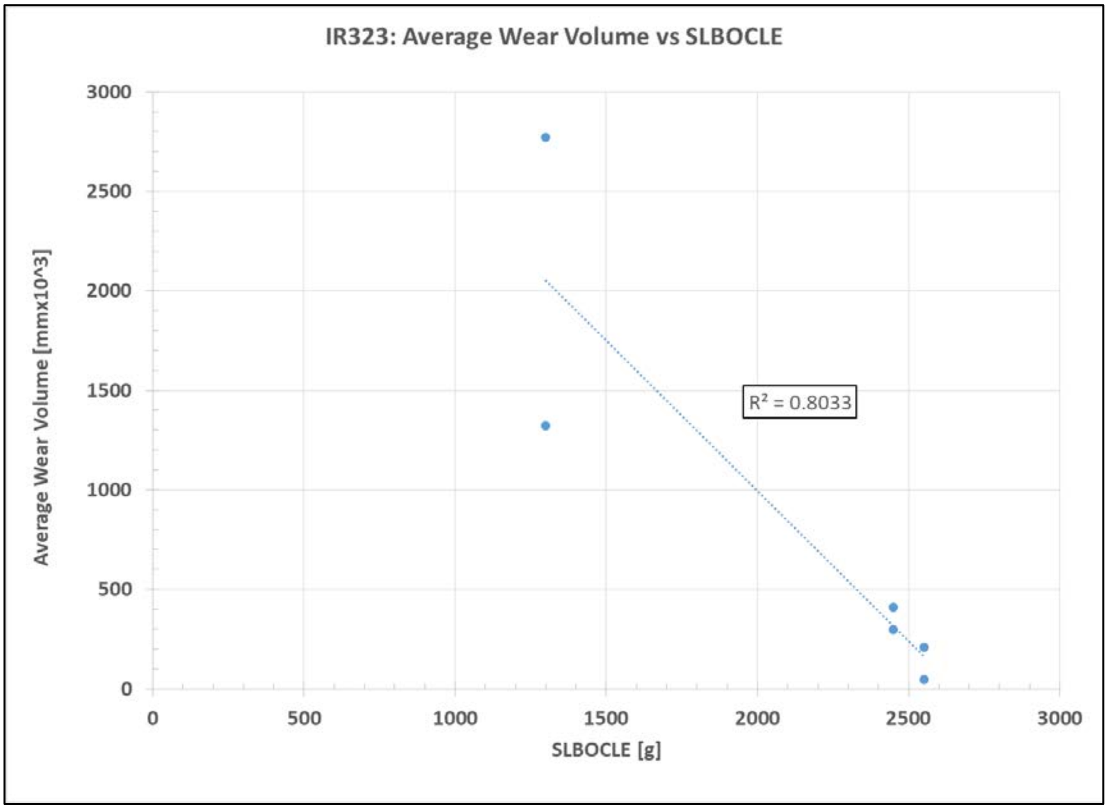

Figure 14. IR323: Average Wear Volume vs SLBOCLE

In IR437, the weight of the transfer pump blades were measured both pre- and post-test, and the difference reported. With low lubricity fuels, wear is likely to occur in the transfer pump blades. Significant wear of these parts can cause the fuel pressure to the pump metering section to drop, subsequently reducing fuel flow of the pump.

However, no significant correlation came from the transfer pump weight change with respect to other wear indicators. The transfer pump weight change is plotted against the BOCLE results in Figure 15. The scattered nature of the plot shows no correlation between the two.

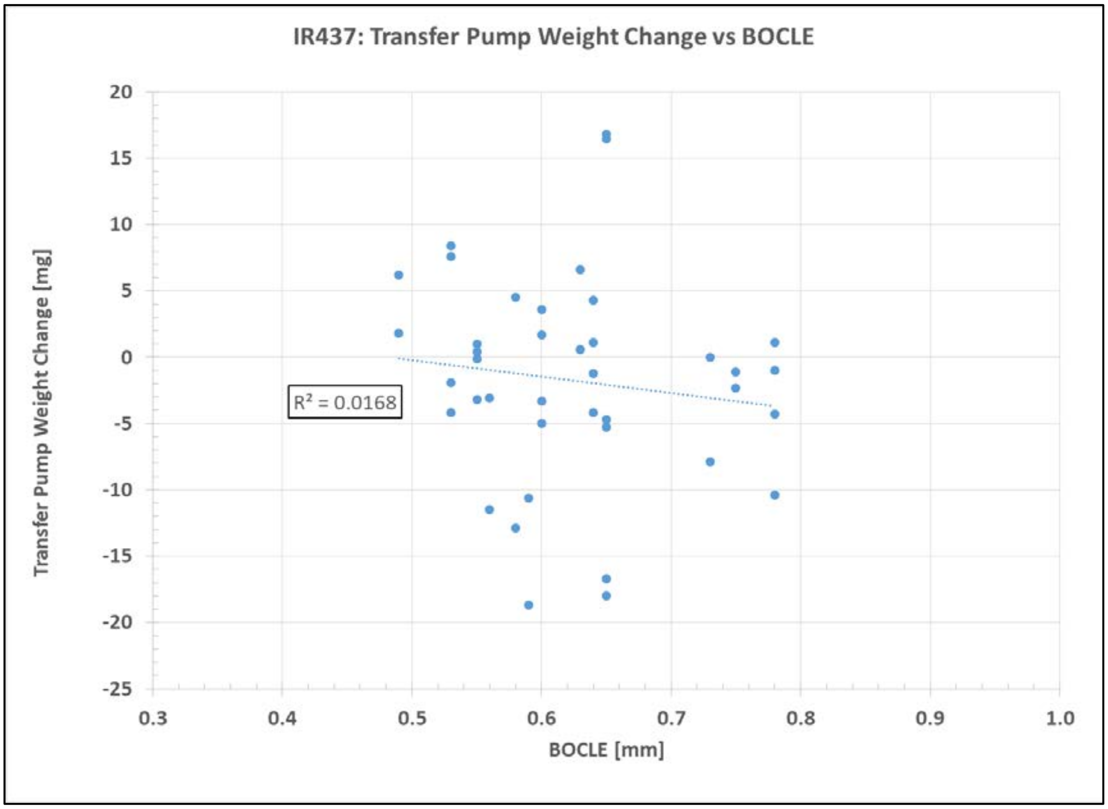

Figure 15. IR437: Transfer Pump Weight Change vs BOCLE

With the exception of IR323, all the pump tests covered reported pre- and post-test roller to roller dimensions. Changes in the roller to roller dimension alter the travel distance of the plungers in the fuel-metering system. This can change both the fuel flow and injection pressure, as well as the injection timing. The roller to roller change is plotted against the BOCLE results for the corresponding test in Figure 16. Again, no large scale correlation is evident between the rate of change of the flow rate and the BOCLE results. While there may be an argument made for pump correlation above a BOCLE result of 0.6, these high BOCLE results are typically from unadditized fuels which are not suitable for long term use in diesel injection equipment. The large amount of data scatter in the BOCLE results also highlight the fact that the BOCLE test was not designed for diesel injection pumps, but for aviation centrifugal style pumps.

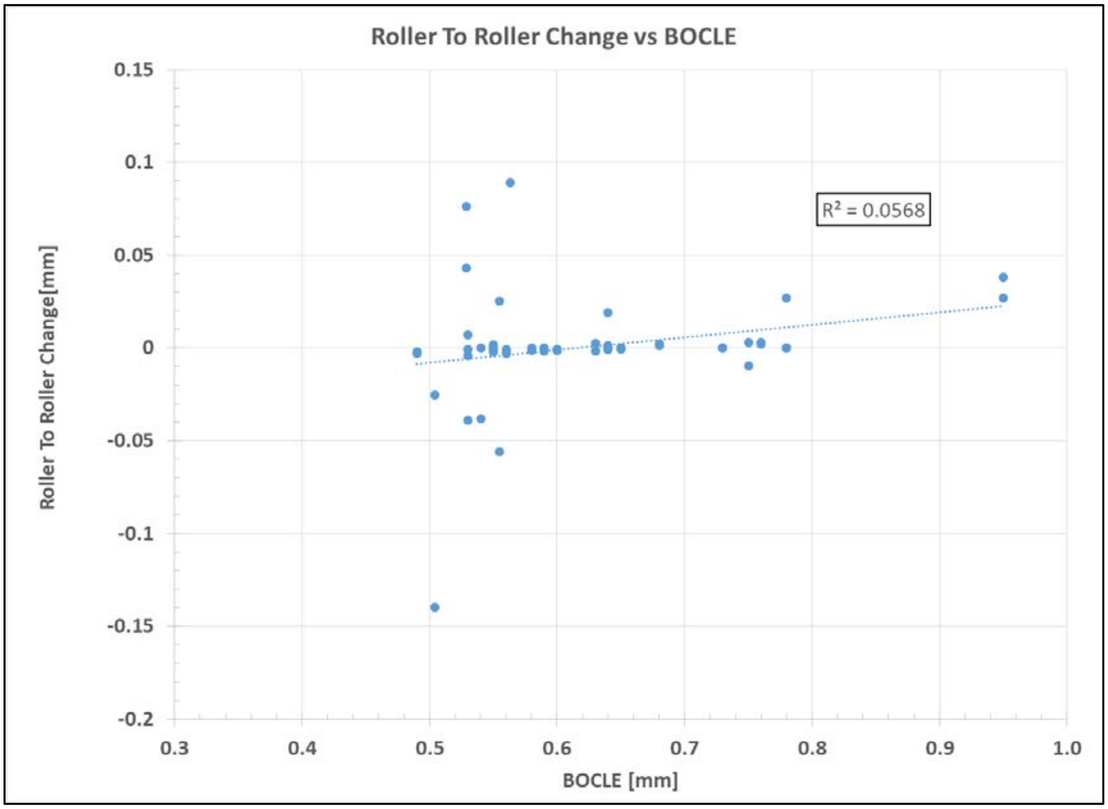

Figure 16. Roller to Roller Change vs BOCLE

3.5 FUEL PROPERTIES

Throughout the history of rotary pump testing conducted by SwRI for the U.S. Army, several fuels have been utilized. These included diesel fuel, which the pumps were designed to run on, and Jet A-1, which is commonly used in ground equipment as part of the single-fuel concept. Additionally, as the U.S. Army sought to diversify energy sources, investigation into alternative fuels, both alone and blended, was completed. Fischer-Tropsch Synthetic Paraffinic Kerosene, alcohol-to-jet (ATJ) Synthetic Paraffinic Kerosene, and various blends of these two with petroleum based aviation fuel have all been investigated.

Before testing a fuel on a full scale pump test, the fuel is typically evaluated for relevant chemical properties. A summary of the fuels and their properties used in testing covered in this report is shown in Table 18. The fuels are evaluated after blending (if applicable) but before any additional treatment by SwRI (e.g., CI/LI additives, clay treatment).

Table 18. Summary of Test Fuel Properties

IR	Fuel	Acid Number	Sulfur Content	Distillation - IBP	Distillation - FBP	Flash Point	Density	Freeze Point	Net Heat of Combustion	Smoke Point	Cetane Number	Derived Cetane Number	Calculated Cetane Index	Aromatics	Viscosity at 40 °C
-	-	[mg KOH / g]	[ppm]	[°C]	[°C]	[°C]	[kg/m^3]	[°C]	[MJ/kg]	[mm]	[-]	[-]	[-]	[vol %]	[mm^2/s]
323	Jet A-1	0.004	20	160.0	218.0	44.0	782.0	-59.5	43.54	29.0	-	-	-	8.1	1.07
367	S-5	-	-	186.0	271.0	64.0	765.0	-53*	44.10	>43	-	-	69.3	0.9	-
437	ULSD	-	14	193.1	341.0	76.6	-	-	-	-	44.0	-	-	29.5	2.53
437	FT-SPK	-	<10	153.3	216.3	42.0	742.0	-55.0	42.00	-	-	-		0.9	0.95
437	Jet A-1	0.001	<10	160.4	219.1	48.0	801.0	-60.0	43.20	21.8	-	-		20.5	1.09
437	50/50 FT-SPK/Jet A-1	-	<10	162.0	223.9	37.0	769.0	-68.0	43.48	35.0	-	-	-	-	1.03
468	25/75 ATJ/JP-8	0.008	749	173.0	254.5	51.5	785.7	-57.0	43.20	27.0	41.0	42.66	50.2	13.7	1.34
482	20/80 DSH8/JP-8	0.004	796	178.6	251.9	61.5	790.6	-56.0	43.10	28.5	-	49.6	54.9	14.7	1.45
488	30 ATJ/70 F-24	0.006	850.22	170.3	262.5	51.0	784.4	-56.0	43.50	26.8	40.8	41.68	49.3	12.9	1.32

4.0 OPERATIONAL DATA ANALYSIS

To date, the majority of the wear analysis on the rotary fuel pumps and components has been subjective. To improve test to test comparison, one or more standard, objective metrics would be ideal. An objective, quantitative method would also allow for a better correlation between the standardized laboratory scale tests and pump performance.

The raw, analog operational data from the programs of interest that utilized Stanadyne pumps were extracted and examined. Each test covered in this report was included with the exception of those from IR367 (Synthetic Fuel Lubricity Evaluation) as the data was not available. Additionally, the data from IR323 (Fuel Lubricity Additive Evaluation) was extracted from the final report rather than the analog data file. All other data was extracted from the test stand operation data files. The parameters analyzed included transfer pump pressure, pump housing pressure, fuel return temperature, and the injected flow rate of the pumps. One test (two pumps) was removed from the data set due to short test time and catastrophic failure. These were pumps SN 15438603 and SN 15438885 that were run on neat FT-SPK fuel.

4.1 TRANSFER PUMP PRESSURE

On the Stanadyne pump, the transfer pump pressure is the regulated pressure the metal blade transfer pump supplies to the pump metering section. With low lubricity fuels, wear is likely to occur in the transfer pump blades, blade slot, and eccentric liner. Wear in these areas generally causes the transfer pump pressure to decrease. However, because the transfer pump has a pressure regulator, significant wear needs to occur in the transfer pump before the fuel pressure drops to below the operating range allowed in the pump specification.

The average slope of the transfer pump pressure over each pump test is plotted in Figure 17 against its respective average wear rating. For pumps with a faster drop in transfer pump pressure, there is evidence that the wear is greater. However, there are instances of more severe wear ratings that see very little change in the transfer pump pressure over the life of the test and no major correlation is evident.

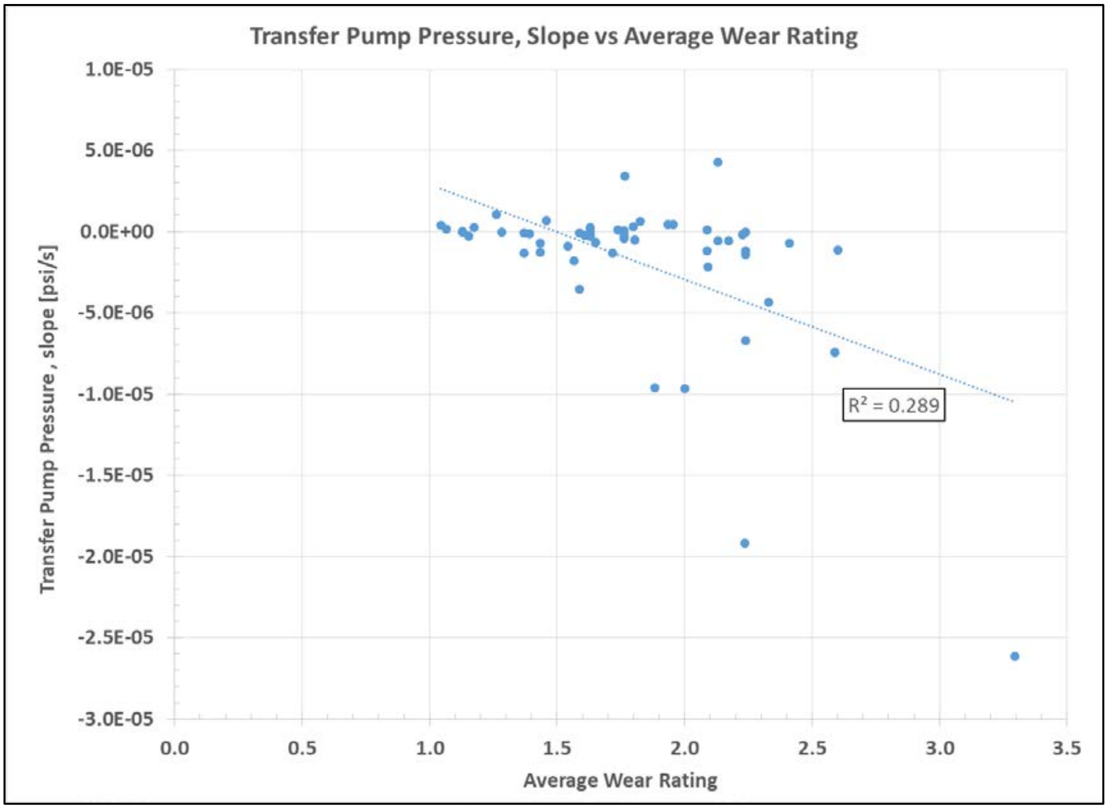

Figure 17. Transfer Pump Pressure, Slope vs Average Wear Rating

The average slope of the transfer pump pressure is plotted against the BOCLE results from each test in Figure 18. The rate of change of the transfer pump pressure does not show a strong relationship with the BOCLE wear scar values.

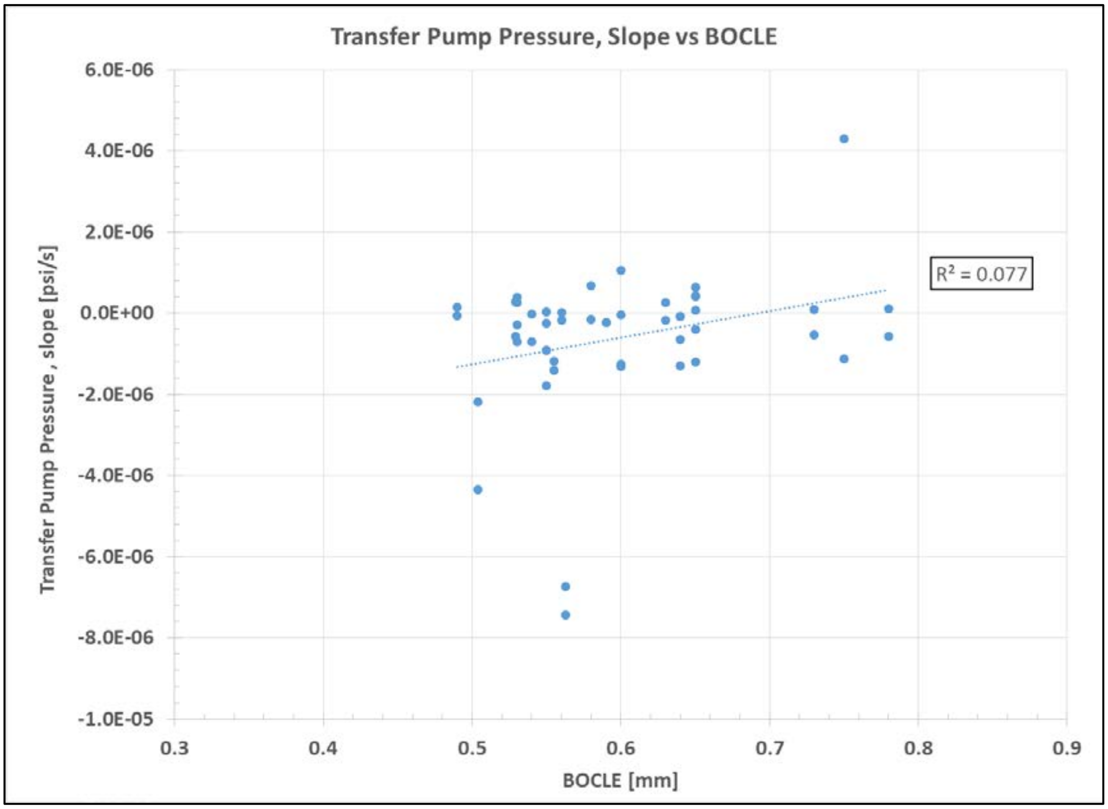

Figure 18. Transfer Pump Pressure, Slope vs BOCLE

4.2 PUMP HOUSING PRESSURE

The housing pressure is the regulated pressure in the pump body that affects fuel metering and timing. With low lubricity fuel, wear occurs in high fuel pressure generating opposed plungers and bores, and between the hydraulic head and rotor. Leakage from increased diametrical clearances within the fuel injection pump manifest as increased housing pressures. The pumping plungers have injection pressure on one end that vents to the housing pressure on the opposite end. The hydraulic head and rotor also vent from injection pressure to housing pressure. Any increase in clearance between plunger and bore or rotor and hydraulic head result in increased leakage and a subsequent housing pressure increase. An increased housing pressure reduces metered fuel and retards injection timing.

The average pump housing pressure rate of change is plotted against the average wear rating for each pump test analyzed and is shown in Figure 19. A faster increase in the pump housing pressure shows a general trend towards higher wear in the pump.

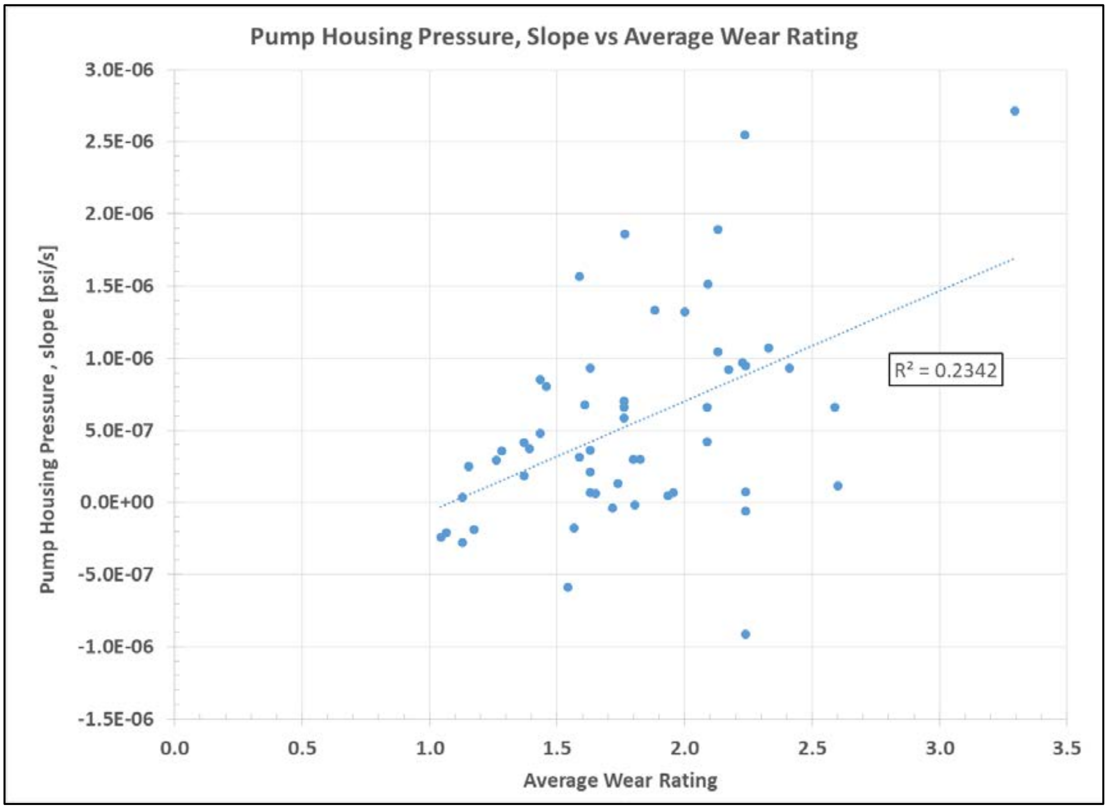

Figure 19. Pump Housing Pressure Slope vs Average Wear Rating

Figure 20 shows the same average slope plotted against the BOCLE results. The scattered nature of the plot indicates no correlation between the rate of change of the pump housing pressure with the BOCLE wear scar results.

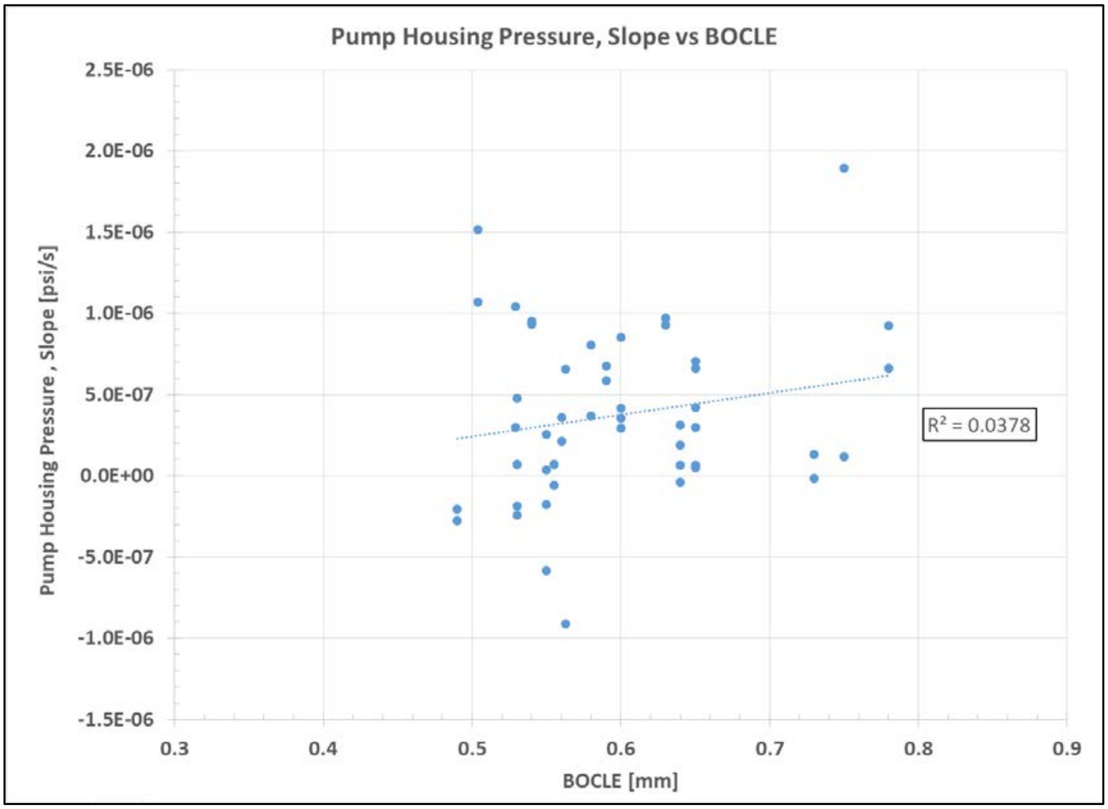

Figure 20. Pump Housing Pressure, Slope vs BOCLE

4.3 FUEL RETURN TEMPERATURE

The fuel return temperature is a function of accelerated pump wear and in general, increases as wear worsens. The average slope of the fuel return temperature is plotted versus the average wear rating in Figure 21. No correlation between fuel return temperature and the wear rating is evident.

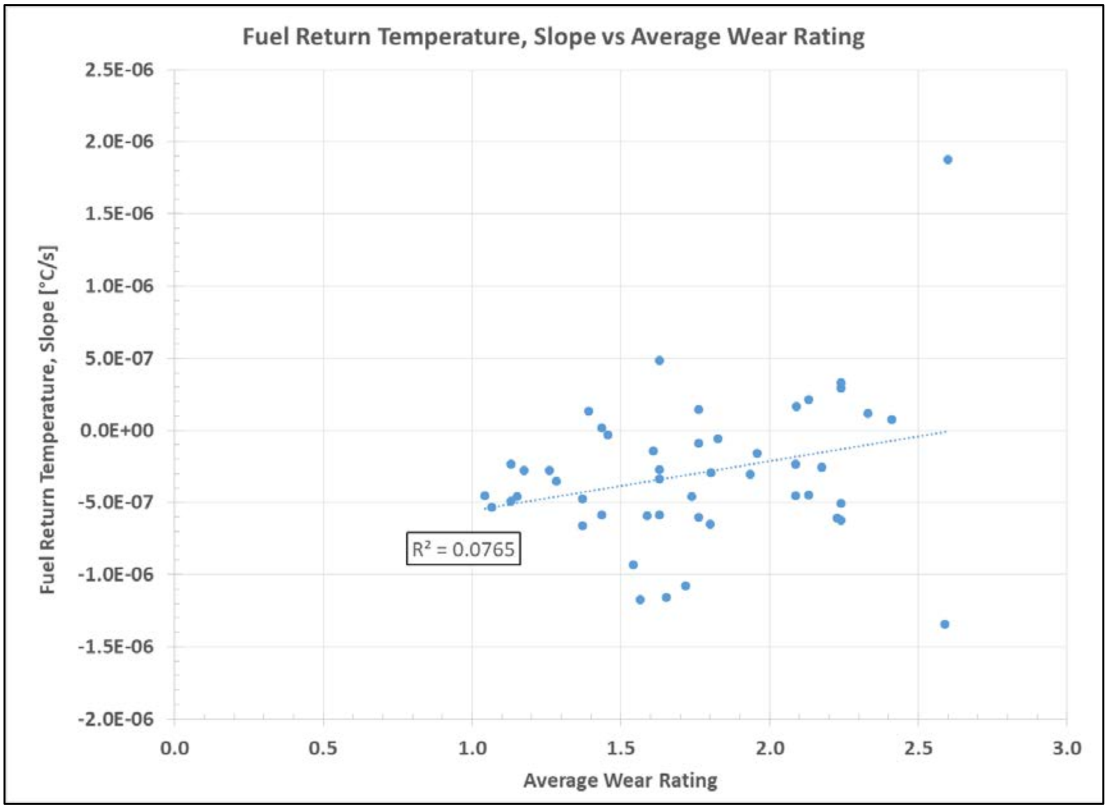

Figure 21. Fuel Return Temperature, Slope vs Average Wear Rating

Figure 22 shows the same average slope plotted against the BOCLE wear scar results. There is no evident correlation between the rate of change of the flow rate and the BOCLE results.

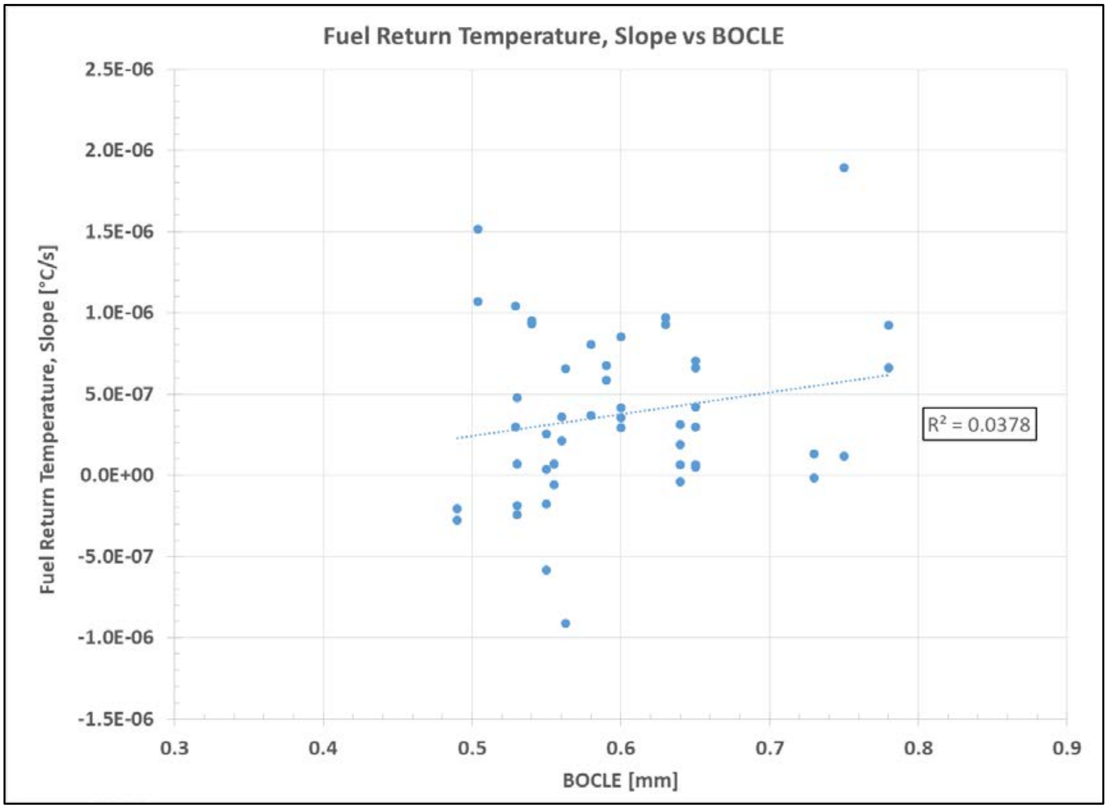

Figure 22. Fuel Return Temperature, Slope vs BOCLE

4.4 INJECTED FLOW RATE

Figure 23 shows the average injected flow rate of change plotted against the average wear rating for each pump test analyzed. The rate of change of the injected fuel does not show a strong relationship to the average wear rating, as shown by the low coefficient of determination (R squared) of 0.0147.

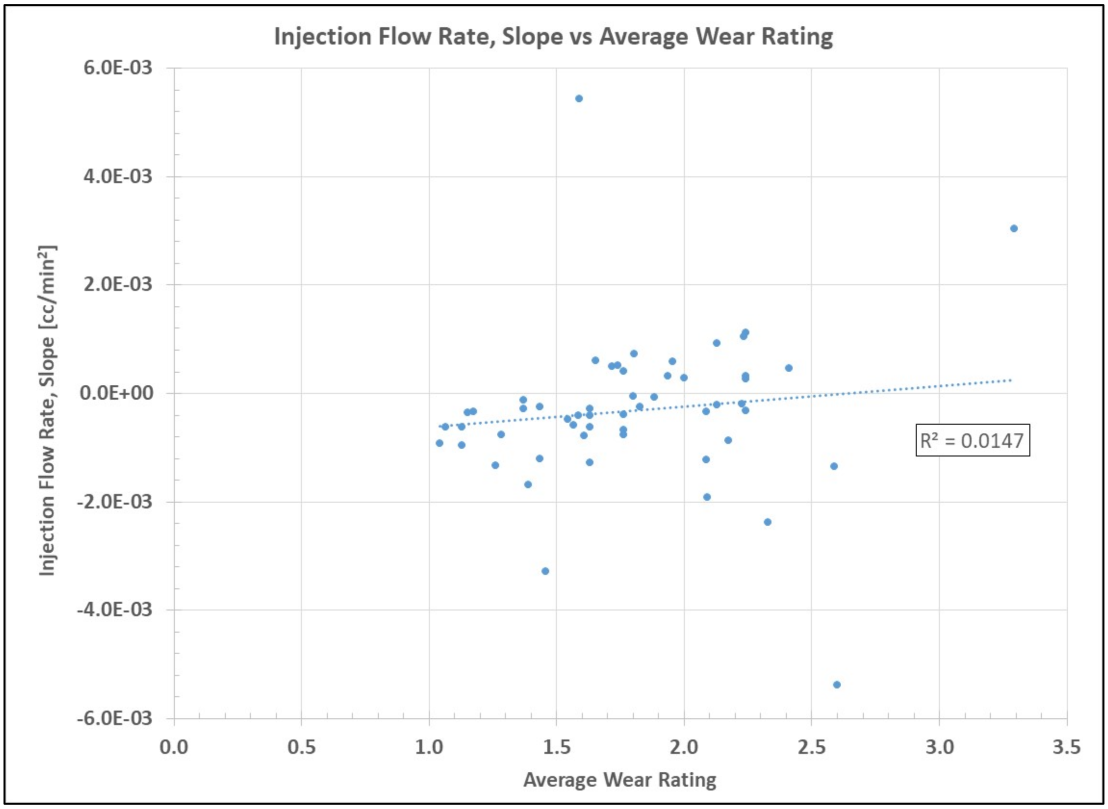

Figure 23. Injection Flow Rate, Slope vs Average Wear Rating

The average slope of the injected fuel rate is plotted against the respective BOCLE wear scar results in Figure 24. Again, no correlation is evident between the rate of change of the flow rate and the BOCLE results.

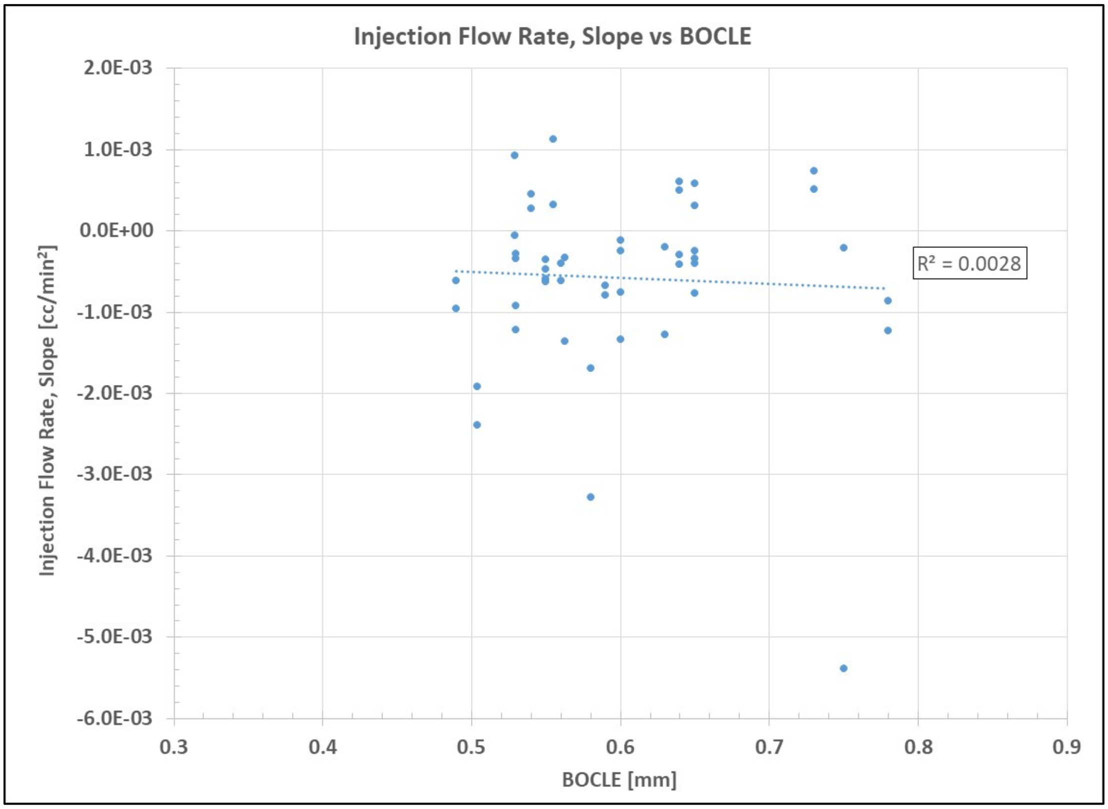

Figure 24. Injection Flow Rate, Slope vs BOCLE

4.5 FAILED PUMPS

This report covers 32 tests that used Stanadyne rotary fuel pumps, all of which ran two pumps simultaneously, for a total of 64 pumps evaluated. Of the 64, eleven pumps did not complete the target test hours.

4.5.1 IR367, Neat S-5

During the testing of neat synthetic S-5 fuel at 40.0 °C outlined in IR367, neither pump completed the 500 hour test as planned. At 95.6 hours of testing, the test stand was shut down due to suspected extreme wear. Upon inspection, Pump 1 was found to have metal debris in the top chamber and shut-off solenoid enclosure. Pump 1 was removed from the test stand and testing of Pump 2 continued.

At 151 hours, the test stand shut down when it reached a high fuel outlet temperature safety. Pump 2 was then removed and inspected; no debris was found to be present.

The raw operational data for IR367 was not available, but the report presents a summary of operating parameters as well as data plots. Both pumps exhibited increases in fuel flow rate at the beginning of testing. At ~35 hours, Pump 1 saw a large decrease in fuel flow, from 100 cc/min to 43 cc/min, with a corresponding increase in transfer pump pressure. Fuel flow continued to increase on Pump 2, while fuel return temperature declined slightly over the duration of the testing. Figure 25 and Figure 26 show the fuel flow and fuel temperatures for Pumps 1 and 2. The transfer pump pressure over the life of the test is shown in Figure 27.

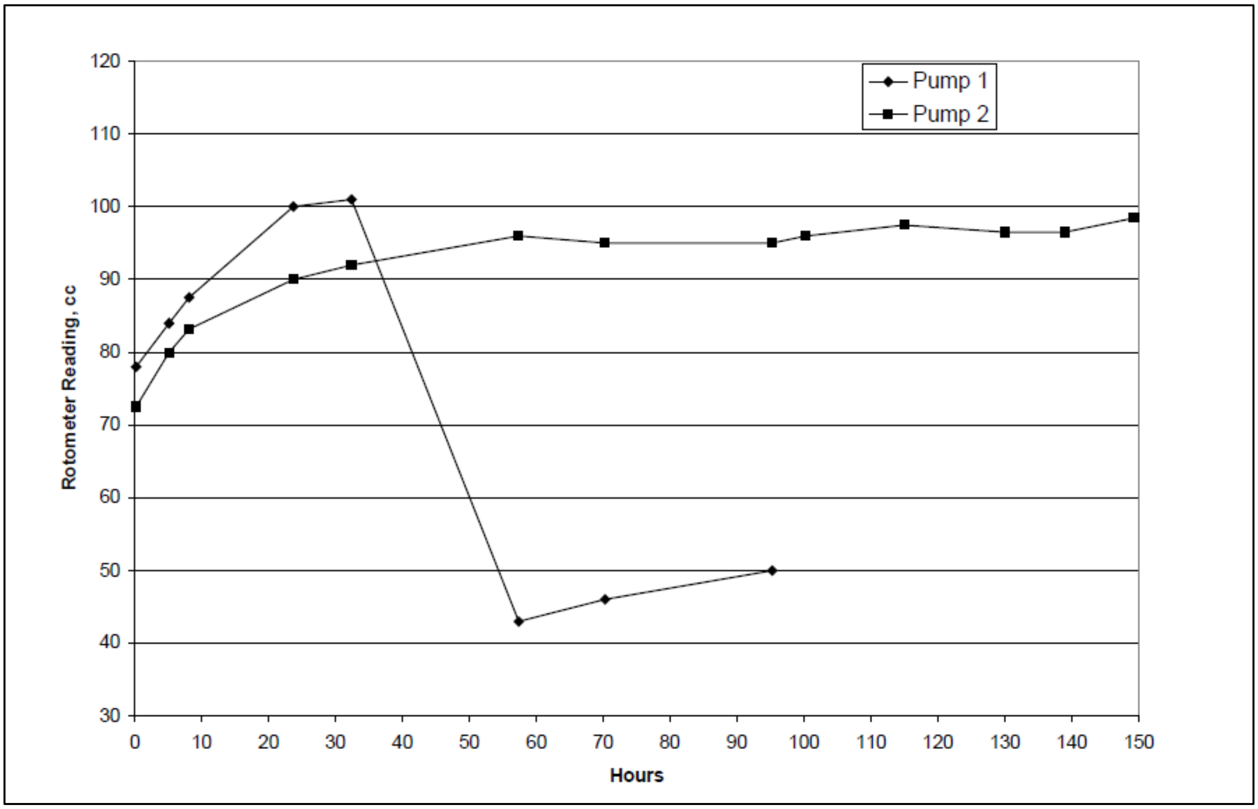

Figure 25. IR367, Neat S-5, Fuel Flow

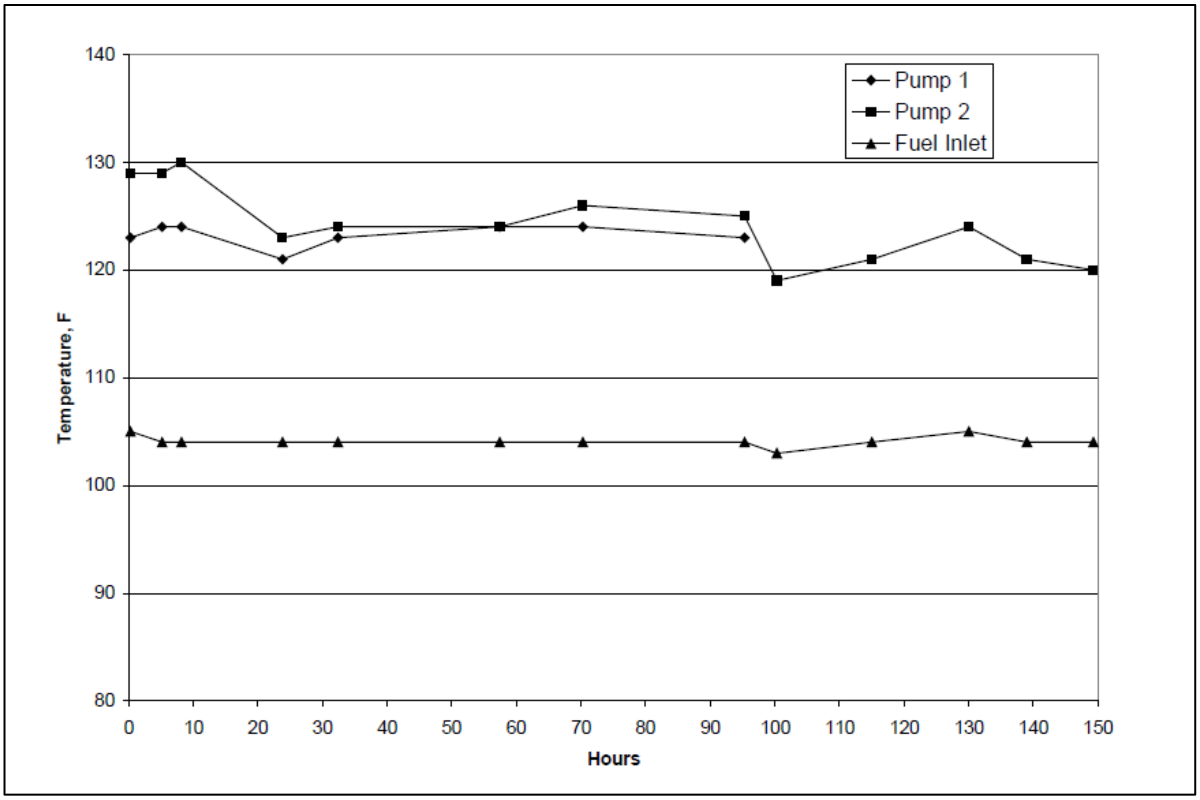

Figure 26. IR367, Neat S-5, Fuel Temperatures

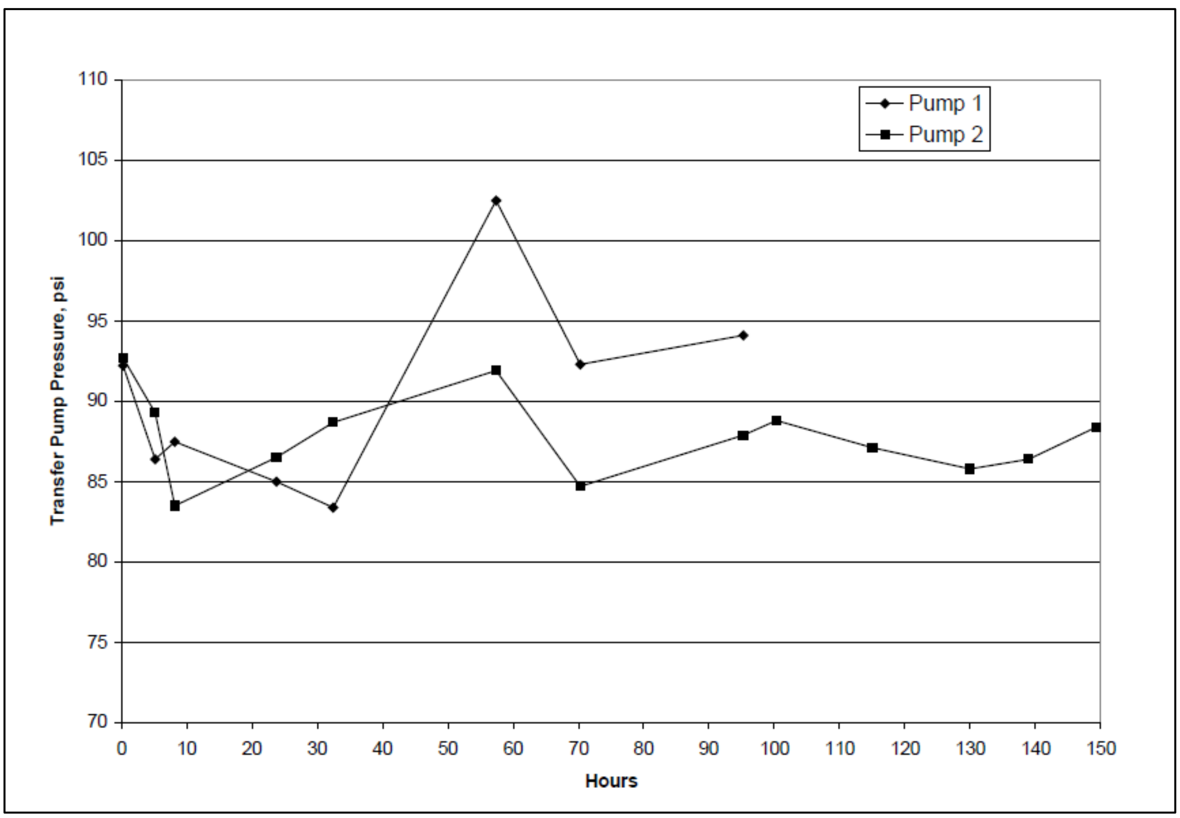

Figure 27. IR367, Neat S-5, Transfer Pump Pressure

When evaluated for post-test performance, Pump 1 failed nine out the 18 specification points, while Pump 2 failed three.

4.5.2 IR437, Neat Jet A-1

One test using neat Jet A-1 fuel at 40.0 °C was conducted for IR437, of which neither of the two pumps completed the 1,000 hours test schedule. At 124.5 test hours, Pump 2 seized, and both pumps were removed from the test stand for post-test analysis. The inspection of the pumps revealed wear debris in both pumps. Pump 1 was evaluated for post-test performance, failing 6 of the 18 calibration parameters. Pump 2 was not evaluated due to pump head and rotor seizure. Both pumps exhibited increased fuel flow early in the test.

Both pumps exhibited increased fuel flow at the onset of the test. Fuel flow data for both pumps is plotted in Figure 28. At 117 hours, Pump 2 experienced a marked increase of fuel flow, followed by a rapid decline at 122 hours, shortly before seizing. Marking each of these changes in fuel flow was a step change increase in fuel return temperature. A plot of fuel flow and fuel temperatures for Pump 2 is shown in Figure 29.

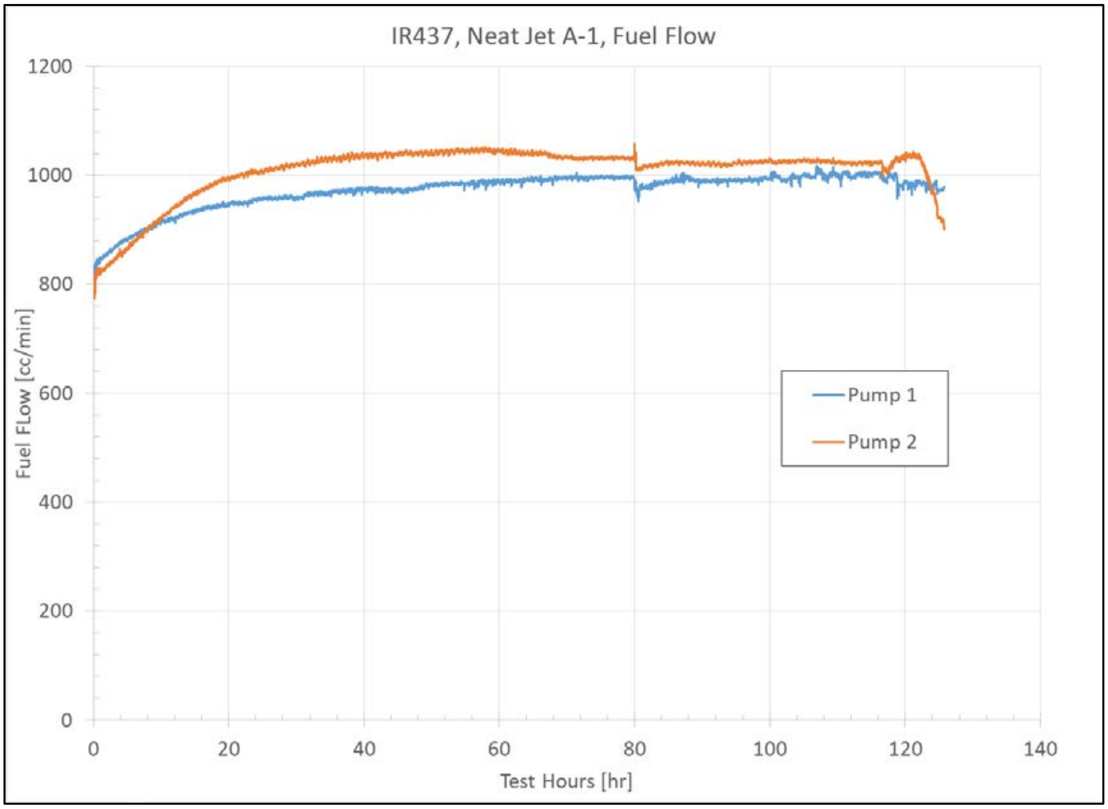

Figure 28. IR437, Neat Jet A-1, Fuel Flow

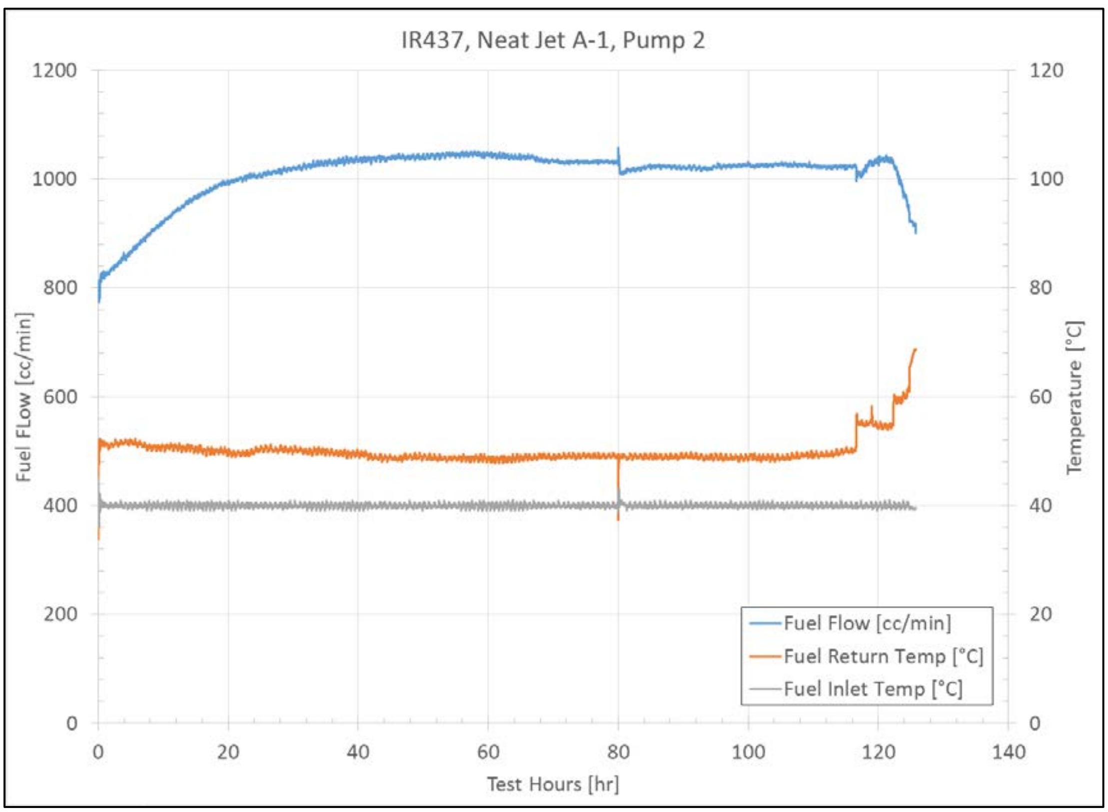

Figure 29. IR437, Neat Jet A-1, Pump 2

4.5.3 IR437, Jet A-1 with 50 mg/L INNOSPEC OLI-9070X

During testing for IR437, using Jet A-1 additized with 50 mg/L INNOSPEC OLI-9070X at 77 °C, Pump 1 experienced a catastrophic failure at 750 hours of testing. The failure occurred on re-start after a scheduled shut down for a fuel changeover. Upon re-start, the housing pressure dropped significantly and subsequently the pump seized. Investigation revealed that the housing needle bearings had worn excessively, creating friction and heat that disintegrated the red fluorosilicone and one of two black viton driveshaft seals.

The raw operational data showed a significant drop in transfer pump pressure at the beginning of the test. Over the life of the test, Pump 1 showed a slight, steady decrease in flow rate and a steady increase in housing pressure. Pump 2 completed the 1,000 hour test operational.

4.5.4 IR437, Neat FT-SPK

Test 15 of IR437 used neat Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) fuel at an inlet temperature of 40.0 °C. Neither of the two pumps completed the 1,000 hour test. Pump 1 sized at 0.59 hours of operation, while Pump 2 seized at 48.2 hours.

Pump 1 had an 8% increase in fuel delivery from the initiation of testing to pump failure. The seizure caused the driveshaft to shear, and the pump was removed from the test rig and the test continued. At 48.2 hours, injected fuel flow on Pump 2 had increased by 28% and the test was shut down for inspection. No debris was visible. Upon re-starting the test, the rotor seized. Subsequent inspection showed severe wear on the rollers. Post-test performance was not completed due to both pumps being inoperable.

The raw data shows no parameters out of the ordinary prior to either pump failure beyond the increase in injected fuel flow. Operational data for Pumps 1 and 2 are shown in Figure 30 and Figure 31, respectively.

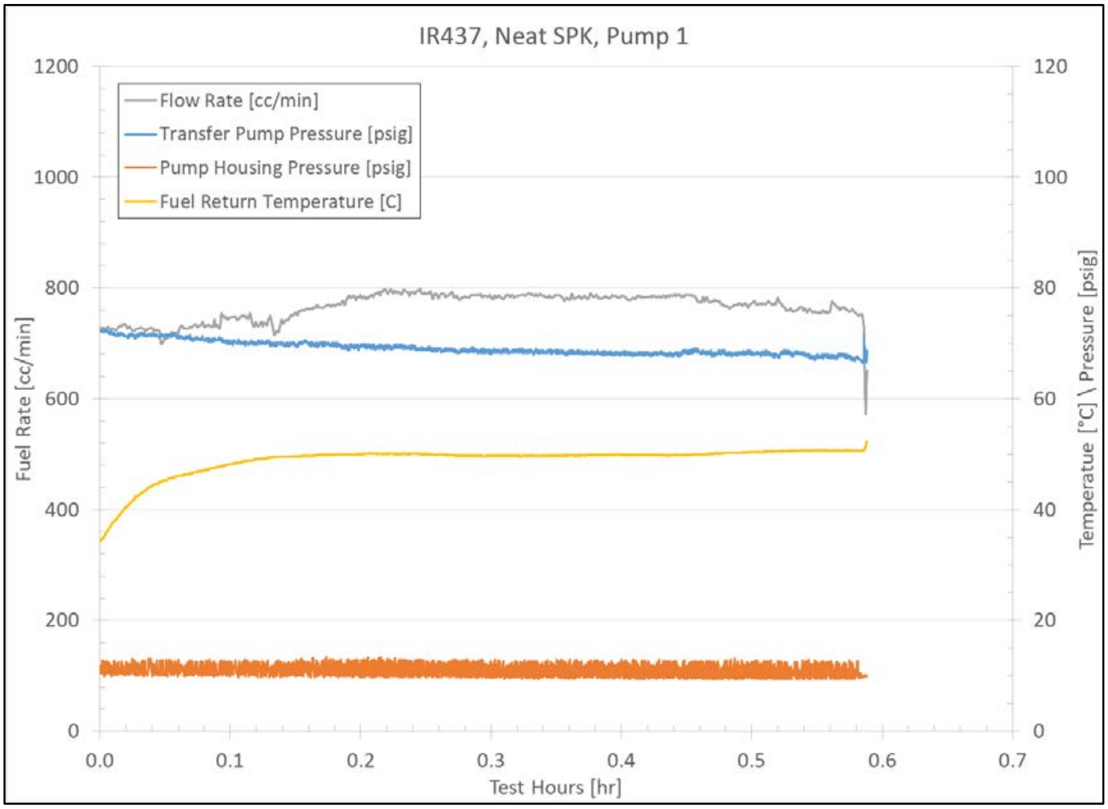

Figure 30. IR437, Neat FT-SPK, Pump 1

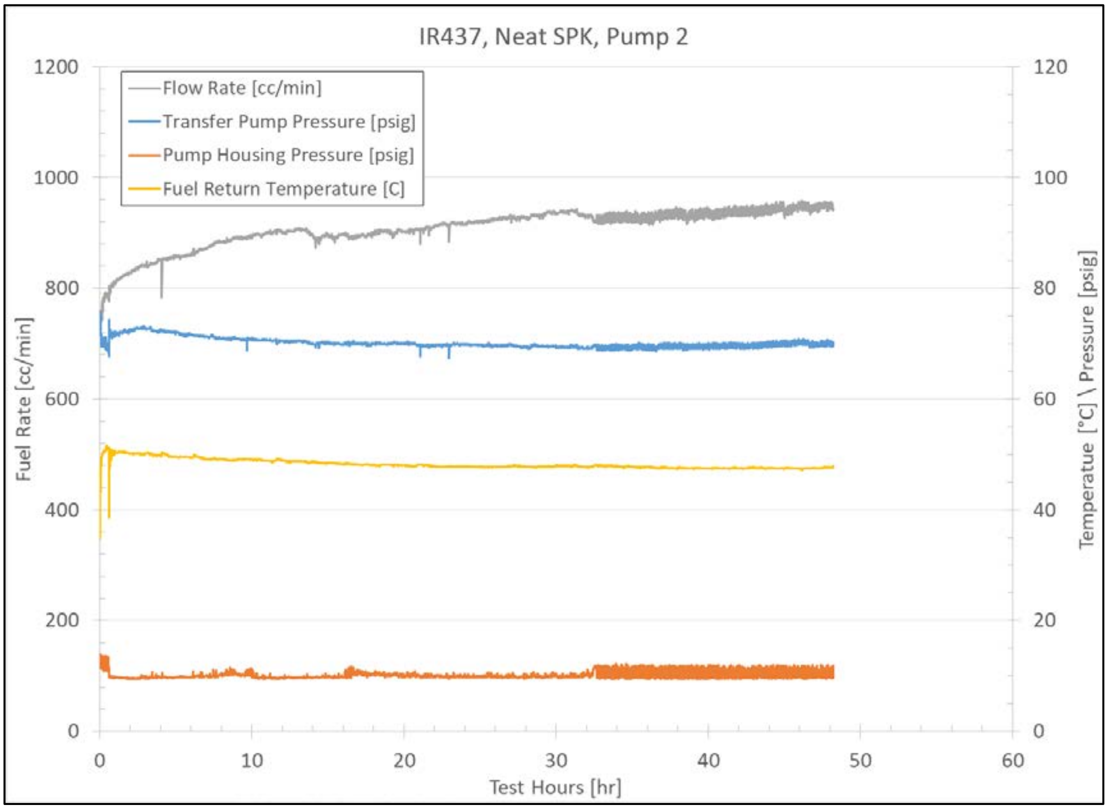

Figure 31. IR437, Neat FT-SPK, Pump 2

4.5.5 IR437, 50/50 FT-SPK/Jet A-1 with 9 mg/L DCI-4A

Test 21 of IR437 was conducted using a 50/50 blend of FT-SPK and Jet A-1 fuel additized with DCI-4A CI/LI at a concentration of 9 mg/L and run at 77.0 °C. In this case, neither pump completed the 1,000 hour scheduled test.

At 372 hours into the test, the fuel flow of Pump 2 had dropped 25% and the test stand was shut down. An inspection conducted on Pump 2 showed visible wear debris in the solenoid assembly. The pump was removed from the test stand for post-test analysis which showed 4 occurrences of calibration parameters out of specification.

At 418 test hours, the test stand was again shut down when Pump 1 became excessively noisy. An inspection revealed heavy wear debris on the linkages and the pump was removed from the test stand. During post-test performance checks, Pump 1 had 11 parameters found to be out of specification.

The operational data of Pump 2, pictured in Figure 32, shows erratic transfer pump pressure at the same time as a drop in fuel flow, occurring at approximately 332 test hours. Fuel flow and transfer pump pressure remain steady until 363 hours, at which point there is a marked increase in fuel flow. Finally, at 367 test hours, the fuel flow begins to decline until the manual shut down at 418 hours.

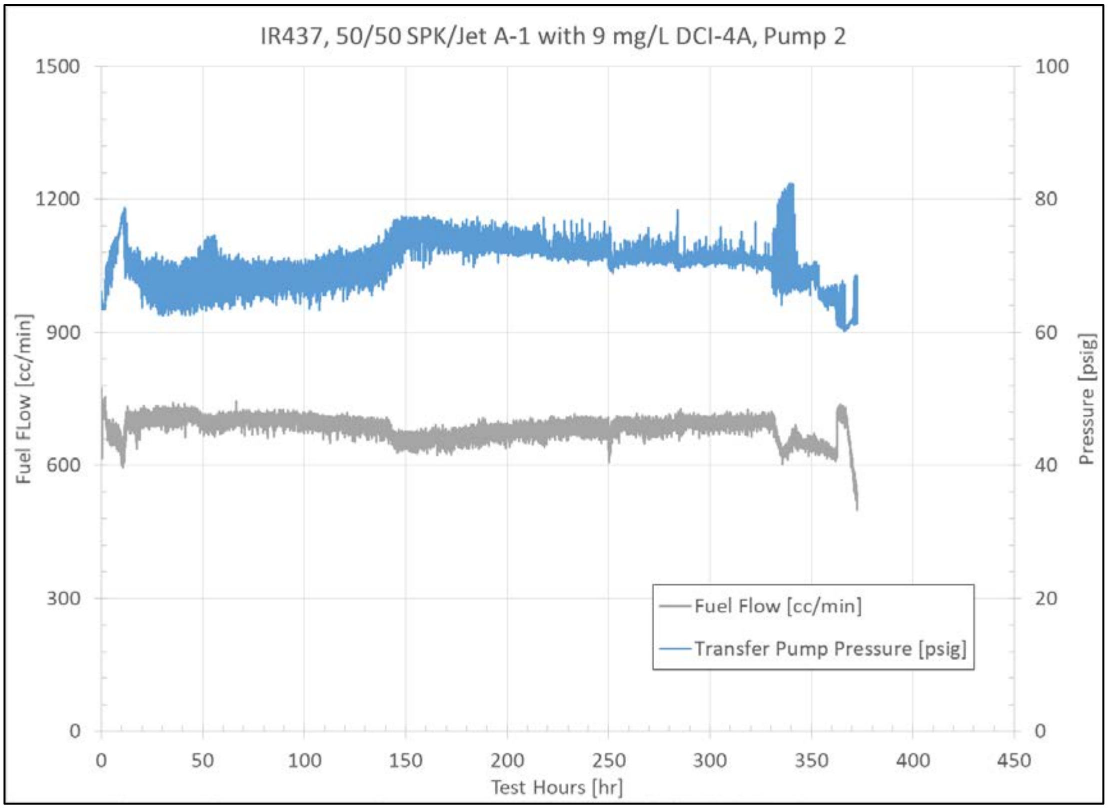

Figure 32. IR437, 50/50 FT-SPK/Jet A-1 with 9 mg/L DCI-4A, Pump 2

At approximately 160 test hours, Pump 1 saw a marked increase in transfer pump pressure which was coupled with a decrease in fueling. Both parameters recovered within ~15 hours and remained steady until around 380 test hours when the same behavior occurred. While the transfer pump pressure recovered, the injected fuel rate continued to decline until the manual shut down. Figure 33 shows both transfer pump pressure and fuel flow over the life of the test for Pump 1.

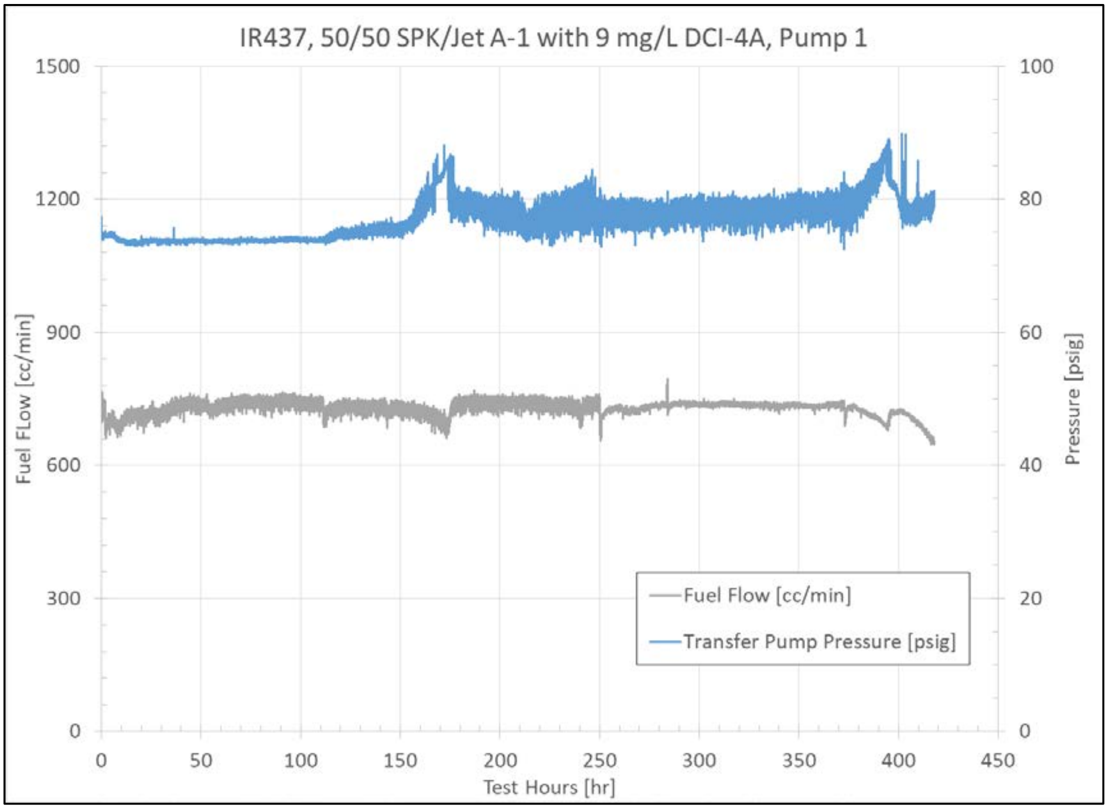

Figure 33. IR437, 50/50 FT-SPK/Jet A-1 with 9 mg/L DCI-4A, Pump 1

4.5.6 IR468, 25/75 ATJ/JP-8 with 9 ppm DCI-4A

IR468 included a test run with a 25/75 blend of ATJ/JP-8 additized with 9 ppm pf DCI-4A, with a target inlet temperature of 77.0 °C. Of the two pumps run at this condition, neither pump completed the desired test duration of 1,000 hours. Pump 1 experienced a failure at 251 hours; the head and rotor seized and fractured the driveshaft. Pump 2 was removed from the stand at 389 hours when an inspection revealed wear debris in the top housing.

Figure 34 shows fuel delivery, fuel return temperature, and housing and transfer pump pressures over the duration of the test. Fuel delivery was slightly erratic at times, which can be caused by excessive wear in in the metering valve, governor linkage, or drive tang. Both the housing pressure and transfer pump pressure had several intermittent increases during the testing, but were stable for the last ~75 hours of the test. Fuel return temperature saw a temporary spike at 150 test hours, but again was stable for the remainder of the testing.

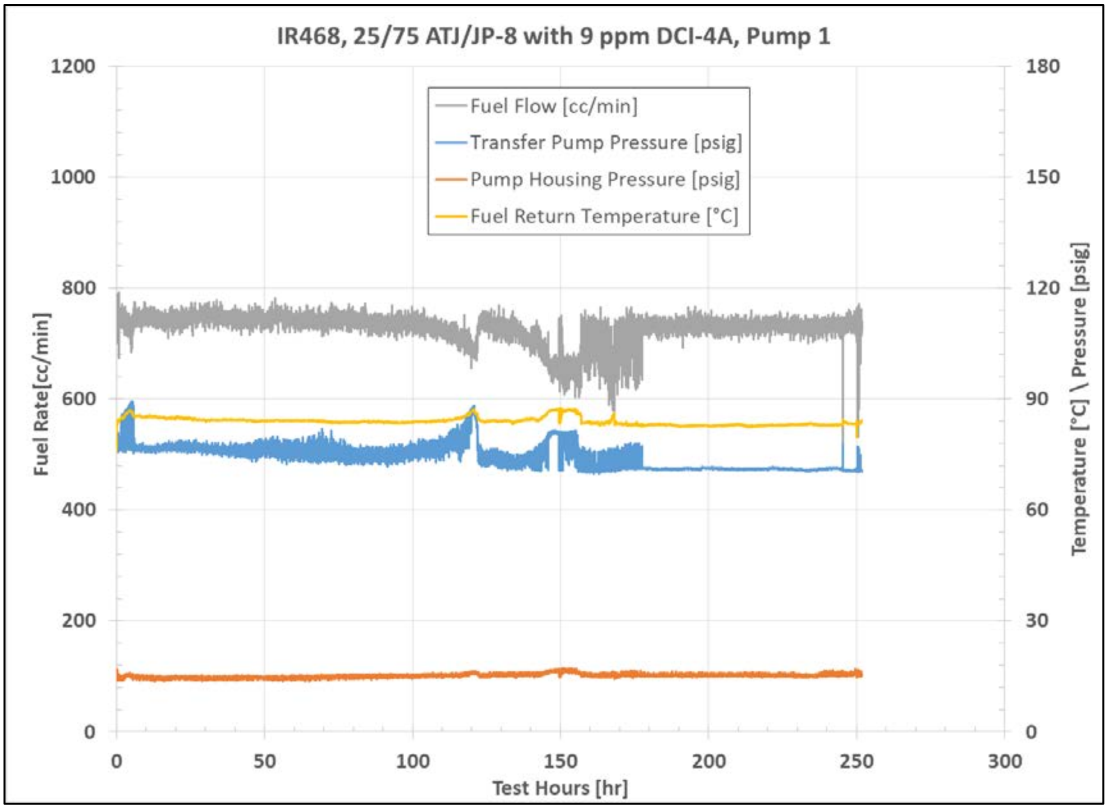

Figure 34. IR468, 25/75 ATJ/JP-8 with 9 ppm DCI-4A, Pump 1

5.0 CONCLUSIONS

5.1 FUEL INJECTION PUMP TEST RESULTS SUMMARY

Based on the cumulative knowledge from the HPCR fuel pump testing performed using several systems, fuel blends, and with varying lubricity additive treat rates, the following conclusions can be made:

- Overall, the indications are that the XPI system is robust with regards to fuel lubricity and viscosity even in relatively extreme combinations such as the unadditized Jet A-1 and SPK test fuels. [5]
- The John Deere 4.5L system was catastrophically sensitive to fuel lubricity and inlet temperature. The minimum acceptable viscosity for the completed tests was found to be 0.68 mm^2/s. 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. [6]

- The Ford 6.7L system tests showed no negative impacts from the use of current military fuels or future blended fuels with the minimum level of lubricity improver (9 ppm). The system was found to be robust even in relatively extreme combinations such as unadditized Jet A-1 and SPK test fuels. [7]
- All testing done on HPCR systems utilized a 400 hour NATO cycle. The typical useful life of a vehicle is 15-20 years which would be represented by a three to four NATO cycle repetition.

Based on the cumulative knowledge from the rotary fuel pump testing performed using several types of fuels, fuel blends, and with varying lubricity additive treat rates, the following conclusions can be made:

- The use of neat Jet A-1 causes unacceptably severe wear in fuel-injection systems and should not be used in rotary, fuel lubricated, fuel injection pumps. The pump wear rate may be significantly reduced through the use of lubricity additives at concentrations below 100 mg/L [1].
- Running 1,000 hour durability pump tests produces some detrimental effects on pump performance when run on diesel fuel. These commonly include moderate wear to the governor which can cause a reduced high idle speed, and low idle fuel injection quantity, which would cause idle instability and/or low idle speed. Clay treated diesel fuel causes greater detrimental impacts on the pump performance than non-clay treated diesel fuel [2].
- Neat FT-SPK should not be used in rotary, fuel-lubricated fuel injection pumps. Full scale pump tests run on neat FT-SPK resulted in premature, catastrophic failure [2].
- The lubricity bench top tests SLBOCLE and BOCLE show a general correlation with the subjective wear ratings reported post-test. Neither the SLBOCLE nor the BOCLE show a strong relationship with the analog test data. Both bench top tests show a correlation with wear volume as measured by profilometry.
- The data from the lubricity bench top test HFRR is more scattered and should not be used to predict wear from aviation or alternative fuels in a fuel-injection system. At the minimum effective concentration of a QPL-25017 CI/LI additive, ATJ/JP-8 blends should NOT be utilized in regions where rotary fuel injection pump equipped engines are exposed to elevated fuel inlet temperatures. When tested on a full scale pump test, the minimum treatment rate of DCI-4A resulted in the premature failure of the pumps. It is recommended that blends of ATJ/JP-8 fuels include the addition of the maximum effective concentration

of CI/LI for use in diesel rotary fuel injection equipment at nominal ambient temperatures [3].

- A 25/75 blend of ATJ/JP-8 with 24 ppm DCI-4A operated at 77.0 °C fuel inlet temperature will allow 1,000 hours of rotary pump operation. However, the performance degradation of the fuel injection pumps at 1,000 hours would impact engine operation, and component inspections suggested excessive wear [3].
- It is recommended that blends of ATJ/F-24 fuels include the addition of the maximum effective concentration of CI/LI for use in diesel rotary fuel injection equipment at nominal ambient temperatures [4].
- Based on the initial limited set of test results, at elevated fuel inlet temperatures, even the use of maximum concentration DCI-4A in a 25% ATJ/F-24 fuel blend appears to result in accelerated wear in fuel-lubricated rotary fuel injection pumps [4].

5.2 PUMP EVALUATION FOR PERFORMANCE AND WEAR

During the history of full scale pump testing on rotary, fuel lubricated, fuel injection pumps at Southwest Research Institute, there have been many different measures of pump performance and wear severity. Over the last 25 years, the techniques used to analyze wear have included metrology, gravimetric analysis, profilometry, and subjective rating. These techniques have not been consistently used in each round of testing. Each of the fuel pump studies conducted have had a slightly different set of methods to evaluate performance and wear, with some overlap between programs.

Several of these methods showed trends within a set of testing, but when evaluated over a larger matrix of pump tests, did not hold the same relationship. In particular, roller to roller measurement showed no correlation with the pump rating and only a slight correlation with the bench top lubricity test results. The bench top lubricity tests BOCLE and SLBOCLE show general trends when compared with the subjective pump rating, profilometry seems to show the strongest correlation with the bench top lubricity tests, although the data set is much smaller than other methods used. The use of profilometry to determine post-test wear scars on select pump components would be of interest especially in the case of marginally performing pumps.

The raw, analog data from the pump tests did not show any consistent correlation between fuel return temperature, transfer pump pressure, or fuel injection flow rate. The pump housing pressure rate of change has a moderate correlation when compared with the subjective pump rating, as shown in Figure 18.

5.3 PROPOSED FUTURE PUMP TESTING

The proposed matrix for future pump testing is shown in Table 19. Based on all prior work, the proposed future pump testing fits inside the box of previous test conditions and contains reasonable assumptions. From the IR437 work with 2 additives from different manufacturers, it was observed that due to similarities in molecular composition (dimer- and trimer- organic acids), there was no significant difference in performance. It is recommended that future pump testing include lubricity additives that are synthetically manufactured, and not naturally derived as the naturally derived products originate from a single organic source: yellow southern pine. Some current synthetic lubricity additives are classified as amines, polyamines, esters from alcohols and carboxylic acids, and glycol esters. A market survey of modern synthetic lubricity additives may be of value as a screening tool for future pump testing.

Table 19. Proposed Future Pump Testing Matrix

Pump	Fuel	Additive Treat Rate	Temperature
DENSO	Diesel	none	40.0 °C and 70.0 °C at each treat rate
	Jet A-1	none	
		9 ppm	
		15 ppm	
		22.5 ppm	
Stanadyne	Diesel	none	
	Jet A-1	none	
		9 ppm	
		15 ppm	
		22.5 ppm	

Additionally, it is recommended to pursue comparison testing of different cycles with the goal of minimizing fretting wear seen on some pump components due to throttle input being held at one position for the duration of the test.

6.0 REFERENCES

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Appendix A

Summary of Pertinent Data for Each Test

IR	Pump	Pump SN	Fuel	Inlet Temperature	Viscosity	Additive	Test Length	Test Hours Completed	Cal Points Failed	Average Wear Rating	Roller to Roller Change	Transfer pump weight loss/gain	SLBOCLE	BOCLE	HFRR	Transfer Pump Pressure, Avg	Pump Housing Pressure, Avg	Inj Flow Rate, Avg	Fuel Return Temperature, Avg
-	-	-	-	[°C]	[mm/s]	-	[hrs]	[hrs]	-	-	[mm]	[g]	[g]	[mm]	[mm]	[psi]	[psi]	[cc/min]	[°C]
323	DB2829-4524	8239197	Jet A-1	77.0	0.72	none	200	200	1	3.30			1300		0.645	98.2	5.5	631.9	
323	DB2829-4523	8164640	Jet A-1	77.0	0.72	none	200	200	1	2.24			1300		0.645	103.2	5.1	636.6	
323	DB2829-4524	8239198	Jet A-1	77.0	0.72	80 mg/L E-2	200	200	1	2.00			2450		0.23	107.4	5.5	646.0	
323	DB2829-4523	8164642	Jet A-1	77.0	0.72	80 mg/L E-2	200	200	0	1.88			2450		0.23	107.8	5.1	641.9	
323	DB2829-4524	8239209	Jet A-1	77.0	0.72	200 mg/L E-2	200	200	1	1.76			2550		0.215	116.7	6.7	664.8	
323	DB2829-4523	8066006	Jet A-1	77.0	0.72	200 mg/L E-2	200	200	1	1.59			2550		0.215	102.3	6.5	596.8	
367	DB2829-4879	10523925	S-5	40.0	1.55	none	500	95.6	9		0.038		967	0.95	0.609				
367	DB2829-4879	10523926	S-5	40.0	1.55	none	500	151	3		0.027		967	0.95	0.609				
367	DB2829-4879	10523924	S-5	40.0	1.55	12 mg/L NALCO 5403	500	500	4		0.003		1450	0.76	0.662				
367	DB2829-4879	10524467	S-5	40.0	1.55	12 mg/L NALCO 5403	500	500	3		0.002		1450	0.76	0.662				
367	DB2829-4879	10524469	S-5	40.0	1.55	22 mg/L NALCO 5403	500	500	1		0.002		1333	0.68	0.668				
367	DB2829-4879	10524470	S-5	40.0	1.55	22 mg/L NALCO 5403	500	500	1		0.001		1333	0.68	0.668				
437	DB2831-5087	15293084	ULSD	40.0	3.00	none	401,000	1,000	5	1.043	-0.004	8.4	5500	0.53	0.257	79.4	11.2	829.0	50.5
437	DB2831-5087	15293089	ULSD	40.0	3.00	none	1,000	1,000	3	1.174	-0.001	7.6	5500	0.53	0.257	79.8	10.0	854.2	51.2
437	DB2831-5087	15382732	ULSD	57.0	n/a	none	1,000	1,000	4	1.13	-0.0005	1	5400	0.55	0.31	80.4	11.0	827.6	65.4
437	DB2831-5087	15382733	ULSD	57.0	n/a	none	1,000	1,000	3	1.152	0.0003	0.4	5400	0.55	0.31	74.9	11.3	850.1	64.8
437	DB2831-5087	15396933	ULSD	77.0	1.20	none	1,000	1,000	2	1.13	-0.002	6.2	6000	0.49	0.294	75.4	10.9	783.1	81.0

IR	Pump	Pump SN	Fuel	Inlet Temperature	Viscosity	Additive	Test Length	Test Hours Completed	Cal Points Failed	Average Wear Rating	Roller to Roller Change	Transfer pump weight loss/gain	SLBOCLE	BOCLE	HFRR	Transfer Pump Pressure, Avg	Pump Housing Pressure, Avg	Inj Flow Rate, Avg	Fuel Return Temperature, Avg
-	-	-	-	[°C]	[mm/s]	-	[hrs]	[hrs]	-	-	[mm]	[g]	[g]	[mm]	[mm]	[psi]	[psi]	[cc/min]	[°C]
437	DB2831-5087	15396934	ULSD	77.0	1.20	none	1,000	1,000	5	1.065	-0.003	1.8	6000	0.49	0.294	74.6	10.4	796.7	81.2
437	DB2831-5087	15396475	ULSD, Clay Treated	40.0	3.00	none	1,000	1,000	2	1.543	-0.002	-3.2	4400	0.55	0.64	78.5	12.4	838.3	52.3
437	DB2831-5087	15396930	ULSD, Clay Treated	40.0	3.00	none	1,000	1,000	4	1.565	0.0015	-0.1	4400	0.55	0.64	79.3	11.8	834.7	51.7
437	DB2831-5087	15396931	Jet A-1	40.0	1.09	none	1,000	124.5	6	1.935	0.027	-1	1800	0.78	0.603	71.0	10.6	926.2	50.4
437	DB2831-5087	15396932	Jet A-1	40.0	1.09	none	1,000	124.5	n/a	2.5	n/a	-10.4	1800	0.78	0.603	67.5	10.5	946.0	50.2
437	DB2831-5087	15396935	Jet A-1	40.0	1.09	DCI-4A @ 22.5 g/m³	1,000	1,000	3	1.37	0.019	-4.2	2500	0.64	0.653	70.3	10.3	804.4	48.3
437	DB2831-5087	15396948	Jet A-1	40.0	1.09	DCI-4A @ 22.5 g/m³	1,000	1,000	4	1.587	-0.001	4.3	2500	0.64	0.653	71.9	10.5	806.2	48.0
437	DB2831-5087	15396951	Jet A-1	57.0	0.89	DCI-4A @ 22.5 g/m³	1,000	1,000	2	1.435	-0.0007	-3.3	1950	0.6	0.68	65.7	11.3	782.3	63.7
437	DB2831-5087	15396952	Jet A-1	57.0	0.89	DCI-4A @ 22.5 g/m³	1,000	1,000	3	1.37	-0.001	-5	1950	0.6	0.68	69.6	13.4	728.6	63.5
437	DB2831-5087	15396955	Jet A-1	77.0	0.73	DCI-4A @ 22. g/m³	1,000	1,000	3	1.283	-0.0011	1.7	2650	0.6	0.72	67.5	13.2	707.2	82.3
437	DB2831-5087	15396956	Jet A-1	77.0	0.73	DCI-4A @ 22. g/m³	1,000	1,000	2	1.261	-0.0013	3.6	2650	0.6	0.72	68.4	13.0	735.0	81.9
437	DB2831-5087	15396949	Jet A-1	40.0	1.09	Nalco 5403 @ 25 g/m³	1,000	1,000	4	1.63	0.007	-4.2	2200	0.53	0.664	71.9	12.3	788.0	48.1
437	DB2831-5087	15396950	Jet A-1	40.0	1.09	Nalco 5403 @ 25 g/m³	1,000	1,000	4	1.435	-0.039	-1.9	2200	0.53	0.664	73.8	13.2	793.5	48.0
437	DB2831-5087	15396953	Jet A-1	57.0	0.89	Nalco 5403 @ 25 g/m³	1,000	1,000	n/a	1.39	-0.0002	-12.90	2650	0.58	0.701	73.5	10.8	655.5	64.5
437	DB2831-5087	15396954	Jet A-1	57.0	0.89	Nalco 5403 @ 25 g/m³	1,000	1,000	3	1.46	-0.0012	4.50	2650	0.58	0.701	74.4	12.4	586.2	64.0
437	DB2831-5087	15438592	Jet A-1	77.0	0.73	Nalco 5403 @ 25 g/m³	1,000	1,000	7	1.61	-0.0002	-18.70	2600	0.59	0.71	79.6	11.7	698.2	81.1
437	DB2831-5087	15438593	Jet A-1	77.0	0.73	Nalco 5403 @ 25 g/m³	1,000	1,000	6	1.76	-0.0019	-10.60	2600	0.59	0.71	78.1	14.6	719.3	81.4
437	DB2831-5087	15438594	Jet A-1	40.0	1.09	INNOSPEC OLI-9070X @50 mg/L	1,000	1,000	1	1.72	0.0013	1.10	2450	0.64	0.71	77.2	10.7	806.9	48.9

IR	Pump	Pump SN	Fuel	Inlet Temperature	Viscosity	Additive	Test Length	Test Hours Completed	Cal Points Failed	Average Wear Rating	Roller to Roller Change	Transfer pump weight loss/gain	SLBOCLE	BOCLE	HFRR	Transfer Pump Pressure, Avg	Pump Housing Pressure, Avg	Inj Flow Rate, Avg	Fuel Return Temperature, Avg
-	-	-	-	[°C]	[mm/s]	-	[hrs]	[hrs]	-	-	[mm]	[g]	[g]	[mm]	[mm]	[psi]	[psi]	[cc/min]	[°C]
437	DB2831-5087	15438595	Jet A-1	40.0	1.09	INNOSPEC OLI-9070X @50 mg/L	1,000	1,000	3	1.65	0.0008	-1.20	2450	0.64	0.71	73.8	10.4	820.1	48.8
437	DB2831-5087	15438596	Jet A-1	57.0	0.89	INNOSPEC OLI-9070X @50 mg/L	1,000	1,000	5	2.23	0.0025	0.60	1850	0.63	0.72	73.0	12.8	739.6	62.7
437	DB2831-5087	15438597	Jet A-1	57.0	0.89	INNOSPEC OLI-9070X @50 mg/L	1,000	1,000	5	1.63	-0.0018	6.60	1850	0.63	0.72	77.4	12.2	739.4	63.0
437	DB2831-5087	5438598.	Jet A-1	77.0	0.73	INNOSPEC OLI-9070X @50 mg/L	1,000	750	n/a	2.09	-0.0004	-18.00	1600	0.65	0.73	66.1	11.0	742.0	82.8
437	DB2831-5087	15438599	Jet A-1	77.0	0.73	INNOSPEC OLI-9070X @50 mg/L	1,000	1,000	3	1.76	-0.0003	-16.70	1600	0.65	0.73	69.8	13.1	725.8	83.1
437	DB2831-5088	15438603	FT-SPK	40.0	0.95	none	1,000	0.59	n/a	1.76	n/a	-18.90	1200	1.01	0.84	69.1	11.0	765.8	48.9
437	DB2831-5089	15438885	FT-SPK	40.0	0.95	none	1,000	48.2	n/a	1.89	n/a	-15.00	1200	1.01	0.84	70.6	10.7	840.2	49.0
437	DB2831-5087	15438886	FT-SPK	40.0	0.95	DCI-4A @ 22.5 g/m³	1,000	1,000	2	1.76	-0.0003	-4.70	1850	0.65	0.8	76.1	11.3	713.6	46.6
437	DB2831-5087	15438887	FT-SPK	40.0	0.95	DCI-4A @ 22.5 g/m³	1,000	1,000	2	1.83	0.0000	-5.30	1850	0.65	0.8	71.6	11.3	778.4	48.0
437	DB2831-5087	15438888	FT-SPK	57.0	0.78	DCI-4A @ 22.5 g/m³	1,000	1,000	2	1.94	-0.0006	16.50	1850	0.65	0.8	72.3	13.3	722.0	63.8
437	DB2831-5087	15438889	FT-SPK	57.0	0.78	DCI-4A @ 22.5 g/m³	1,000	1,000	1	1.96	-0.0002	16.80	1850	0.65	0.8	71.1	10.2	727.6	63.8
437	DB2831-5087	15438891	FT-SPK	77.0	0.65	DCI-4A @ 22.5 g/m³	1,000	1,000	2	1.63	-0.0030	-11.50	1800	0.56	0.784	68.9	14.7	670.6	80.4
437	DB2831-5087	15438892	FT-SPK	77.0	0.65	DCI-4A @ 22.5 g/m³	1,000	1,000	2	1.63	-0.0010	-3.10	1800	0.56	0.784	68.3	16.2	700.6	81.0
437	DB2831-5087	15442444	50/50 FT-SPK /Jet A-1	40.0	1.03	DCI-4A @ 9 g/m³	1,000	1,000	1	1.74	0.0000	-7.90	2100	0.73	0.681	70.6	12.3	825.6	48.6
437	DB2831-5087	15442445	50/50 FT-SPK /Jet A-1	40.0	1.03	DCI-4A @ 9 g/m³	1,000	1,000	2	1.80	0.0001	0.00	2100	0.73	0.681	74.2	10.7	810.2	48.2
437	DB2831-5087	15442663	50/50 FT-SPK /Jet A-1	57.0	0.85	DCI-4A @ 9 g/m³	1,000	1,000	6	2.09	0.0000	1.10	1700	0.78	0.719	73.2	15.3	591.8	63.7
437	DB2831-5087	15442664	50/50 FT-SPK /Jet A-1	57.0	0.85	DCI-4A @ 9 g/m³	1,000	1,000	4	2.17	-0.0001	-4.30	1700	0.78	0.719	72.9	16.3	747.1	64.0

IR	Pump	Pump SN	Fuel	Inlet Temperature	Viscosity	Additive	Test Length	Test Hours Completed	Cal Points Failed	Average Wear Rating	Roller to Roller Change	Transfer pump weight loss/gain	SLBOCLE	BOCLE	HFRR	Transfer Pump Pressure, Avg	Pump Housing Pressure, Avg	Inj Flow Rate, Avg	Fuel Return Temperature, Avg
-	-	-	-	[°C]	[mm/s]	-	[hrs]	[hrs]	-	-	[mm]	[g]	[g]	[mm]	[mm]	[psi]	[psi]	[cc/min]	[°C]
437	DB2831-5087	5848225.	50/50 FT-SPK /Jet A-1	77.0	0.69	DCI-4A @ 9 g/m³	1,000	418	4	2.13	0.0029	-2.30	1700	0.75	0.719	77.2	15.0	727.4	83.0
437	DB2831-5087	15848373	50/50 FT-SPK /Jet A-1	77.0	0.69	DCI-4A @ 9 g/m³	1,000	372	11	2.60	-0.01	-1.10	1700	0.75	0.719	68.6	14.7	666.8	85.3
468	DB2831-5079	16756534	25/75 ATJ/JP-8	77.0	0.85	9 ppm CI/LI	1,000	251	n/a	2.59	n/a			0.563	0.67	74.2	15.2	733.0	83.8
468	DB2831-5079	16756535	25/75 ATJ/JP-8	77.0	0.85	9 ppm CI/LI	1,000	389	n/a	2.24	0.09			0.563	0.67	76.8	14.8	711.2	84.3
468	DB2831-5079	16756536	25/75 ATJ/JP-8	77.0	0.85	24 ppm CI/LI	1,000	1,000	n/a	2.09	-0.03			0.504	0.729	75.0	15.3	719.5	81.9
468	DB2831-5079	16756538	25/75 ATJ/JP-8	77.0	0.85	24 ppm CI/LI	1,000	1,000	4	2.33	-0.14			0.504	0.729	82.1	15.5	723.8	83.4
482	DB2831-6282	17102937	20/80 DSH8/ JP-8	77.0	0.91	9 ppm CI/LI	500	500	4	1.80	0.04			0.529	0.67	66.5	13.6	776.8	81.6
482	DB2831-6282	17102938	20/80 DSH8/ JP-8	77.0	0.91	9 ppm CI/LI	500	500	4	2.13	0.08			0.529	0.67	73.3	12.9	759.6	82.6
488	DB2831-6282	17200043	30 ATJ / 70 F-24	77.0	0.86	24 ppm DCI-4A CI/LI	1,000	1,000	3	2.24	-0.04			0.54	0.723	71.0	13.4	779.3	82.8
488	DB2831-6282	17200045	30 ATJ / 70 F-24	77.0	0.86	24 ppm DCI-4A CI/LI	1,000	1,000	2	2.41	0.00			0.54	0.723	83.6	13.2	795.4	84.1
488	DB2831-6282	17200072	30 ATJ / 70 F-24	40.0	1.32	24 ppm DCI-4A CI/LI	1,000	1,000	3	2.24	0.0254			0.555	0.718	79.7	11.1	825.3	49.8
488	DB2831-6282	17200858	30 ATJ / 70 F-24	40.0	1.32	24 ppm DCI-4A CI/LI	1,000	1,000	3	2.24	-0.0559			0.555	0.718	81.2	12.2	839.8	49.2