ADA

USING 25% / 75% ATJ/JP-8 BLEND ROTARY FUEL INJECTION PUMP WEAR TESTING AT ELEVATED TEMPERATURE

INTERIM REPORT
TFLRF No. 468

By
Douglas M. Yost
Edwin A. Frame

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

For
Patsy A. Muzzell
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD24 Task 2.5)

September 2015

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Contracted Author

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14. ABSTRACT
A 25%/75% blend of ATJ/JP-8 fuels at two CI/LI additive concentrations were operated in rotary, mechanical, fuel-lubricated , fuel injection pumps for a 1000-hour target at 77 °C fuel inlet temperature. The test with the 9-ppm CI/LI treatment failed early with a head and rotor seizure on one pump and wear and performance degradation on the other. The test with the 24-ppm CI/LI treatment lasted the 1000-hour duration, but with severe wear and degraded fuel injection pump performance was seen on both pumps.

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JP-8, ATJ, Alcohol to Jet, Alternative Fuels, General Engine Products 6.5LT, Rotary Fuel Injection Pump, Wear, Durability

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EXECUTIVE SUMMARY

Endurance tests were performed using a motorized pump stand to define the effects of fuel and fuel additives on full-scale fuel injection system equipment durability. Two distinct tests were performed utilizing a 1000-hour fuel injection pump operating procedure. The specific tests performed included:

1. A blend of 25/75 ATJ/JP-8 with 9-ppm CI/LI with a fuel inlet temperature of 77 °C.
2. A blend of 25/75 ATJ/JP-8 with 24-ppm CI/LI with a fuel inlet temperature of 77 °C.

The following conclusions can be made from the cumulative knowledge of utilizing JP-8, synthetic aviation kerosene fuel blends, and 25/75 ATJ/JP-8 in diesel rotary fuel injection pumps at elevated temperature:

1. For elevated fuel inlet temperature operation, even with petroleum JP-8 at 77 °C, the maximum effective CI/LI concentration is required to provide adequate wear protection.
2. For elevated fuel inlet temperature operation, with 25/75 ATJ/JP-8 at 77 °C, the minimum effective CI/LI concentration is inadequate.
3. A 25/75 blend of ATJ/JP-8 with 24-ppm CI/LI operated at 77 °C fuel inlet temperature will allow 1000-hours of rotary pump operation. However, the performance degradation of the fuel injection pumps at 1000-hours would impact engine operation, and component inspections suggested excessive wear.

The technical feasibility of using ATJ/JP-8 fuel at elevated temperatures in rotary fuel injection equipment when blended with a CI/LI additive has been investigated and it is recommended:

1. 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.
2. 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. The use of maximum concentration CI/LI in ATJ/JP-8 fuel blends at elevated fuel inlet temperatures appear to result in accelerated wear in rotary fuel injection pumps.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period September 2013 through September 2015 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the TARDEC contracting officer's technical representative and the project technical monitor.

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

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ACRONYMS AND ABBREVIATIONS

° C	degrees Centigrade
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
cSt	Centistokes
ft	Foot
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
HEFA	Hydro-treated Esters and Fatty Acid(s)
HFRR	High Frequency Reciprocating Rig
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
hr	Hour
in	Inch
JP-8	Jet Propulsion 8
kW	Kilowatt
L	Liter
lb	Pound
m	Meter
mg	milligram
mg/L	milligrams per Liter concentration
mL	milliliter
mm	millimeter
ppm	parts per million
psi	pounds per square inch
QPL	Qualified Products List
RPM	rotation(s) per minute
SwRI®	Southwest Research Institute®
SOW	Scope of Work
SPK	Synthetic Paraffinic Kerosene
TACOM	Tank Automotive and Armaments Command
TARDEC	Tank Automotive RD&E Center
TFLRF	TARDEC Fuel and Lubricants Research Facility
WOT	Wide Open Throttle
WD	Work Directive
WSD	Wear Scar Diameter

1.0 BACKGROUND & INTRODUCTION

The United States Department of Defense Operational Energy Strategy has outlined a goal "to diversify its energy sources and protect access to energy supplies to have a more assured supply of energy for military missions"[1]. In accordance with this directive, the U.S. Army had conducted extensive research to investigate alternative fuels viability in military equipment. This has included basic chemical and physical property investigation to identify surrogate fuel sources with similar properties as traditional petroleum fuels, to full scale equipment and fleet testing to determine resulting component and vehicle performance. This report covers investigation into the use of blended Alcohol to Jet (ATJ) based fuel and traditional petroleum derived JP-8 in a fuel sensitive rotary fuel injection pump at elevated fuel inlet temperatures. All work was completed by the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF), located at Southwest Research Institute (SwRI) in San Antonio, TX.

Initial tests with synthetic aviation kerosene fuels revealed severe wear and extreme life reduction of rotary fuel injection pumps for diesel engines. The untreated fuels caused performance degrading wear on rotary fuel injection pumps within 25-hours of operation on the untreated fuel. However, prior work with synthetic fuels have shown those fuels responded well to the addition of a Corrosion Inhibitor/Lubricity Improver (CI/LI) additive to extend the life of the rotary fuel injection equipment. In addition, it is likely that most synthetic fuel will be used as a blending component with petroleum JP-8 fuel at a maximum 50-percent in order to maintain fuel density above the JP-8 specification minimum.

In conducting previous additive treated synthetic fuel pump stand tests, it was found that the tests could be operated to conclusion at 500-hours if the maximum concentration of CI/LI additive is utilized at 40 °C fuel inlet temperature. Prior testing also indicated a synthetic fuel that is blended 50-percent with JP-8, and treated with an approved CI/LI additive, will also provide adequate diesel fuel injection pump wear protection at 40 °C fuel inlet temperature.

2.0 TEST OBJECTIVE

The objective of this test was to evaluate the durability of the fuel injection system utilized on a V8-cylinder General Engines Products (GEP) 6.5L engine with a 25%ATJ/75%JP-8 fuel blend at elevated fuel inlet temperature for 1000-hours.

3.0 TEST APPROACH

Endurance tests were performed using a motorized pump stand to define the effects of fuel and fuel additives on full-scale fuel injection equipment durability. The test series attempted to determine the level of fuel injection system degradation due to wear and failure of the boundary film using the HMMWV engine opposed-piston, rotary distributor, fuel injection pumps with an Alcohol-to-Jet (ATJ) synthetic fuel blended with petroleum JP-8 with CI/LI additive treatments. Two distinct tests were performed utilizing a fuel injection pump operating procedure with targeted 1000-hours of operation. The specific tests performed included:

1. Blend of 25-percent ATJ and 75-percent JP-8, the minimum level of DCI-4A CI/LI additive specified as 9-ppm, with a fuel inlet temperature of 77 °C.
2. Blend of 25-percent ATJ and 75-percent JP-8, the maximum level of DCI-4A CI/LI additive specified as 24-ppm, with a fuel inlet temperature of 77 °C.

3.1 FUEL PROPERTIES

As specified in the Scope of Work (SOW) for this project, the desire was to evaluate a 25/75 blend of ATJ/JP-8 to determine changes in injection pump durability as a function of the CI/LI additive concentration at elevated fuel inlet temperature. The 25/75 blend of ATJ/JP-8 was investigated in a prior work directive task to find the maximum ATJ blend component that would result in a 40-cetane number finished fuel blend. Table 1 and Table 2 show the resulting chemical and physical analysis of the test fuels and blend evaluated and requirements cited by MIL-DTL-83133, Detail Specification: Turbine Fuel, Aviation, Kerosene Type, JP-8, NATO F35, and JP-8 +100. Table 3 shows the bulk speed of sound and bulk modulus data for the JP-8, 100% ATJ and 25/75 ATJ/JP-8 test fuels.

Table 1. Neat ATJ, JP8, and ATJ Fuel Blend Chemical/Physical Properties

Test	Method	Units	MIL-DTL-83133H Limits	SwRI Sample ID CL13-5979 Results	SwRI Sample ID CL13-5980 Results	SwRI Sample ID CL14-6189 Results
				100% ATJ	JP-8	25% ATJ
Water Reaction	**D1094**					
Volume change of aqueous layer		mL	-	1.0	0.0	0.5
Interface condition		rating	1b	1b	1b	1b
Separation		-	-	2	2	2
Copper Strip Corrosion (100°C, 2 hrs)	**D130**	rating	1	1B	1A	1A
Smoke Point	**D1322**	mm	min 25	35.0	25.5	27.0
Saybolt Color	**D156**	-	report	28	29	27
Freeze Point (manual)	**D2386**	°C	-47 max	<-80	-60.0	-57.0
Electrical Conductivity v. Temperature	**D2624**					
Temperature		°C	-	22.2	21.9	23.9
Electrical Conductivity		pS/m	150-700	0	1110	470
JFTOT-Breakpoint	**D3241**					
Test Temperature		°C	260	260	260	260
ASTM Code		rating	<3	1	1	<1
Maximum mmHg		mmHg	25 max	0.0	0.0	0.1
Acid Number	**D3242**	mg KOH/g	0.015 max	0.007	0.007	0.008
Existent Gum	**D381**	mg/100mL	7 max	10	1	2
Density	**D4052**					
15°C		g/ml	0.775 to 0.840	0.7575	0.7950	0.7857
Kinematic Viscosity	**D445**					
100°C		cSt	-	0.75	0.68	0.68
40°C		cSt	-	1.48	1.31	1.34
-20°C		cSt	8 max	4.82	4.45	4.50
Lubricity (BOCLE)	**D5001**	mm	-	0.930	0.660	0.650
Lubricity (HFRR) at 60°C	**D6079**	µm	-	698	676	749
Fuel System Icing Inhibitor (FSII) Content at 24°C	**D5006**	vol %	0.07 to 0.10	0.00	0.09	0.09
Particulate Contamination in Aviation Fuels	**D5452**					
Total Contamination		mg/L	1.0 max	0.30	0.30	0.30
Total Volume Used		mL	-	1000	1000	1000
Distillation	**D86**					
IBP		°C	-	174.1	173.6	173.0
5%		°C	-	176.8	183.7	181.5
10%		°C	250 max	177.7	186.9	183.5
15%		°C	-	178.1	189.3	185.3
20%		°C	-	178.2	192.0	187.1
30%		°C	-	179.2	197.1	191.3
40%		°C	-	175.8	202.1	195.4
50%		°C	-	180.5	206.5	199.6
60%		°C	-	181.4	211.5	205.3
70%		°C	-	183.6	217.2	212.3
80%		°C	-	189.9	224.0	221.5
90%		°C	-	214.8	234.1	233.8
95%		°C	-	241.9	242.5	243.2
FBP		°C	300 max	259.1	253.5	254.5
Residue		%	1.5	1.3	1.3	1.4
Loss		%	1.5	0.6	0.3	0.5
T50-T10		°C	-	2.8	19.6	16.1
T90-T10		°C	-	37.1	47.2	50.3

Table 2. Neat ATJ, JP8, and ATJ Fuel Blend Chemical/Physical Properties

Test	Method	Units		SwRI Sample ID CL13-5979 Results	SwRI Sample ID CL13-5980 Results	SwRI Sample ID CL14-6189 Results
				100% ATJ	JP-8	25% ATJ
Flash Point (Pensky Martin)	D93	°C	min 38	44.5	53.5	51.5
Cetane Index	D976	-	-	53.9	49.2	50.2
Particle Count by APC (Cumulative)	ISO-4406					
>= 4µm(c)		class code	-	16	17	18
>= 6µm(c)		class code	-	15	15	16
>= 14µm(c)		class code	-	12	12	14
>= 21µm(c)		class code	-	11	10	14
>= 38µm(c)		class code	-	7	7	13
>= 70µm(c)		class code	-	0	0	13
Heat of Combustion - Net Intermediate	D4809	MJ/kg	42.8 min	43.60	43.00	43.18
Sulfur-Mercaptan	D3227	mass %	0.002 max	<0.0003	0.0004	0.0003
Derived Cetane Number	D6890					
Ignition Delay, ID		ms	-	20.505	4.317	4.885
Derived Cetane Number		---	*	15.65	47.68	42.66
Cetane Number	D613	-	-	<19.4	47	41
MSEP	D7224	rating	-	93	57	55
Aromatic Content	D1319					
Aromatics		vol %	25 max **	0.7	16.8	13.7
Olefins		vol %		2.3	2.0	2.1
Saturates		vol %		97.0	81.2	84.2
Naphthalene Content	D1840	vol%	3.0 max	0.0	0.8	0.5
Hydrogen Content (NMR)	D3701	mass %	13.4 min	15.53	14.20	14.51
Sulfur Content	D4294	ppm	3000 max	<100	997	749
* Derived Cetane Number of 40 min per table A-II, ** Aromatic minimum of 8 per table A-II						

Table 3. Neat ATJ, JP8, and ATJ Fuel Blend Chemical/Physical Properties

Test	Method	Units	SwRI Sample ID CL13-5979 Results		SwRI Sample ID CL13-5980 Results		SwRI Sample ID CL14-6189 Results	
			100% ATJ		JP-8		25% ATJ	
Speed of Sound @ 35°C	**SwRI**		**@**		**@**		**@**	
		m/s	184 psi	1,175.2	222 psi	1,264.8	413 psi	1,247.4
		m/s	756 psi	1,201.9	832 psi	1,294.4	870 psi	1,269.4
		m/s	1366 psi	1,230.8	1977 psi	1,326.6	1710 psi	1,307.8
		m/s	2015 psi	1,257.3	2816 psi	1,365.2	2473 psi	1,329.8
		m/s	3083 psi	1,308.1	3770 psi	1,393.1	3846 psi	1,378.7
		m/s	3808 psi	1,329.0	4990 psi	1,428.9	4838 psi	1,421.4
		m/s	4533 psi	1,356.9	5944 psi	1,453.8	-	-
		m/s	5563 psi	1,392.2	--	--	-	-
Speed of Sound @ 75°C	**SwRI**		**@**		**@**		**@**	
		m/s	222 psi	1,031.0	184 psi	1,108.3	222 psi	1,093.6
		m/s	794 psi	1,062.0	756 psi	1,133.0	794 psi	1,116.4
		m/s	1366 psi	1,094.7	1366 psi	1,168.2	1519 psi	1,151.1
		m/s	2053 psi	1,130.8	2511 psi	1,216.2	2511 psi	1,192.7
		m/s	2740 psi	1,157.9	3426 psi	1,245.8	2892 psi	1,215.1
		m/s	3541 psi	1,196.2	4571 psi	1,290.9	3541 psi	1,234.0
		m/s	4304 psi	1,225.2	5715 psi	1,319.8	4609 psi	1,281.5
		m/s	5334 psi	1,265.0	--	--	-	-
Isentropic Bulk Modulus @ 35°C	**SwRI**		**@**		**@**		**@**	
		psi	184 psi	149,859	222 psi	180,503	413 psi	173,700
		psi	756 psi	157,484	832 psi	189,866	870 psi	180,522
		psi	1366 psi	165,935	1977 psi	200,836	1710 psi	192,639
		psi	2015 psi	173,892	2816 psi	213,736	2473 psi	200,043
		psi	3083 psi	189,642	3770 psi	223,720	3846 psi	216,736
		psi	3808 psi	196,628	4990 psi	236,804	4838 psi	231,626
		psi	4533 psi	205,833	5944 psi	246,317	-	-
		psi	5563 psi	217,909	--	--	-	-
Isentropic Bulk Modulus @ 75°C	**SwRI**		**@**		**@**		**@**	
		psi	222 psi	111,354	184 psi	133,212	222 psi	128,337
		psi	794 psi	118,908	756 psi	139,986	794 psi	134,404
		psi	1366 psi	127,042	1366 psi	149,678	1519 psi	143,772
		psi	2053 psi	136,374	2511 psi	163,538	2511 psi	155,554
		psi	2740 psi	143,790	3426 psi	172,729	2892 psi	161,877
		psi	3541 psi	154,372	4571 psi	186,854	3541 psi	167,659
		psi	4304 psi	162,898	5715 psi	196,528	4609 psi	182,077
		psi	5334 psi	174,815	--	--	-	-

3.2 STANADYNE ROTARY FUEL INJECTION SYSTEM

Rotary distributor fuel injection pumps are fuel lubricated, thus sensitive to fuel lubricity. Highly refined, low sulfur and low aromatic fuels can cause substantial performance degradation with these pumps. Wear seen in the Stanadyne pumps could be interpolated to rotary distributor pumps of other manufacturers.

3.3 PUMP TEST PROCEDURE

Full-scale equipment tests were performed using new fuel injection pumps and fuel injectors with each test fuel. The pump tests were performed in duplicate in order to obtain average wear results. Four fifty-five gallon drums of the appropriate test fuel are normally required for each 1000-hour pump tests. The 1000-hour tests were performed under steady state conditions at maximum fuel delivery for the test pump, as summarized in Table 4. The tests were occasionally halted and restarted as necessary due to scheduling requirements or technical reasons. The pumps were started gradually to prevent seizure due to thermal shock. To further reduce the risk of seizure due to differential expansion, the fuel was not preheated prior to starting the pumps.

Table 4. Pump Operating Conditions

Parameter:	Value:
Duration, hrs	1000
Speed, RPM	1700
Fuel Inlet Temperature, °C	77
Throttle position	Full
Fuel-drum temperature, °C	<30

The test stand included injection flow and pump return pipes, lift pumps, filters, flow meters, a fuel pre-heater and a heat exchanger to reduce the temperature of the fuel before returning to the storage tank. A schematic diagram of the fuel supply system proposed for the pump stand is shown in Figure 1. The temperature of the incoming fuel to each fuel injection pump was controlled to 77 °C. The high-pressure outlets from the pumps were connected to fuel injectors assembled in a collection canister.

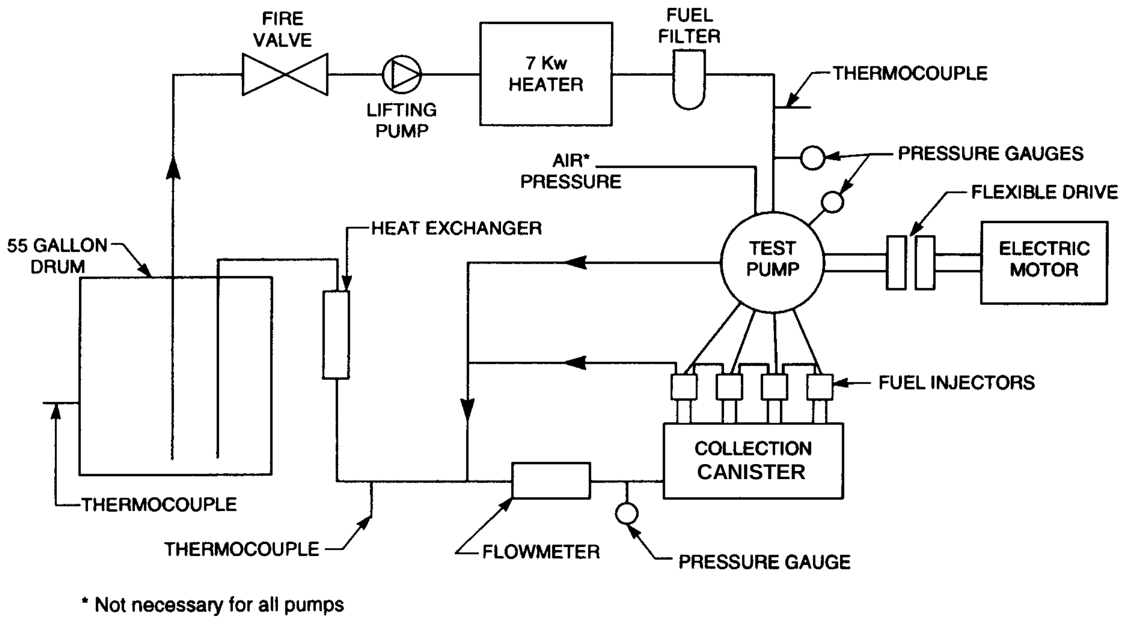


Figure 1. Schematic Diagram of Fuel Delivery System

3.4 LABORATORY SCALE WEAR TESTS

Stanadyne has indicated the lubricity of the test fuel should be determined prior to testing. Stanadyne has recommended the test fuel be changed at 250-hour intervals. The laboratory scale wear performed on the test fuels was the Ball on Cylinder Lubricity Evaluator procedure described in ASTM D-5001, because that procedure is called out for aviation kerosene fuels and additives. The ASTM D-6079 High Frequency Reciprocating Rig (HFRR) wear tests were also performed on the test fuels. The bench test results are shown in Table 5.

Table 5. Beach Wear Test Results for 25/75 ATJ/JP-8 at Two CI/LI Concentrations

CI/LI Concentration	ASTM Method	Description	Result	Units
9-ppm	D 5001	BOCLE	0.563	mm
	D 6079	HFRR	670	µm
24-ppm	D 5001	BOCLE	0.504	mm
	D 6079	HFRR	729	µm

3.5 EVALUATION OF THE PUMPS USING A CALIBRATED TEST STAND

Prior to and following each scheduled pump test, the performance of each of the Stanadyne pumps was evaluated using a calibrated test stand. The objective of the calibration stand evaluation is to define the effect of the durability testing on pump performance. The calibration stand evaluations were performed at an authorized pump distributor. No adjustments were made to any of the pumps to achieve the manufacturer's specifications, either before, during, or following the scheduled pump stand tests.

The appropriate inspection and test procedures for determining fuel injector performance were followed prior to, and after each fuel evaluation.

3.6 PUMP DISASSEMBLY AND WEAR EVALUATION

The fuel injection pumps and fuel injectors were disassembled at SwRI® following completion of the durability tests and the subsequent evaluation using the calibrated test stand. A SwRI disassembly and rating procedure was originally developed for the U.S. Army for use with Stanadyne fuel injection equipment. Each sliding contact within the pump is rated on a scale from 0 to 5, with 0 corresponding to no wear and 5 corresponding to severe wear and failure. The wear scars on components throughout the pump are evaluated visually and quantitative measurements of wear volume were made on the critical pump components. The SwRI procedure looks at all wear contacts within the fuel injection pump, which are lubricated by the fuel.

4.0 PUMP TEST STAND EVALUATIONS

4.1 ROTARY PUMP TEST PROCEDURE

The Stanadyne arctic pumps used for this program are opposed-piston, inlet-metered, positive-displacement, rotary-distributor, fuel-lubricated injection pumps, model DB2831-5079, for a General Engine Products 6.5L turbocharged engine application. The arctic pump is equipped with hardened transfer pump blades, transfer pump liner, governor thrust washer, and drive shaft tang to reduce wear in these critical areas of the pump. A schematic diagram of the principal pump components is provided in Figure 2.

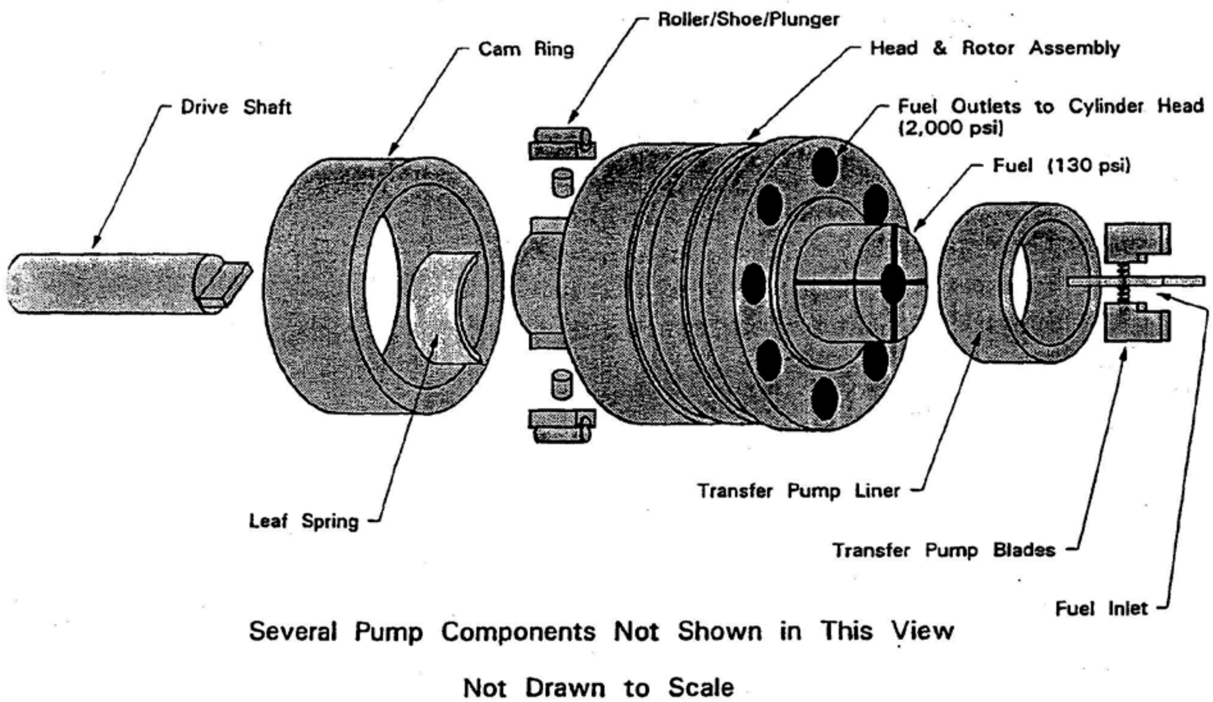


Figure 2. Schematic Diagram of Principal Pump Components

The new pumps were disassembled, and pre-test roller-to-roller dimensions and transfer pump blade heights were obtained. Roller-to-roller dimensions were set per Stanadyne Diesel Systems Injection Pump Specifications for the DB2831-5079 model. The specification calls for a roller-to-roller dimension setting of 50.19 mm ± .026 mm, with a 0.2 mm maximum eccentricity. All pumps were set prior to testing with instructions that the roller-to-roller dimension not be adjusted during pre- and post-performance evaluations so that wear in these components could be accurately measured. Although there are not any min-max specifications other than initial assembly values, wear calculation from the roller-to-roller dimension is an excellent benchmark for the effects of fuel lubricity.

The pumps were reassembled and pre-test performance evaluations were conducted. The pumps were then mounted on the test stand and operated at 1700-RPM; with the fuel levels in the wide open throttle position (WOT) for targeted 1000-hour increments (or less). Fuel flow, fuel inlet and outlet temperatures, transfer pump, pump housing pressures, and RPM were tracked and recorded. Flow meter readings reflect the injected fuel from the eight fuel injectors in each collection canister. Any wear in the fuel injection pump metering section was reflected as an increased or reduced flow reading. For these sets of tests the fuel inlet temperature control target was 77 °C. Fuel inlet temperature variations directly can affect the fuel return temperature; the fuel return temperature is a function of accelerated pump wear. 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 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 the increased diametrical clearances of the plunger bores and the hydraulic head and rotor, results in increased housing pressures. Increased housing pressure reduces metered fuel and retards injection timing.

4.2 PUMP TEST STAND

The rotary pumps were tested on a drive stand with a common fuel supply. To insure a realistic test environment, the mounting arrangement and drive gear duplicate that of the 6.5LT engine. The fuel was maintained in a 55-gallon drum and continuously recirculated throughout the duration of each test. A gear pump provided a positive head of 3 psig at the inlet to the test pumps. A cartridge filter rated at 2 microns was used to remove wear debris and particulate contamination. Finally, a 7-kW Chromalox explosion-resistant circulation heater produced the required fuel inlet temperature.

The high-pressure outlets from the pumps were connected to eight Bosch Model O432217276 fuel injectors for a 6.5LT engine and assembled in a collection canister. Fuel from both canisters was then returned to the 55-gallon drum. A separate line was used to return excess fuel from the governor housing to the fuel supply. Fuel-to-water heat exchangers on both the return lines from the injector canisters and the governor housing were used to cool the fuel. The test stand with pumps mounted is shown in Figure 3.

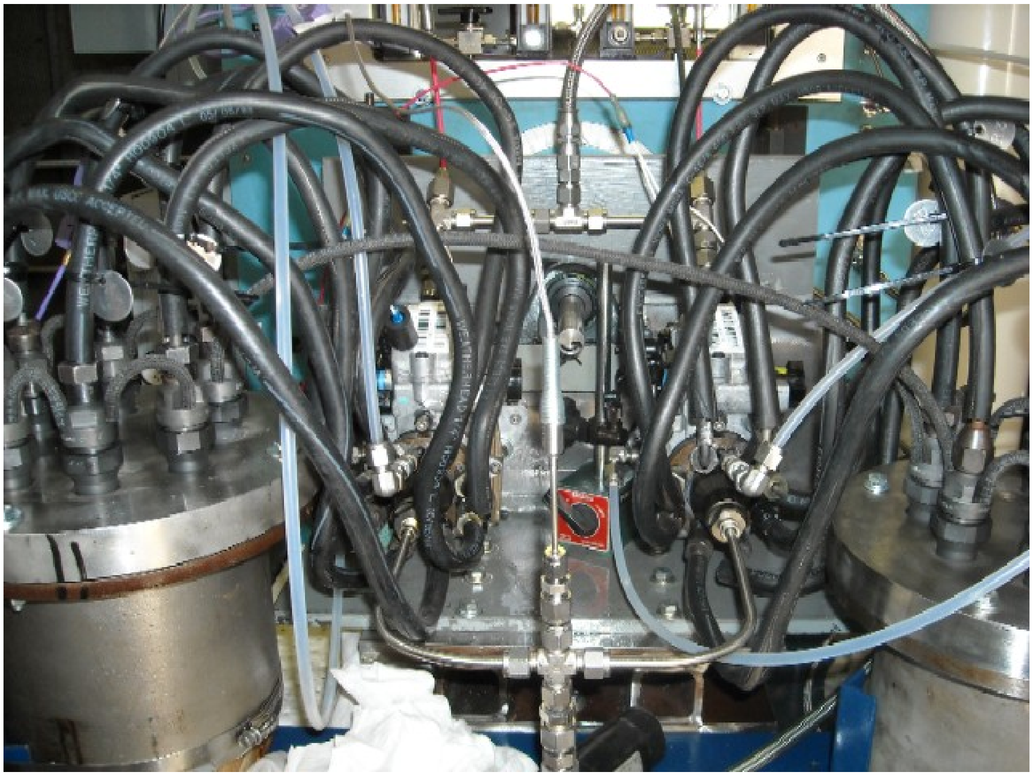


Figure 3. Dual Stanadyne Rotary Fuel Injection Pumps Mounted on Stand with Fuel Injectors

A data acquisition and control system recorded pump stand RPM, fuel inlet pressure, fuel inlet and return temperature, transfer pump pressures, pump housing pressures, and fuel flow readings. The entire rig was equipped with safety shutdowns that would turn off the drive motor in the event of low fluid level in the supply drum, high inlet and return fuel temperature (100 ºC), or low or high transfer pump and housing pressure. Since high-return fuel temperature is a precursor of accelerated wear, this fail-safe feature reduces the possibility of head and rotor seizure.

5.0 ROTARY FUEL INJECTION PUMP EVALUATIONS AND RESULTS

5.1 ROTARY FUEL INJECTION PUMPS WITH ELEVATED TEMPERATURE ATJ/JP-8 FUEL

5.1.1 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI at 77 °C

The Stanadyne model DB2831-5079 rotary fuel injection pumps were received from a supplier and the pumps appeared to be in good condition. The fuel injection pumps were installed on the test stand and the pumps were operated for an hour to validate their operation and to run-in the components with a good lubricity calibration fluid. The pumps were run for 30-minutes at 1200-RPM pump speed, with a half-rack fuel flow setting. For the final 30-minutes of the run-in the pumps were operated at the test condition of 1700-RPM pump speed, with a full-rack fuel flow setting.

The test bench and pumps were flushed with isooctane to attempt to remove any remaining run-in fluid. The isooctane was forced through the fuel injection pumps with pressure; the pumps were not run with isooctane in them. Following the isooctane flush, the treated JP-8 was introduced into the test stand and the stand was operated at an idle condition until 2L of fuel was flushed through each set of eight injectors.

The testing with the blend was initiated and the fuel injection pumps and stand control system appeared to function properly. The operating summaries for the respective fuel injection pumps are shown in Table 6, averaged over the operating interval for each pump, 251-hours for pump SN:16756534 and 389-hours for pump SN:16756535.

Table 6. 25/75 ATJ/JP-8 with 9-ppm CI/LI Pump Operating Summary

Parameter	Unit	Average	Std. Dev.
Pump Speed	RPM	1683	31
Fuel Inlet Pressure	psig	2.99	0.24
Fuel Inlet Temperature	°C	77.0	0.7
Housing Pressure, SN:16756535	psig	14.79	0.97
Housing Pressure, SN:16756534	psig	15.17	0.51
Transfer Pump Pressure, SN:16756535	psig	76.63	4.11
Transfer Pump Pressure, SN:16756534	psig	74.21	3.35
Pump Fuel Return Temperature, SN:16756535	°C	84.3	1.1
Pump Fuel Return Temperature, SN:16756534	°C	83.8	1.1
Injected Flow Rate, SN:16756535	ml/min	711.4	22.1
Injected Flow Rate, SN:16756534	ml/min	732.8	21.8

The first pump test was initiated with the minimum level CI/LI additive blend at a 77 °C fuel inlet temperature. At 251 hours, after the first fuel drum change, pump SN:16756534 seized and fractured the drive shaft. Examination of the driveshaft pieces reveled substantial wear on the drive tang that contributed to internal pump backlash and caused a fracture of the governor weight cage. Internal pump debris eventually contributed to the head and rotor seizure. The fractured drive shaft, drive tang wear and rotor distress for pump SN:16756534 is evident in Figure 3.

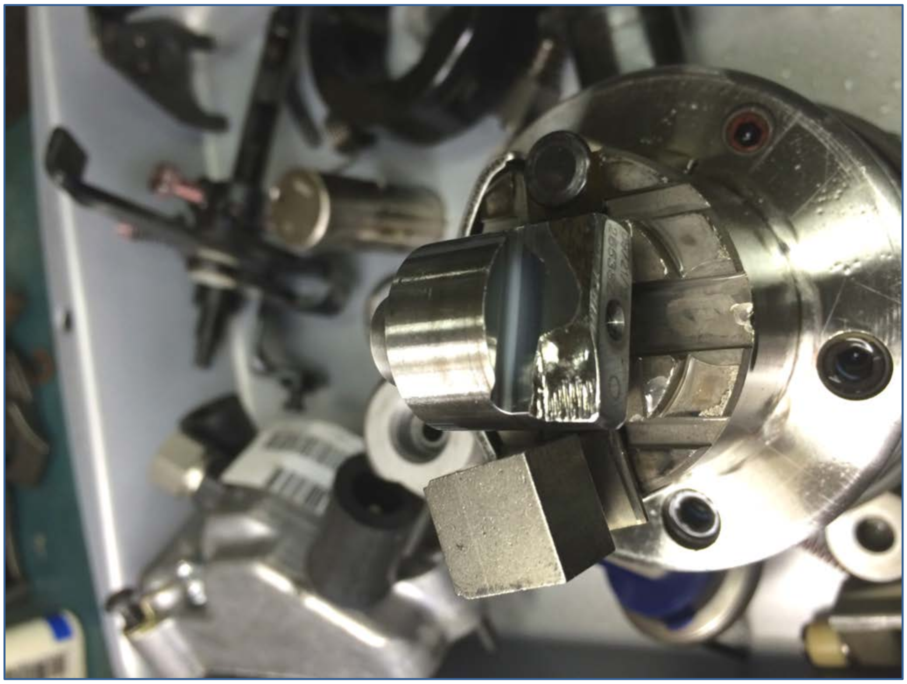


Figure 4. Pump SN:16756534 Showing Fractured Drive Shaft, Drive Tang Wear, and Rotor Distress at 251-hours with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI at 77 °C Inlet Temperature

An artifact of the 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. It has been noted that with low viscosity fuels at elevated temperatures this interaction causes the fuel injection pumps to rattle. It is felt the pump rattle can cause excessive drive tang wear. 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 performance degradation.

For pump SN:16756535 that was still operational, the testing speed was lowered to keep the pump from rattling while on the test stand. Eventually the test speed was low enough that the injection quantity was dropping off, and the pump would still rattle. Inspection of the pump at 389-hours indicated there was wear debris evident in the top housing, as shown in Figure 5, so the testing was terminated. The functional pump was sent for post test calibration, however the drive tang wear was so severe that the calibrations could not be performed due to excessive backlash.

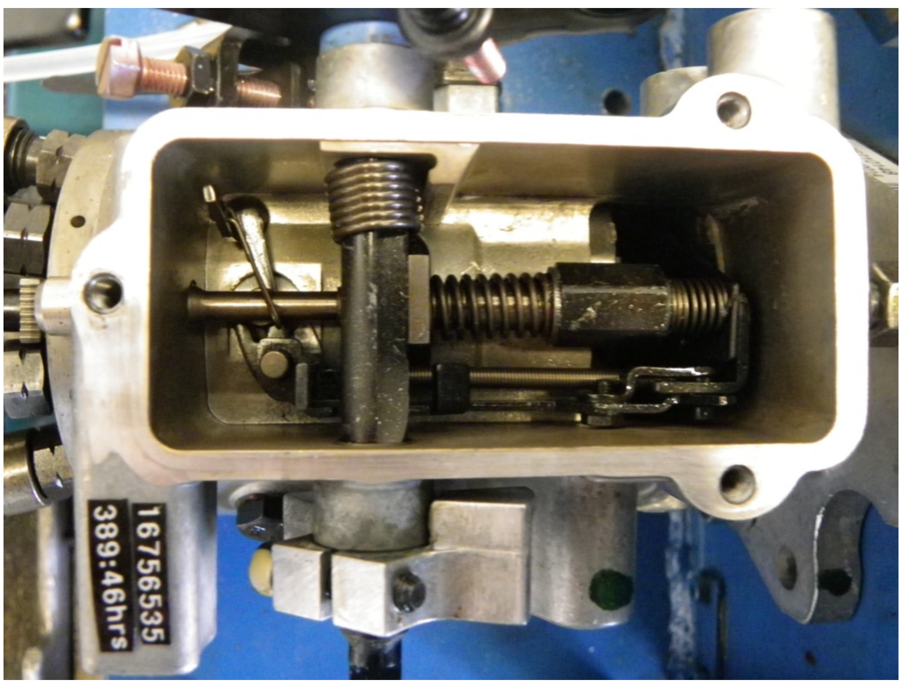


Figure 5. Pump SN:16756535 Showing Wear Debris at 389-hours with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI at 77°C Inlet Temperature

The fuel injection pump delivery histories are shown in Figure 6 for both fuel injection pumps for operation on the ATJ/JP-8 fuel with 9-ppm CI/LI at 77 °C fuel inlet temperature. Both injection pumps revealed slightly erratic delivery characteristics. Erratic delivery in these pumps could be due to metering valve wear, governor linkage wear, or excessive backlash due to drive tang wear. The reductions of the pump drive speed, and the effect of pump speed on fuel delivery for the respective pump times are shown in Figure 6.

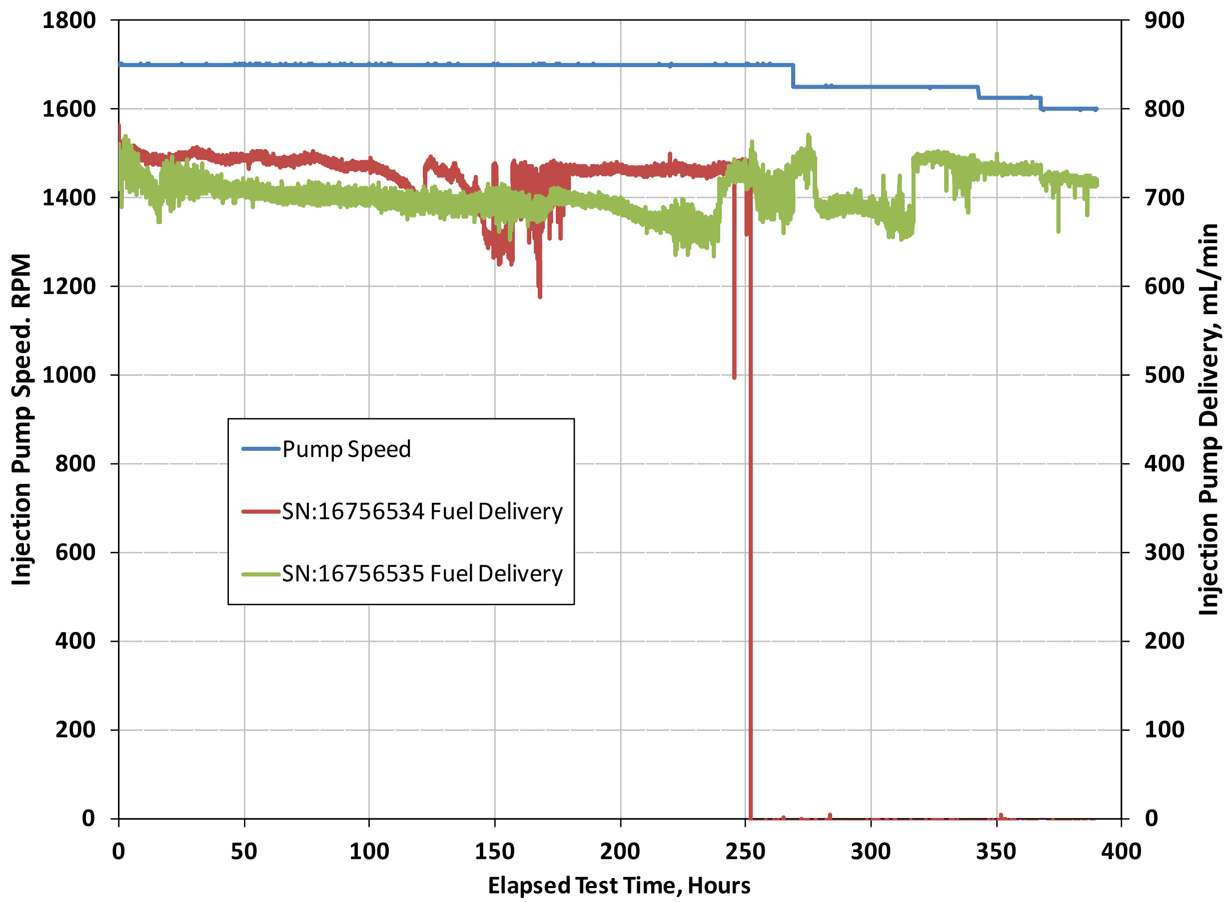


Figure 6. Fuel Flow Rate Histories for 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI at Elevated Temperature

The fuel injection pump temperature histories are shown in Figure 7 for both fuel injection pumps for operation on ATJ/JP-8 fuel with 9-ppm CI/LI at 77 °C fuel inlet temperature. The test stand was converted to single pump operation with the removal of pump SN:16756534. The fuel inlet temperature controller had a difficult time maintaining the fuel inlet temperature. The controller was re-tuned, after which a consistent fuel inlet temperature was maintained. It is possible the swings in fuel inlet temperature may have hastened the wear with pump SN:16756535 after the 251-hour re-start, as the housing fuel return temperature settled at an elevated value after re-tuning the temperature controller. Prior to the test termination with either fuel injection pump, the housing fuel return temperatures are seen to increase at various times, due to increased internal friction in the fuel injection pumps.

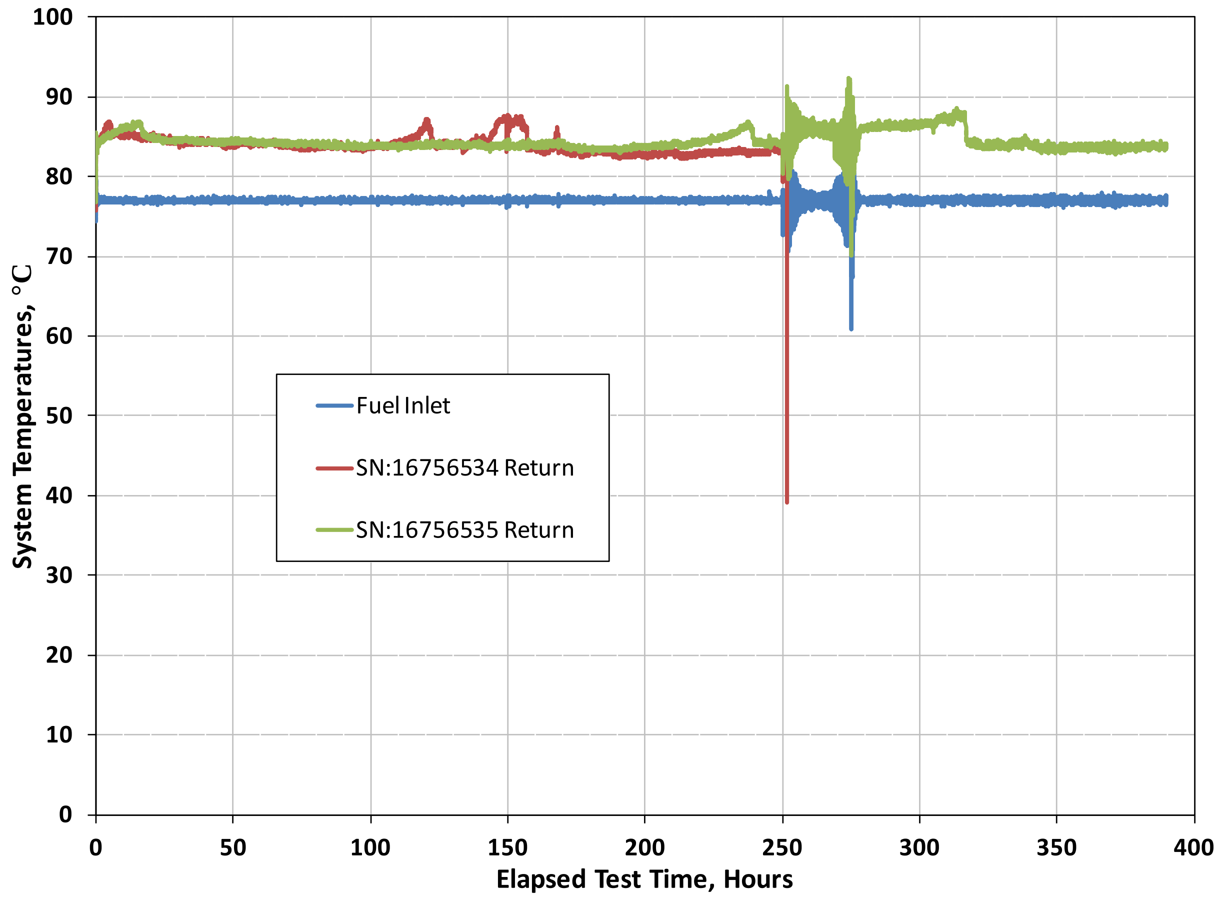


Figure 7. Fuel Inlet and Fuel Return Temperatures for 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI at Elevated Temperature

Shown in Figure 8 are the pressure histories for the elevated temperature ATJ/JP-8 fuel with 9-ppm CI/LI testing. Fuel injection pump SN:16756534 revealed a slight decrease in fuel delivery with a slight increase in housing pressure towards the end of testing. Housing pressure usually increases in these pumps when an excessive amount of high-pressure fuel leaks past the pumping plungers, indicating an increase of the plunger-to-bore clearance. The transfer pump pressure histories for both pumps indicate wear in the transfer pump and transfer pump regulator led to some erratic transfer pump pressure histories. Fluctuations in the transfer pump pressure mirrors the fluctuations in pump fuel delivery.

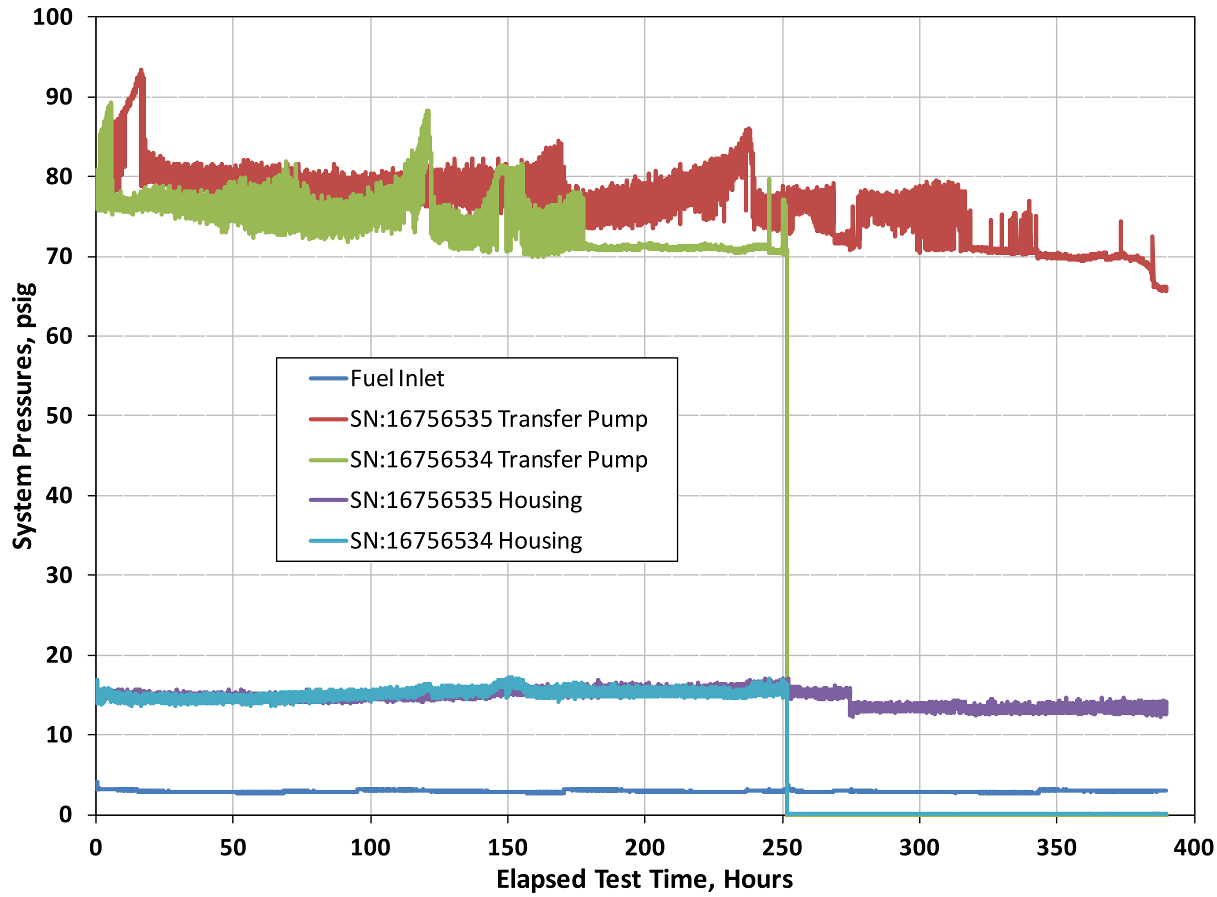


Figure 8. Fuel Inlet, Fuel Transfer Pump, and Housing Pressure Histories for 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI at Elevated Temperature

5.2 25/75 ATJ/JP-8 WITH 24-PPM CI/LI FUEL AT 77 °C

Two Stanadyne model DB2831-5079 fuel injection pumps were installed on the test stand and the pumps were operated for an hour to validate their operation and to run-in the components with a good lubricity calibration fluid. The pumps were run for 30-minutes at 1200-RPM pump speed, with a half-rack fuel flow setting. For the final 30-minutes of the run-in the pumps were operated at the test condition of 1700-RPM pump speed, with a full-rack fuel flow setting.

The test bench and pumps were flushed with isooctane to attempt to remove any remaining run-in fluid. The isooctane was forced through the fuel injection pumps with pressure; the pumps were not run with isooctane in them. Following the isooctane flush, the treated ATJ/JP-8 fuel was introduced into the test stand and the stand was operated at an idle condition until 2L of fuel was flushed through each set of eight injectors.

The testing with the ATJ/JP-8 fuel with 24-ppm CI/LI was initiated and the fuel injection pumps and stand control system functioned normally. The operating summaries for the respective fuel injection pumps are shown in Table 7, averaged over the 1000-hour operating interval for each fuel injection pump.

Table 7. 25/75 ATJ/JP-8 with 24-ppm CI/LI Pump Operating Summary

Parameter	Unit	Average	Std. Dev.
Pump Speed	RPM	1680	35.5
Fuel Inlet Pressure	psig	2.91	0.15
Fuel Inlet Temperature	°C	76.9	1.6
Housing Pressure, SN:16756538	psig	15.47	1.16
Housing Pressure, SN:16756536	psig	15.34	1.55
Transfer Pump Pressure, SN:16756538	psig	82.01	5.71
Transfer Pump Pressure, SN:16756536	psig	75.01	2.50
Pump Fuel Return Temperature, SN:16756538	°C	83.3	2.2
Pump Fuel Return Temperature, SN:16756536	°C	81.8	2.0
Injected Flow Rate, SN:16756538	ml/min	723.7	44.3
Injected Flow Rate, SN:16756536	ml/min	718.9	33.8

The flow histories of the fuel injection pumps operating on the ATJ/JP-8 blend with 24-ppm CI/LI at 77 °C fuel inlet temperature, are shown in Figure 9. From the onset of testing both fuel injection pumps exhibited a slight increase in fuel delivery, followed by a steady delivery decline. Pump SN:167565386 decreased injected delivery fairly steadily during the hours of operation, except directly after the first fuel drum exchange. Pump SN:16756538 exhibited more erratic delivery, with delivery rising and falling during testing, with more severe fluctuations at the end of testing. Pump drive speed was lowered throughout testing in an attempt to reduce the rattle from the fuel injection pumps. However both fuel injection pumps appeared to be functioning on the ATJ/JP-8 blend with 24-ppm CI/LI at the conclusion of the 1000-hours of operation.

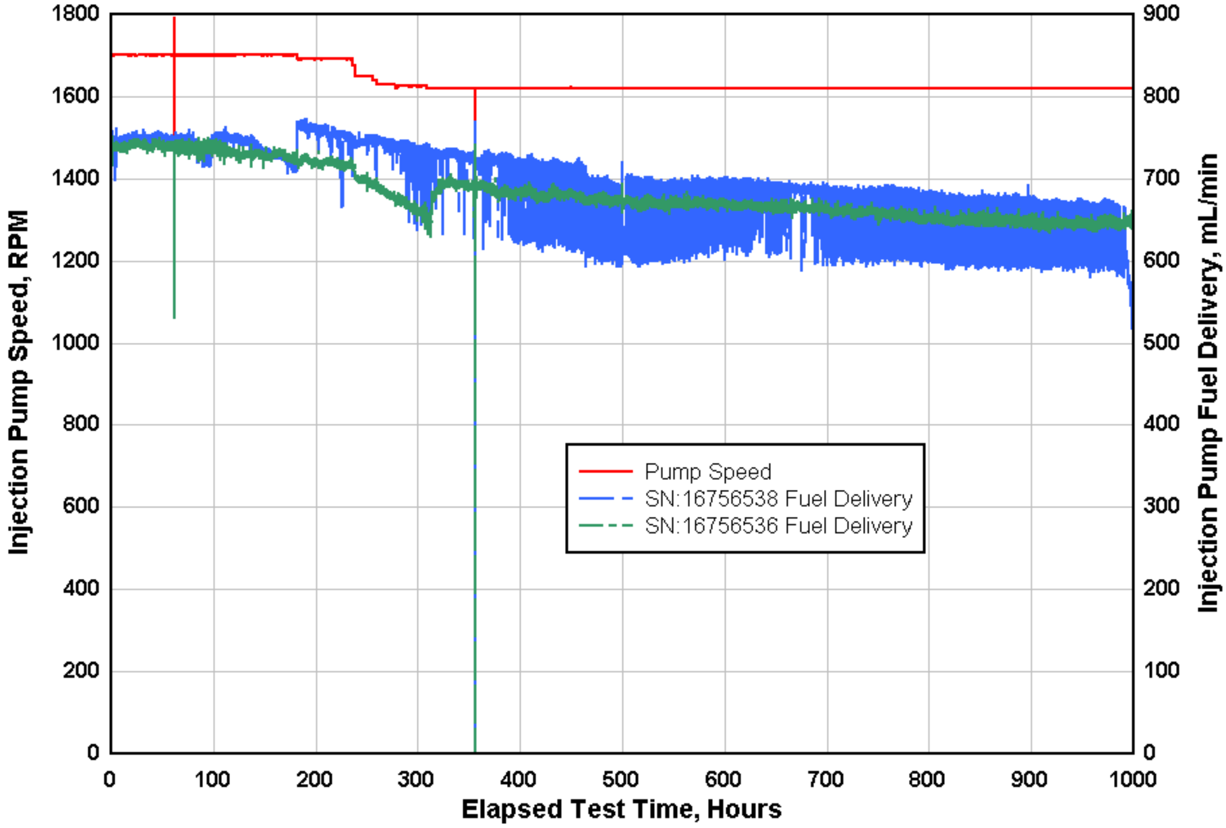


Figure 9. Injection Pump Delivery Histories for 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI Evaluation

The temperature histories of the fuel injection pumps are shown in Figure 10. From the onset of testing both fuel injection pumps exhibited some form of erratic fuel return temperature behavior. For pump SN:16756538 the return fuel temperature increased, usually a sign of increased internal friction, then decreased and increased again towards end of test. Pump SN:16756536 exhibited steady initial fuel return temperature that decreased until about mid-test, then gradually increased towards test conclusion, indicating increasing internal friction. Unusual wear in the pumps usually result in increases and variability of the fuel return temperatures. The fuel inlet temperature to both pumps was very consistent throughout testing.

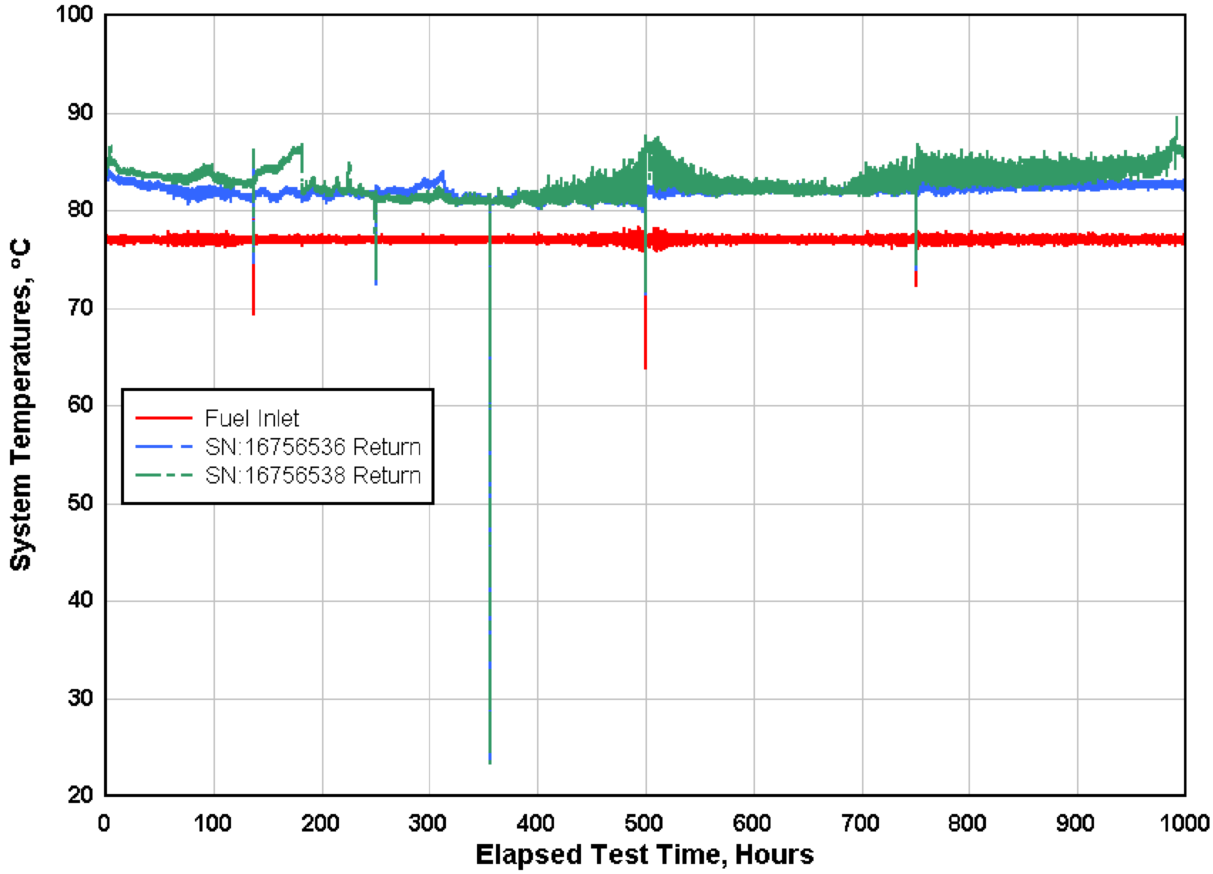


Figure 10. Injection Pump Temperature Histories for 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI Evaluation

Figure 11 shows the fuel pressure histories for the test with the ATJ/JP-8 fuel with 24-ppm CI/LI. The fuel inlet pressure for pumps SN:16756536 and SN:16756538 maintained a consistent level throughout the 1000-hours of operation. Housing pressures for pumps SN:16756536 and SN:16756538 maintained a steady increase throughout the test duration. Housing pressures increase due to leakage from the high pressure section of the pump. The transfer pump pressure for pump SN:16756536 revealed a steady decrease in pressure for the first 250-hours, exhibited a sharp increase, followed by significant variability, then a fairly steady value towards the end of the test. Pump SN:16756538 reveals an initial series of transfer pump pressure spikes and decreases over the first 200-hours, than rapidly fluctuating pressures around a steady mean value until the end of the test. The erratic pressure excursions of the transfer pump indicate pump liner, pump blade, and pump regulator wear.

At 1000-hours of testing the tops of both fuel injection pumps were removed for inspection of wear debris. The housing for pump SN:16756536 is shown in Figure 12 and there is not any wear debris or housing staining evident. The housing for pump SN:16756538 is shown in Figure 13, for which wear debris is evident along with light amber staining of the housing. Pump SN:16756538 displayed more erratic behavior and rattling throughout testing.

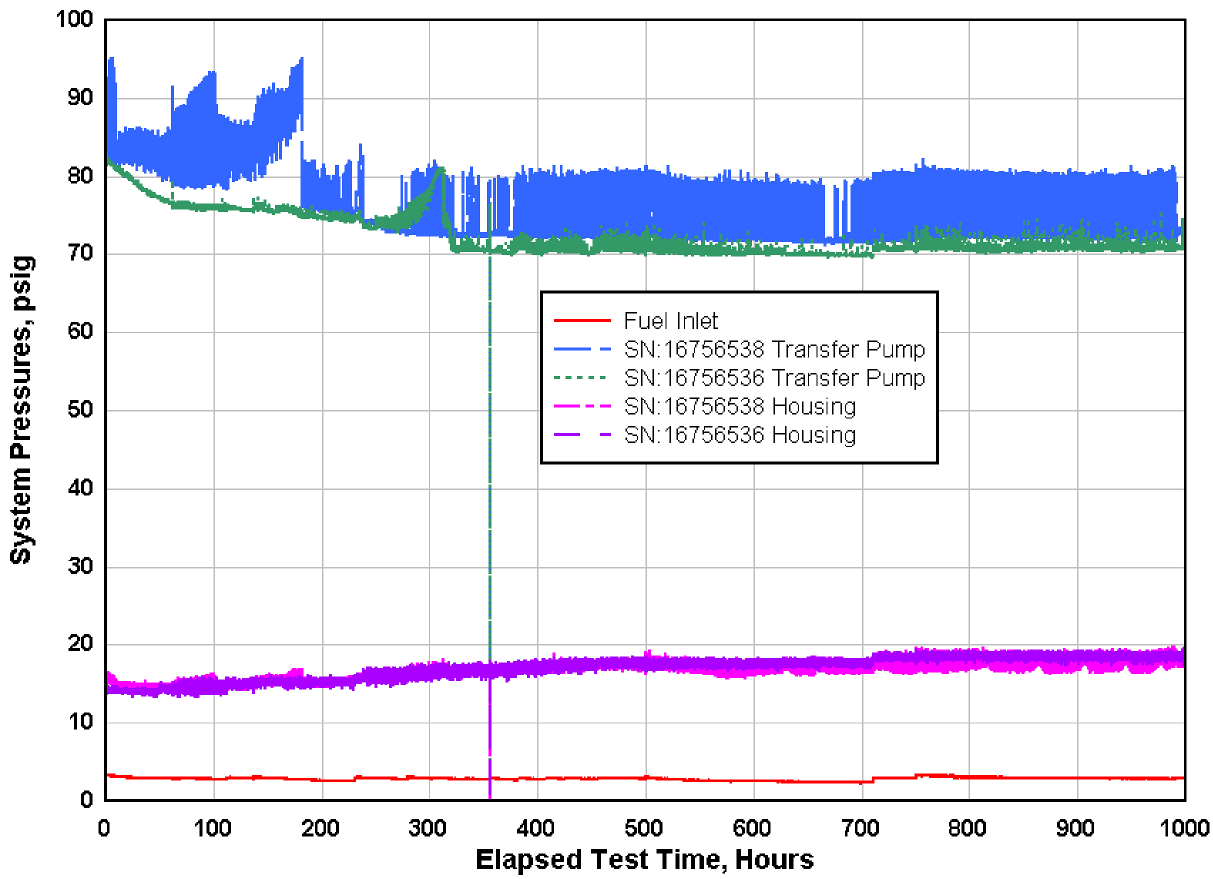


Figure 11. Injection Pump Pressure Histories for 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI Evaluation

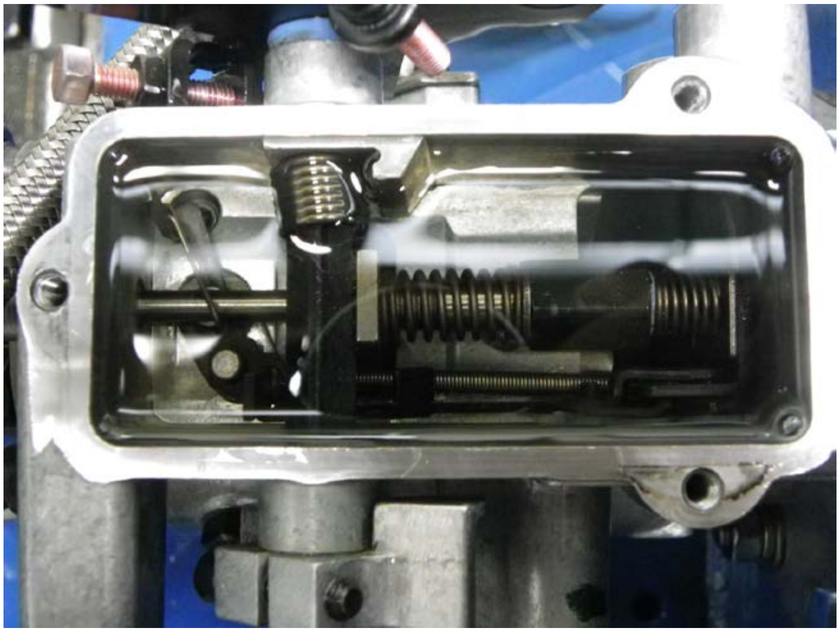


Figure 12. Pump SN:16756536 Governor Assembly with 1000-Hours Testing with ATJ/JP-8 Fuel

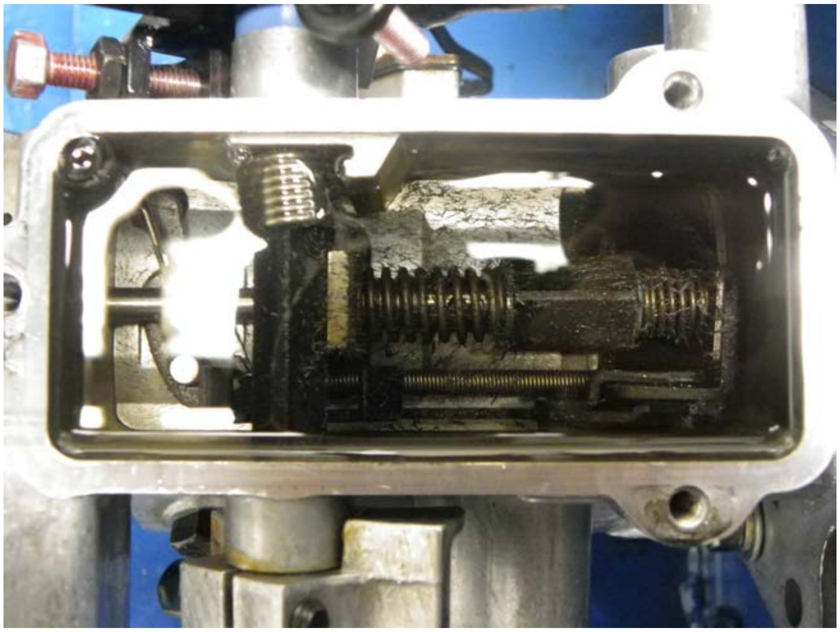


Figure 13. Pump SN:16756538 Governor Assembly with 1000-Hours Testing with ATJ/JP-8 Fuel

5.3 ROTARY PUMP PERFORMANCE MEASUREMENTS

Prior to the durability testing all the fuel injection pumps were run on an injection pump calibration stand to verify their performance with respect to their model number and application specification sheet. Although the pumps came from the factory set to meet their designated specification, because SwRI disassembles the pumps to take transfer pump blade measurements and roller-to-roller dimensions the fuel injection pumps performance is validated by this pre-test calibration. At the conclusion of testing the fuel injection pumps were installed on the calibration stand and checked for performance changes due to the test fuel. There were not any adjustments made to the fuel injection pumps by the calibration personnel nor was the pump disassembled prior to completion of this calibration.

5.3.1 25/75 ATJ/JP-8 with 9-ppm CI/LI Fuel at 77 °C

The Pre- and Post-Test performance curves for fuel injection pump SN:16756534 are included as Table 8. Bold items in boxes in Table 8 are values that fall outside of the specification for the fuel injection pump model. Red bolding is for values below the specification minimums, blue bolding for values above the specification maximums. At the start of testing, the 900-RPM, 1600-RPM, and 200-RPM delivery quantities were out of specification which could lead to a reduction in engine peak power. A decision was made to document only, and not to make any pump adjustments. Due to the seizure of the head and rotor, post test calibration documentation was not feasible.

The Pre- and Post-Test performance curves for fuel injection pump SN:16756535 are included as Table 9. At the start of testing, the 900-RPM, 1600-RPM, and 200-RPM delivery quantities were out of specification which could lead to a reduction in engine peak power. Due to substantial drive tang wear, the pump could not be operated on the calibration stand. The increased backlash due to drive tang wear caused excessive vibration and unsteady operation on the calibration stand.

Both pumps experienced operational issues as a result of operation with the ATJ/JP-8 fuel with 9-ppm CI/LI at the elevated 77 °C fuel inlet temperature. It can be concluded that the 9-ppm CI/LI additive treatment of the 25/75 ATJ/JP-8 fuel had insufficient lubricity for rotary fuel injection pump operation at elevated temperature.

Table 8. Injection Pump SN:16756534 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-5079 (arctic)	SN : 16756534
Test condition : 251 hours @ FIT 77°C and 1700 RPM	Test : AF8639-25-C3ATJ1-77-1000
Fuel : 25% ATJ/75% JP8, 9-ppm CI/LI, AF-8639	

PUMP RPM	Description	Spec.	Before	After	Change
1000	Transfer pump psi.	60-62 psi	60 psi	Head and Rotor Seized, Fuel Injection Pump NOT Functional	Head and Rotor Seized, Fuel Injection Pump NOT Functional
	Return Fuel	225-375 cc	320 cc		
350	Low Idle	12-16 cc	15.8 cc		
	Housing psi.	8-12 psi	10.8 psi		
	Advance	3.5 deg. min	6.5°		
	Cold Advance Solenoid	0-1 psi.	.7 psi		
750	Shut-Off	4 cc max.	0 cc		
900	Fuel Delivery	66.5 - 69.5cc	**63.3 cc**		
1600	WOT Fuel delivery	59.5 cc min.	**58.6 cc**		
	WOT Advance	2.5 - 3.5 deg.	3.5°		
	Face Cam Fuel delivery	21.5 - 23.5 cc	22.0 cc		
	Face Cam Advance	5.25 - 7.25 deg.	5.5°		
	Low Idle	11 - 12 deg.	11.5°		
1825	Fuel Delivery	33 cc min.	42.0 cc		
1950	High Idle	15 cc max.	12 cc		
	Transfer pump psi.	125 psi max.	97.8 psi		
200	WOT Fuel Delivery	58 cc min.	**57.8 cc**		
	WOT Shut-Off	4 cc max.	0 cc		
75	Low Idle Fuel Delivery	37 cc min.	50.4 cc		
	Transfer pump psi.	16 psi min.	19.0 psi		
	Housing psi.	0 -12 psi	8.0 psi		
	Air Timing	-.5 deg.(+/-.5 deg)	-.5°		
	Fluid Temp. Deg. C		45.3°		
	Date		7/21/2014		

Notes : Head and Rotor Seized

Table 9. Injection Pump SN:16756535 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-5079 (arctic)	SN : 16756535
Test condition : 389 hours @ FIT 77°C and 1700 RPM	Test : AF8639-25-C3ATJ1-77-1000
Fuel : 25% ATJ/75% JP8, 9-ppm CI/LI, AF-8639	

PUMP RPM	Description	Spec.	Before	After	Change
1000	Transfer pump psi.	60-62 psi	61 psi	Excessive Backlash due to Drive Tang Wear, CAL NOT Available	Excessive Backlash due to Drive Tang Wear, CAL NOT Available
	Return Fuel	225-375 cc	350 cc		
350	Low Idle	12-16 cc	15.4 cc		
	Housing psi.	8-12 psi	11.1 psi		
	Advance	3.5 deg. min	6.0°		
	Cold Advance Solenoid	0-1 psi.	1.0 psi		
750	Shut-Off	4 cc max.	.7 cc		
900	Fuel Delivery	66.5 - 69.5cc	**62.4 cc**		
1600	WOT Fuel delivery	59.5 cc min.	**58.0 cc**		
	WOT Advance	2.5 - 3.5 deg.	3.5°		
	Face Cam Fuel delivery	21.5 - 23.5 cc	22.0 cc		
	Face Cam Advance	5.25 - 7.25 deg.	6.0°		
	Low Idle	11 - 12 deg.	12.0°		
1825	Fuel Delivery	33 cc min.	39.9 cc		
1950	High Idle	15 cc max.	0 cc		
	Transfer pump psi.	125 psi max.	93.5 psi		
200	WOT Fuel Delivery	58 cc min.	**57.0 cc**		
	WOT Shut-Off	4 cc max.	0 cc		
75	Low Idle Fuel Delivery	37 cc min.	48.3 cc		
	Transfer pump psi.	16 psi min.	19.0 psi		
	Housing psi.	0 -12 psi	9.0 psi		
	Air Timing	-.5 deg.(+/-.5 deg)	-.5°		
	Fluid Temp. Deg. C		45.2°		
	Date		7/21/2014		

Notes : Could not post-test CAL due to drive Tang wear

5.3.2 25/75 ATJ/JP-8 with 24-ppm CI/LI Fuel at 77 °C

The Pre- and Post-Test performance curves for fuel injection pump SN:16756536 are included as Table 10. Items in bold in Table 10 are values that fall outside of the specification for the fuel injection pump model. Red bolding is for values below the specification minimums, blue bolding for values above the specification maximums. At the start of testing, the 900-RPM, 1600-RPM, and 200-RPM delivery quantities were out of specification which could lead to a reduction in engine peak power. A decision was made to document only, and not to make any pump adjustments. At the end of testing the same delivery parameters were further below minimum specifications. The delivery characteristics at 900-RPM would likely impact the peak torque of the engine. At low idle, 350-RPM, pump SN:16756536 was below the minimum delivery value that could result in an erratic engine idle or stalling. At 1600-RPM the delivered quantity was out of specification which could lead to a decrease in engine power. The results at 1950-RPM suggest the governor operation had not been compromised for the SN:16756536 pump on the ATJ/JP-8 fuel blend with 24-ppm CI/LI. The minimum delivery value at 75-RPM was met, so engine starting with this pump would not be an issue. The low delivery at 200-RPM may indicate the engine could stall during the run-up to idle speed.

The Pre- and Post-Test performance curves for fuel injection pump SN:16756538 are included as Table 11. At the start of testing, the 900-RPM, 1600-RPM, and 200-RPM delivery quantities were out of specification which could lead to a reduction in engine peak power. Due to substantial drive tang wear, the pump could not be operated on the calibration stand. The increased backlash due to drive tang wear caused excessive vibration and unsteady operation on the calibration stand.

Both fuel injection pumps completed 1000-hours of operation at elevated temperature with the ATJ/JP-8 fuel with 24-ppm CI/LI. Both pumps exhibited some performance degradation with respect to their calibration performance criterion or due to excessive drive tang wear. The pumps would likely result in erratic engine behavior if installed in a vehicle.

Table 10. Injection Pump SN:16756536 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-5079 (arctic)	SN : 16756536
Test condition : 1000 hours @ FIT 77°C and 1700 RPM	Test : AF8902-25-C3ATJ2-77-1000
Fuel : 25% ATJ/75% JP8, 22-ppm CI/LI, AF-8902	

PUMP RPM	Description	Spec.	Before	After	Change
1000	Transfer pump psi.	60-62 psi	62 psi	62 psi	-1 psi
	Return Fuel	225-375 cc	**217 cc**	258 cc	-41 cc
350	Low Idle	12-16 cc	14.2 cc	**8.9 cc**	5.3 cc
	Housing psi.	8-12 psi	9.8 psi	11.0 psi	-1.2 psi
	Advance	3.5 deg. min	6.3°	5.5°	.8°
	Cold Advance Solenoid	0-1 psi.	.3 psi	1.0 psi	-.7 psi
750	Shut-Off	4 cc max.	0 cc	0 cc	0 cc
900	Fuel Delivery	66.5 - 69.5cc	**62.8 cc**	**60.6 cc**	2.2 cc
1600	WOT Fuel delivery	59.5 cc min.	**57.9 cc**	**55.8 cc**	2.1 cc
	WOT Advance	2.5 - 3.5 deg.	3.5°	3.0°	.5°
	Face Cam Fuel delivery	21.5 - 23.5 cc	22.0 cc	22.0 cc	.0 cc
	Face Cam Advance	5.25 - 7.25 deg.	6.5°	6.0°	.5°
	Low Idle	11 - 12 deg.	11.0°	10.5°	.5°
1825	Fuel Delivery	33 cc min.	35.0 cc	41.6 cc	-6.6 cc
1950	High Idle	15 cc max.	0 cc	0 cc	0 cc
	Transfer pump psi.	125 psi max.	99.0 psi	97.8 psi	1.2 psi
200	WOT Fuel Delivery	58 cc min.	**56.6 cc**	**53.6 cc**	3.0 cc
	WOT Shut-Off	4 cc max.	0 cc	0 cc	0 cc
75	Low Idle Fuel Delivery	37 cc min.	47.6 cc	43.8 cc	3.8 cc
	Transfer pump psi.	16 psi min.	17.1 psi	21.3 psi	-4.2 psi
	Housing psi.	0 -12 psi	10.0 psi	11.1 psi	-1.1 psi
	Air Timing	-.5 deg.(+/-.5 deg)	-.5°	-.5°	.0°
	Fluid Temp. Deg. C		45.4°	45.3°	
	Date		7/31/2014	12/1/2014	

Notes :

Table 11. Injection Pump SN:16756538 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-5079 (arctic)	SN: 16756538
Test condition : 1000 hours @ FIT 77°C and 1700 RPM	Test: AF8902-25-C3ATJ2-77-1000
Fuel : 25% ATJ/75% JP8, 22-ppm CI/LI, AF-8902	

PUMP RPM	Description	Spec.	Before	After	Change
1000	Transfer pump psi.	60-62 psi	62 psi	Could not post-test CAL due to drive Tang wear	Could not post-test CAL due to drive Tang wear
	Return Fuel	225-375 cc	237 cc		
350	Low Idle	12-16 cc	14.0 cc		
	Housing psi.	8-12 psi	11.2 psi		
	Advance	3.5 deg. min	6.3°		
	Cold Advance Solenoid	0-1 psi.	.8 psi		
750	Shut-Off	4 cc max.	0 cc		
900	Fuel Delivery	66.5 - 69.5cc	**64.8 cc**		
1600	WOT Fuel delivery	59.5 cc min.	59.5 cc		
	WOT Advance	2.5 - 3.5 deg.	3.5°		
	Face Cam Fuel delivery	21.5 - 23.5 cc	22.0 cc		
	Face Cam Advance	5.25 - 7.25 deg.	6.3°		
	Low Idle	11 - 12 deg.	11.0°		
1825	Fuel Delivery	33 cc min.	34.8 cc		
1950	High Idle	15 cc max.	0 cc		
	Transfer pump psi.	125 psi max.	99.0 psi		
200	WOT Fuel Delivery	58 cc min.	59.2 cc		
	WOT Shut-Off	4 cc max.	0 cc		
75	Low Idle Fuel Delivery	37 cc min.	51.3 cc		
	Transfer pump psi.	16 psi min.	25.0 psi		
	Housing psi.	0 -12 psi	9.0 psi		
	Air Timing	-.5 deg.(+/-.5 deg)	-.5°		
	Fluid Temp. Deg. C		45.4°		
	Date		7/31/2014		

Notes : Could not post-test CAL due to drive Tang wear

5.4 ROTARY PUMP WEAR MEASUREMENTS

The transfer pump and plunger assemblies are integral to the fuel-metering system in the Stanadyne rotary pump, and by function are the most affected by low lubricity fuel. Accelerated wear in either the transfer pump blades or the roller-to-roller dimension results in a change of fueling condition that jeopardizes the quantity of fuel injected into the hydraulic head assembly. Wear in the transfer pump blades limits the amount of pressure necessary to maintain the proper amount of fuel in the chamber where opposing plungers, actuated by the rollers and cam, inject the metered fuel into the hydraulic head assembly. Roller-to-roller dimension variations alter the travel distance of the plungers, effectively changing metered fuel, injection pressure, and injection timing.

5.4.1 25/75 ATJ/JP-8 with 9-ppm CI/LI at 77 °C

Table 12 and Table 13 present the transfer pump blade and roller-to-roller dimension measurement results for the two fuel injection pumps that operated on ATJ/JP-8 fuel with 9-ppm CI/LI at elevated temperature. There were not any out-of-specification transfer blade measurements based on the dimension length C for either pump SN:16756534 or SN:16756535. The width of the blades did not change dramatically, nor did the blade’s thicknesses decrease much due to the shortened test durations. The pump roller-to-roller dimension change for pump SN:16756534 could not be evaluated due to the seizure of the head and rotor. The change for pump SN:16756535 was less than the ± 0.127-mm assembly specification tolerance. However the roller-to-roller dimensions did slightly increase for pump SN:16756535. The roller-to-roller eccentricity specification is 0.2032-mm maximum, which the pump met for testing with the ATJ/JP-8 fuel with 9-ppm CI/LI at elevated temperature. In general all transfer pump blades were in fair condition, and the roller-to-roller dimensions changes reflect some of the performance changes exhibited.

Table 12. Pump SN:16756534 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-5079	**SN: 16756534**	**Test Number : AF8639-25-C3ATJ1-77-1000**
Fuel description : 25% ATJ/75% JP8, 9-ppm CI/LI, AF-8639		

	Date:	7/10/2014	12/5/2014	
Dimensional Measurements (mm)		***0 hrs.***	***251 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.7008	13.6982	-0.0025
	Dimension B	9.8387	9.8349	-0.0038
	Dimension C	12.6771	12.6759	-0.0013
	Dimension D	3.1280	3.1280	0.0000
	Dimension E	3.1280	3.1242	-0.0038
	Dimension F	3.1267	3.1255	-0.0013
Transfer Pump Blade 2	Dimension A	13.7135	13.7084	-0.0051
	Dimension B	9.8882	9.8831	-0.0051
	Dimension C	12.6708	12.6708	0.0000
	Dimension D	3.1280	3.1267	-0.0013
	Dimension E	3.1293	3.1280	-0.0013
	Dimension F	3.1293	3.1267	-0.0025
Transfer Pump Blade 3	Dimension A	13.6944	13.6919	-0.0025
	Dimension B	9.9073	9.8781	-0.0292
	Dimension C	12.6733	12.6721	-0.0013
	Dimension D	3.1280	3.1280	0.0000
	Dimension E	3.1267	3.1255	-0.0013
	Dimension F	3.1280	3.1267	-0.0013
Transfer Pump Blade 4	Dimension A	13.7325	13.7249	-0.0076
	Dimension B	9.9009	9.8946	-0.0063
	Dimension C	12.6746	12.6746	0.0000
	Dimension D	3.1280	3.1280	0.0000
	Dimension E	3.1280	3.1280	0.0000
	Dimension F	3.1293	3.1280	-0.0013
	Roller to Roller (mm)	50.1396	-	-
	Eccentricity (mm)	0.1270	-	-
	Drive Backlash (mm)	0.1016	SEIZED	-

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222

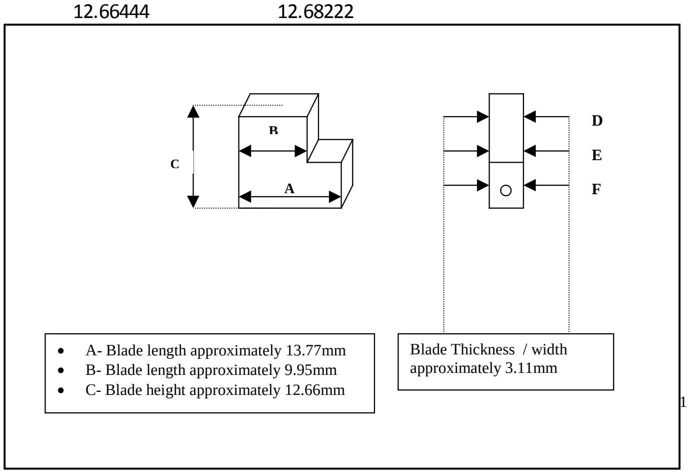


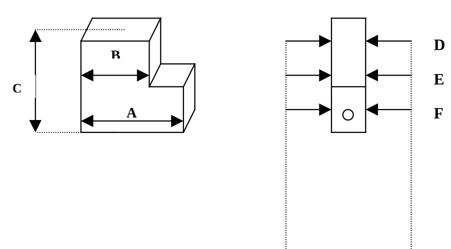
Table 13. Pump SN:16756535 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-5079	SN: 16756535	Test Number : AF8639-25-C3ATJ1-77-1000
Fuel description : 25% ATJ/75% JP8, 9-ppm CI/LI, AF-8639		

	Date:	7/10/2014	12/5/2014	
Dimensional Measurements (mm)		***0 hrs.***	***389 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.6944	13.6906	-0.0038
	Dimension B	9.9200	9.9124	-0.0076
	Dimension C	12.6771	12.6771	0.0000
	Dimension D	3.1280	3.1255	-0.0025
	Dimension E	3.1293	3.1255	-0.0038
	Dimension F	3.1293	3.1242	-0.0051
Transfer Pump Blade 2	Dimension A	13.6690	13.6589	-0.0102
	Dimension B	9.8552	9.8489	-0.0064
	Dimension C	12.6771	12.6746	-0.0025
	Dimension D	3.1255	3.1229	-0.0025
	Dimension E	3.1255	3.1217	-0.0038
	Dimension F	3.1255	3.1229	-0.0025
Transfer Pump Blade 3	Dimension A	13.7325	13.7262	-0.0063
	Dimension B	9.8006	9.7904	-0.0102
	Dimension C	12.6746	12.6721	-0.0025
	Dimension D	3.1267	3.1229	-0.0038
	Dimension E	3.1255	3.1217	-0.0038
	Dimension F	3.1242	3.1191	-0.0051
Transfer Pump Blade 4	Dimension A	13.7249	13.7122	-0.0127
	Dimension B	9.8984	9.8908	-0.0076
	Dimension C	12.6771	12.6746	-0.0025
	Dimension D	3.1280	3.1255	-0.0025
	Dimension E	3.1280	3.1242	-0.0038
	Dimension F	3.1280	3.1242	-0.0038
	Roller to Roller (mm)	50.1472	50.2361	0.0889
	Eccentricity (mm)	0.0762	0.0508	-0.0254
	Drive Backlash (mm)	0.1524	1.0668	0.9144

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



- A- Blade length approximately 13.77mm
- B- Blade length approximately 9.95mm
- C- Blade height approximately 12.66mm

Blade Thickness / width approximately 3.11mm

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5.4.2 25/75 ATJ/JP-8 with 24-ppm CI/LI Fuel at 77°C

Table 14 and Table 15 present the transfer pump blade and roller-to-roller dimension measurement results for the two fuel injection pumps that operated on the ATJ/JP-8 fuel blend with 24-ppm CI/LI at elevated temperature. There were not any out-of-specification transfer blade measurements based on the dimension length C for either pump SN:16756536 or SN:16756538. The width of the blades did not change dramatically, nor did the blade's thicknesses decrease much. Pump SN:16756536 roller-to-roller dimensions decreased, changing less than the ±0.127-mm assembly specification tolerance and pump SN:16756538 roller-to-roller dimension decreased slightly more than the tolerance. The roller-to-roller dimensions decrease for both pumps is reflected in the decreased delivery seen for both pumps during testing. The roller-to-roller eccentricity specification is 0.2032-mm maximum, which pump SN:16756538 approached after 1000-Hours testing with the ATJ/JP-8 fuel blend with 24-ppm CI/LI. In general all transfer pump blades were in fair condition, and the roller-to-roller dimensions changes reflected the performance changes seen on the test stand.

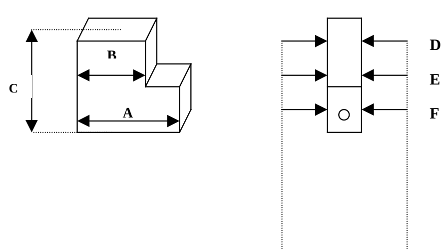
Table 14. Pump SN:16756536 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-5079	SN: 16756536	Test Number : AF8902-25-C3ATJ2-77-1000
Fuel description : 25% ATJ/75% JP8, 22-ppm CI/LI, AF-8902		

Dimensional Measurements (mm)		0 hrs.	1000 hrs.	Change
	Date:	7/9/2014	3/4/2015	
Transfer Pump Blade 1	Dimension A	13.7071	13.6487	-0.0584
	Dimension B	9.7434	9.6990	-0.0444
	Dimension C	12.6784	12.6746	-0.0038
	Dimension D	3.1267	3.1204	-0.0063
	Dimension E	3.1267	3.1217	-0.0051
	Dimension F	3.1280	3.1217	-0.0063
Transfer Pump Blade 2	Dimension A	13.7020	13.6550	-0.0470
	Dimension B	9.8971	9.8514	-0.0457
	Dimension C	12.6771	12.6759	-0.0013
	Dimension D	3.1318	3.1242	-0.0076
	Dimension E	3.1318	3.1242	-0.0076
	Dimension F	3.1331	3.1255	-0.0076
Transfer Pump Blade 3	Dimension A	13.7338	13.6957	-0.0381
	Dimension B	9.7638	9.7257	-0.0381
	Dimension C	12.6784	12.6721	-0.0063
	Dimension D	3.1293	3.1229	-0.0064
	Dimension E	3.1293	3.1217	-0.0076
	Dimension F	3.1306	3.1229	-0.0076
Transfer Pump Blade 4	Dimension A	13.7224	13.6754	-0.0470
	Dimension B	9.9479	9.9047	-0.0432
	Dimension C	12.6733	12.6717	-0.0017
	Dimension D	3.1331	3.1255	-0.0076
	Dimension E	3.1344	3.1267	-0.0076
	Dimension F	3.1344	3.1255	-0.0089
	Roller to Roller (mm)	50.1650	50.1396	-0.0254
	Eccentricity (mm)	0.0254	0.0762	0.0508
	Drive Backlash (mm)	0.0889	0.3302	0.2413

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



- A- Blade length approximately 13.77mm
- B- Blade length approximately 9.95mm
- C- Blade height approximately 12.66mm

Blade Thickness / width approximately 3.11mm

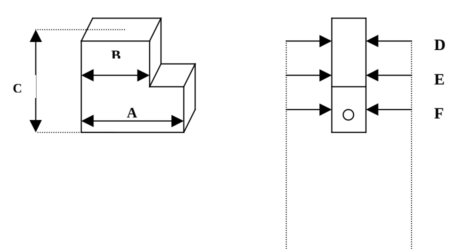
Table 15. Pump SN:16756538 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-5079	SN: 16756538	Test Number : AF8902-25-C3ATJ2-77-1000
Fuel description : 25% ATJ/75% JP8, 22-ppm CI/LI, AF-8902		

	Date:	7/9/2014	3/3/2015	
Dimensional Measurements (mm)		***0 hrs.***	***1000 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.7033	13.6970	-0.0063
	Dimension B	9.7765	9.7523	-0.0241
	Dimension C	12.6797	12.6771	-0.0025
	Dimension D	3.1267	3.1204	-0.0063
	Dimension E	3.1267	3.1191	-0.0076
	Dimension F	3.1255	3.1204	-0.0051
Transfer Pump Blade 2	Dimension A	13.7185	13.6970	-0.0216
	Dimension B	9.9797	9.9644	-0.0152
	Dimension C	12.6759	12.6733	-0.0025
	Dimension D	3.1267	3.1229	-0.0038
	Dimension E	3.1267	3.1229	-0.0038
	Dimension F	3.1267	3.1242	-0.0025
Transfer Pump Blade 3	Dimension A	13.6843	13.6474	-0.0368
	Dimension B	9.8400	9.8285	-0.0114
	Dimension C	12.6733	12.6733	0.0000
	Dimension D	3.1280	3.1217	-0.0063
	Dimension E	3.1280	3.1229	-0.0051
	Dimension F	3.1280	3.1242	-0.0038
Transfer Pump Blade 4	Dimension A	13.7262	13.6855	-0.0406
	Dimension B	9.9403	9.9263	-0.0140
	Dimension C	12.6733	12.6733	0.0000
	Dimension D	3.1280	3.1217	-0.0063
	Dimension E	3.1267	3.1204	-0.0063
	Dimension F	3.1267	3.1204	-0.0063
	Roller to Roller (mm)	50.2031	50.0634	-0.1397
	Eccentricity (mm)	0.0508	0.2032	0.1524
	Drive Backlash (mm)	0.1270	1.6510	1.5240

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



- A- Blade length approximately 13.77mm
- B- Blade length approximately 9.95mm
- C- Blade height approximately 12.66mm

Blade Thickness / width approximately 3.11mm

1

5.5 FUEL INJECTOR RESULTS

Fuel injector nozzle tests were performed in accordance with procedures set forth in an approved 6.5LT diesel engine manual using diesel nozzle tester J 29075B. Nozzle testing is comprised of the following checks:

- Nozzle Opening Pressure
- Leakage
- Chatter
- Spray Pattern

Each test is considered independent of the others, and if any one of the tests is not satisfied, the injector should be replaced.

The normal opening pressure specification for these injectors is 1500 psig minimum. The specified nozzle leakage test involves pressurizing the injector nozzle to 1400 psig and holding for 10 seconds – no fuel droplets should separate from the injector tip. The chatter and spray pattern evaluations are subjective. A sharp audible chatter from the injector and a finely misted spray cone are required.

New Bosch Model O432217276 injectors were used for both of the fuels tests. The injector performance tests and rating results are shown in Table 16 for the ATJ/JP-8 test with 9-ppm CI/LI at elevated temperature. All sixteen fuel injectors passed the post-test opening pressure evaluations after the shortened testing intervals. All sixteen fuel injectors passed the injector tip leakage, chatter, and spray pattern checks.

The injector performance tests and rating results are shown in Table 17 for the elevated temperature ATJ/JP-8 fuel with 24-ppm CI/LI test. All sixteen fuel injectors met the minimum nozzle opening pressure after 1000-hours of operation. Only fourteen fuel injectors passed the injector tip leakage, thirteen passed the chatter, and thirteen passed the spray pattern evaluations after 1000-hours of operation. All the failed injectors operated with pump SN:16756538, indicating wear debris from the pump may have compromised the fuel injectors.

Table 16. Fuel Injector Performance Evaluations after 251/389-Hours ATJ/JP-8 with 9-ppm CI/LI Fuel Usage

Stanadyne Rotary Pump Lubricity Evaluation

6.5L Fuel Injector Test Inspection

Test No.	Inj. Pump ID No.	Fuel	Inj. ID No.	Opening Pressure (pre-test)	Opening Pressure (post-test)	Tip Leakage (pre-test)	Tip Leakage (post-test)	Chatter (pre-test)	Chatter (post-test)	Spray pattern (pre-test)	Spray pattern (post-test)	Date (pre-test)	Date (post-test)	Test Hours	Tech.
AF8639-25-C3ATJ1-77-1000	SN : 16756534	25% ATJ/75% JP8, 9-ppm CI/LI, AF-8639	ATJ1-1	2150	2000	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	251	REG
			ATJ1-2	2150	2000	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	251	REG
			ATJ1-3	2175	2000	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	251	REG
			ATJ1-4	2175	2000	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	251	REG
			ATJ1-5	2150	2000	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	251	REG
			ATJ1-6	2150	2025	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	251	REG
			ATJ1-7	2150	2000	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	251	REG
			ATJ1-8	2150	2000	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	251	REG
AF8639-25-C3ATJ1-77-1000	SN : 16756535	25% ATJ/75% JP8, 9-ppm CI/LI, AF-8639	ATJ1-9	2125	1875	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	389	REG
			ATJ1-10	2100	1900	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	389	REG
			ATJ1-11	2150	1875	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	389	REG
			ATJ1-12	2200	1975	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	389	REG
			ATJ1-13	2150	1925	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	389	REG
			ATJ1-14	2100	1925	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	389	REG
			ATJ1-15	2150	1875	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	389	REG
			ATJ1-16	2200	1925	pass	pass	pass	pass	pass	pass	7/10/2014	10/4/2014	389	REG
			Spec. :	1500psig min	1500psig min	no drop off in 10 sec. @ 1400 psi	no drop off in 10 sec. @ 1400 psi	chatter	chatter	fine mist	fine mist				

Comments :

Table 17. Fuel Injector Performance Evaluations after 1000-Hours ATJ/JP-8 with 24-ppm CI/LI Fuel Usage

Stanadyne Rotary Pump Lubricity Evaluation

6.5L Fuel Injector Test Inspection

Test No.	Inj. Pump ID No.	Fuel	Inj. ID No.	Opening Pressure (pre-test)	Opening Pressure (post-test)	Tip Leakage (pre-test)	Tip Leakage (post-test)	Chatter (pre-test)	Chatter (post-test)	Spray pattern (pre-test)	Spray pattern (post-test)	Date (pre-test)	Date (post-test)	Test Hours	Tech.
AF8902-25-C3ATJ2-77-1000	SN : 16756536	25% ATJ/75% JP8, 22-ppm CI/LI, AF-8902	ATJ2-1	2150	1900	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-2	2175	1800	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-3	2125	1850	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-4	2125	1875	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-5	2175	1875	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-6	2175	1900	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-7	2175	1875	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-8	2150	1875	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
AF8902-25-C3ATJ2-77-1000	SN : 16756538	25% ATJ/75% JP8, 22-ppm CI/LI, AF-8902	ATJ2-9	2125	1675	pass	**fail**	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-10	2200	1750	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-11	2150	1750	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-12	2150	1775	pass	pass	pass	**fail**	pass	**fail**	7/10/2014	1/4/2015	1000	REG
			ATJ2-13	2175	1875	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-14	2150	1550	pass	**fail**	pass	**fail**	pass	**fail**	7/10/2014	1/4/2015	1000	REG
			ATJ2-15	2150	1850	pass	pass	pass	pass	pass	pass	7/10/2014	1/4/2015	1000	REG
			ATJ2-16	2175	1725	pass	pass	pass	**fail**	pass	**fail**	7/10/2014	1/4/2015	1000	REG
			Spec. :	1500psig min	1500psig min	no drop off in 10 sec. @ 1400 psi	no drop off in 10 sec. @ 1400 psi	chatter	chatter	fine mist	fine mist				

Comments :

5.6 ROTARY PUMP COMPONENT WEAR EVALUATIONS

After the fuel injection pump calibration and functional performance checks, the fuel injection pumps were disassembled and the components critical to pump operation were evaluated for parts conditions. A technician with over twenty five years experience rebuilding, servicing, and testing Stanadyne fuel injection pumps performed the subjective wear ratings.

5.6.1 25/75 ATJ/JP-8 with 9-ppm CI/LI Fuel at 77 °C – Pump SN:16756534

The parts conditions and subjective wear ratings for fuel injection pump SN:16756534 are summarized in Table 18. Images of the wear seen on the components of fuel injection pump SN:16756534 are shown in Figure 14 through Figure 32. Figure 14 and Figure 15 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure 14 and Figure 15 reveal some distress at the rotor discharge ports, likely due to debris from backlash and seizure, and the location of the rotor seizure near the plunger bores is evident with the ATJ/JP-8 fuel with 9-ppm CI/LI at 77 °C.

The broken governor weight cage shown in Figure 16 is very unusual for only 251-hours of pump operation. Likely debris from the broken weight cage contributed to the head and rotor seizure. The location of rotor seizure is usually due to misalignment, it is likely the broken weight cage contributed to the misalignment of the rotor within the hydraulic head. In addition it was noted there was rarely seen pump housing damage likely due to debris from the broken governor weight cage.

Figure 17 and Figure 18 are the Pre-Test and Post-Test conditions of the fuel injection pump SN:16756534 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure 17. Figure 18 reveals a wear scar on the roller shoe from the leaf spring contact, heavy burnishing of the rollers, and pitting and scoring of the rollers. The rollers tend to discolor when combination rolling-sliding action occurs as the rollers follow the injection cam profile. Figure 19 and Figure 20 show the relatively small wear scar due to 251-hours operation on the roller shoe plunger contact.

Table 18. Pump SN:16756534 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-5079	**SN : 16756534**
Test condition : 251 hours @ FIT 77°C and 1700 RPM	**TEST : AF8639-25-C3ATJ1-77-1000**
Fuel : 25% ATJ/75% JP8, 9-ppm CI/LI, AF-8639	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Wear at rotor slots and liner contact	2.5
BLADE SPRINGS	Rubbing wear	2
LINER	85% Wear and scarring	2.5
TRANSFER PUMP REGULATOR	Polishing wear from blades and rotor	1.5
REGULATOR PISTON	Polishing wear	2
ROTOR	Seized	5
ROTOR RETAINERS	Wear from rotor contacts	2
DELIVERY VALVE	Polishing wear	2
PLUNGERS	Polishing wear	2
SHOES	Scarring from roller, light wear from leaf spring contact, dimples at plunger contacts.	3.5
ROLLERS	Light scarring and pitting.	2.5
LEAF SPRING	Wear from shoe contact	2
CAM RING	Pitting and scarring	4
THRUST WASHER	Polishing wear from weights and sleeve	2
THRUST SLEEVE	Wear from linkage hook and weights	3.5
GOVERNOR WEIGHTS	Wear at foot from thrust washer contact.	3
LINK HOOK	Wear on arm/fingers/hook connections and pivot spot	3
METERING VAVLE	Polishing wear	2
DRIVE SHAFT TANG	Broken (Seized head and rotor)	5
DRIVE SHAFT SEALS	Good	1
CAM PIN	OK in specification	1
ADVANCE PISTON	Polishing wear and light scuffing	2.5
HOUSING	Damaged from weight cage brakage	3
	AVERAGE DEMERIT RATINGS	2.59

The injection pump cam ring shown in Figure 21 and Figure 22 reveals heavy distress, with evidence of sliding contact, and fairly heavy lobe wear considering only 251-hours of operation with the ATJ/JP-8 fuel with 9-ppm CI/LI at elevated temperature. The excessive cam lobe wear likely contributed to the wear seen on the rollers.

The governor thrust washer condition before and after 251-hours are shown in Figure 23 and Figure 24. The polishing wear seen on the thrust washer in Figure 24 is excessive for 251-hours of injection pump operation. Light scuffing and polishing seen on the advance piston suggests the fuel pressure may have been fluctuating in that area of the fuel injection pumps housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The wear on these components is greater than normal considering the 251-hour duration of testing. The wear on the thrust washer, the advance piston wear, and the metering valve may have affected fuel injection pump operation.

Figure 25 and Figure 26 illustrate the level of wear seen in the transfer pump section of fuel injection pump SN:16756534. Figure 25 shows the surface condition of the transfer pump liner prior to testing and Figure 26 shows the surface with scarring seen on 85% of the area after 251-hours of operation on the ATJ/JP-8 fuel with 9-ppm CI/LI at elevated temperature. Also illustrative of the transfer pump section wear are the transfer pump blade conditions shown in Figure 27 through Figure 30. The edge wear shown in Figure 27 and Figure 28 corresponds to the surface on the transfer pump blades that contact and slide on the transfer pump liner, separated by a film of fuel. The blade edge conditions in Figure 28 reflect the scoring seen on the transfer pump liner, excessive for 251-hours operation. The side polishing shown in Figure 29 and Figure 30 reflect wear from the transfer pump blade slots on the injection pump rotor, and is relatively mild. The wear seen on the transfer pump components seems excessive considering the testing duration for pump SN:16756534.

Figure 31 and Figure 32 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure 31 and Figure 32 reveal a severe wear scar that indicates backlash and timing were altered with the ATJ/JP-8 fuel with 9-ppm CI/LI at elevated temperature after 251-hours. Also evident in Figure 32 is the sheared drive shaft due to the head and rotor seizure

Figure 14. Pump SN:16756534 Distributor Rotor before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 15. Pump SN:16756534 Distributor Rotor with 251-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 16. Pump SN:16756534 Governor Weight Cage Breakage with 251-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 17. Pump SN:16756534 Rollers and Shoe before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 18. Pump SN:16756534 Rollers and Shoe with 251-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 19. Pump SN:16756534 Roller Shoe before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 20. Pump SN:16756534 Roller Shoe with 251-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 21. Pump SN:16756534 Cam Ring before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 22. Pump SN:16756534 Cam Ring with 251-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 23. Pump SN:16756534 Thrust Washer before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 24. Pump SN:16756534 Thrust Washer with 251-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 25. Pump SN:16756534 Transfer Pump Liner before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 26. Pump SN:16756534 Transfer Pump Liner with 251-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

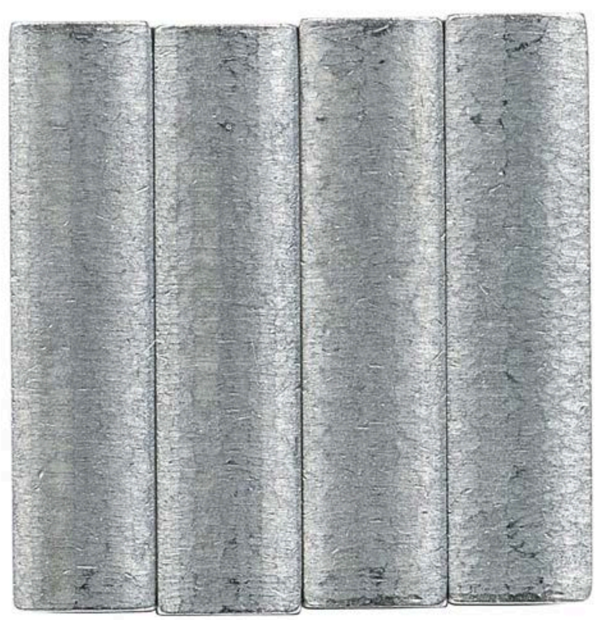


Figure 27. Pump SN:16756534 Transfer Pump Blade Edges before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 28. Pump SN:16756534 Transfer Pump Blade Edges with 251-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

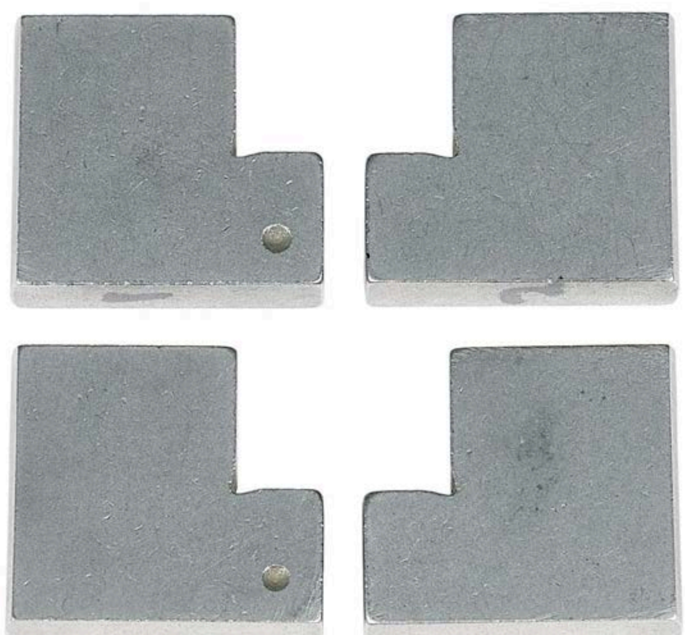


Figure 29. Pump SN:16756534 Transfer Pump Blade Sides before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 30. Pump SN:16756534 Transfer Pump Blade Sides with 251-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 31. Pump SN:16756534 Driveshaft Drive Tang before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 32. Pump SN:16756534 Driveshaft Drive Tang with 251-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

5.6.2 25/75 ATJ/JP-8 with 9-ppm CI/LI Fuel at 77 °C – Pump SN:16756535

The parts conditions and subjective wear ratings for fuel injection pump SN:16756535 are summarized in Table 19. Images of the wear seen on the components of fuel injection pump SN:16756535 are shown in Figure 33 through Figure 50. Figure 33 and Figure 34 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure 34 reveal the very light scratches at the rotor discharge ports, usually from wear debris, after the 389-hours.

Figure 35 and Figure 36 are the Pre-Test and Post-Test conditions of the fuel injection pump SN:16756535 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure 35. Figure 36 reveals only light polishing wear on the roller shoe from the leaf spring contact. Figure 36 shows the Rollers and Roller Shoes with heavy roller discoloration due to burnishing and some heavy roller scratching. Figure 37 and Figure 38 show the wear scar due to 389-hours operation on the roller shoe plunger contact area.

Table 19. Pump SN:16756535 Component Wear Ratings
Stanadyne Pump Parts Evaluation

Pump Type : DB2831-5079	**SN : 16756535**
Test condition : 389 hours @ FIT 77°C and 1700 RPM	**TEST : AF8639-25-C3ATJ1-77-1000**
Fuel : 25% ATJ/75% JP8, 9-ppm CI/LI, AF-8639	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Wear at rotor slots and liner contact	2.5
BLADE SPRINGS	Light rubbing wear	1
LINER	85% Wear and scarring	3.5
TRANSFER PUMP REGULATOR	Polishing wear from blades	2
REGULATOR PISTON	Polishing wear and light scuffing	2.5
ROTOR	Light wear marks at distributor ports	1.5
ROTOR RETAINERS	Wear from rotor	2
DELIVERY VALVE	Polishing wear	2
PLUNGERS	Polishing wear	2
SHOES	Scarring wear, leaf spring wear, light dimple on back.	3
ROLLERS	Discolored with scuffing wear and chipping	3
LEAF SPRING	Wear from shoe contact	2
CAM RING	Chipping on lobes	3.5
THRUST WASHER	Polishing wear from weights and sleeve	2
THRUST SLEEVE	Wear from linkage hook fingers	3.5
GOVERNOR WEIGHTS	Wear from thrust washer contact	1.5
LINK HOOK	Wear on arm/hook/fingers/pivot spot	3
METERING VAVLE	Polishing wear	1.5
DRIVE SHAFT TANG	Heavy wear from rotor contact	4
DRIVE SHAFT SEALS	Normal	1
CAM PIN	OK in specification	1
ADVANCE PISTON	Polishing wear and light scuffing	2.5
HOUSING	Normal	1
	AVERAGE DEMERIT RATINGS	2.24

The injection pump cam ring conditions are shown in Figure 39 and Figure 40. The cam ring the rollers ride on exhibited flattened cam lobes towards the edges as seen in Figure 40.

The governor thrust washer condition before and after 389-hours is seen in Figure 41 and Figure 42. The polishing wear seen on the thrust washer in Figure 42 is excessive for only 389-hours of injection pump operation. Light scoring wear seen on the advance piston suggests the fuel pressure may have been fluctuating in that area of the fuel injection pumps housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The wear on these components is greater than normal considering the 389-hour duration of testing. The wear on the thrust washer, the advance piston wear, and the metering valve had an effect on pump operation.

Figure 43 and Figure 44 illustrates the level of wear seen in the transfer pump section of fuel injection pump SN:16756535. Figure 43 shows the surface condition of the transfer pump liner prior to testing and Figure 44 shows the surface with 85% surface area scored after 389-hours of operation on the elevated temperature ATJ/JP-8 fuel with 9-ppm CI/LI. Also illustrative of wear in the transfer pump section are the transfer pump blade conditions shown in Figure 45 through Figure 48. The edge wear shown in Figure 45 and Figure 46 corresponds to the surface on the transfer pump blades that contact the transfer pump liner. The blade edge conditions in Figure 46 reflect the scoring seen on the transfer pump liner, excessive for 389-hours operation. The side polishing shown in Figure 47 and Figure 48 reflect wear from the transfer pump blade slots on the injection pump rotor. The wear seen on the transfer pump components is excessive considering the testing duration for pump SN:16756535.

Figure 49 and Figure 50 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure 50 reveals a mild wear scar that indicates backlash was occurring. For both pumps the cumulative effect of all the worn components contributed to the performance degradation with the ATJ/JP-8 fuel with 9-ppm CI/LI at 77°C fuel inlet temperature.

Figure 33. Pump SN:16756535 Distributor Rotor before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 34. Pump SN:16756535 Distributor Rotor with 389-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 35. Pump SN:16756535 Rollers and Shoe Condition before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 36. Pump SN:16756535 Rollers and Shoe with 389-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 37. Pump SN:16756535 Roller Shoe Condition before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 38. Pump SN:16756535 Roller Shoe with 389-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 39. Pump SN:16756535 Cam Ring Before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 40. Pump SN:16756535 Cam Ring with 389-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 41. Pump SN:16756535 Thrust Washer Before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 42. Pump SN:16756535 Thrust Washer with 389-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 43. Pump SN:16756535 Transfer Pump Liner before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 44. Pump SN:16756535 Transfer Pump Liner with 389-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

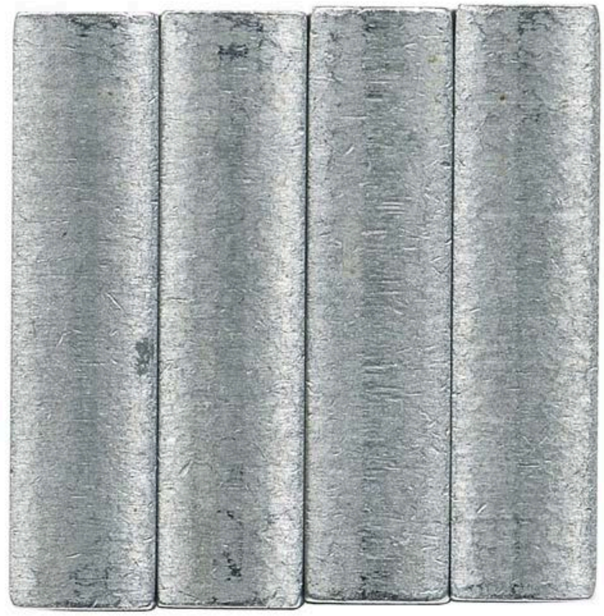


Figure 45. Pump SN:16756535 Transfer Pump Blade Edges before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 46. Pump SN:16756535 Transfer Pump Blade Edges with 389-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

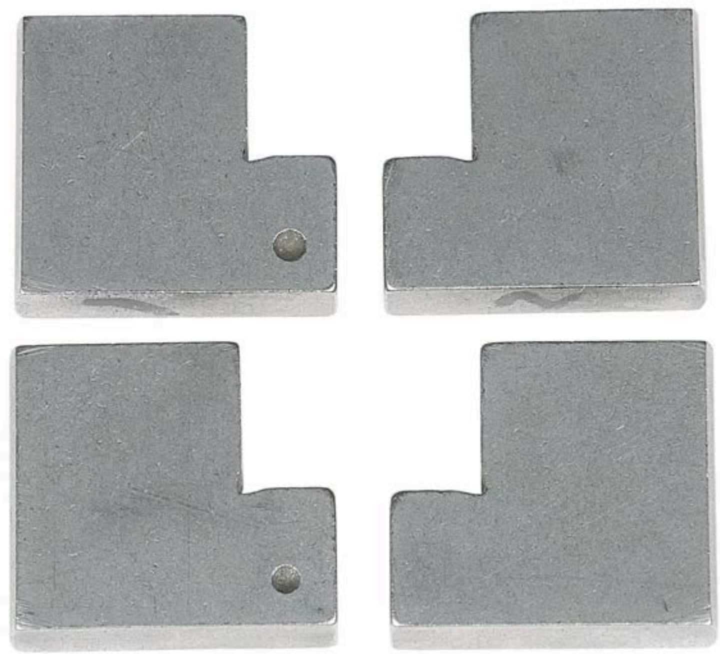


Figure 47. Pump SN:16756535 Transfer Pump Blade Sides before Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 48. Pump SN:16756535 Transfer Pump Blade Sides with 389-hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

Figure 49. Pump SN:16756535 Driveshaft Drive Tang before Testing

Figure 50. Pump SN:16756535 Driveshaft Drive Tang with 389-Hours Testing with 25/75 ATJ/JP-8 Fuel with 9-ppm CI/LI

5.6.3 25/75 ATJ/JP-8 with 24-ppm CI/LI Fuel Blend at 77°C – Pump SN:16756536

The parts conditions and subjective wear ratings for fuel injection pump SN:16756536 are summarized in Table 20. Images of the wear seen on the components of fuel injection pump SN:16756536 are shown in Figure 51 through Figure 68. Figure 51 and Figure 52 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure 52 shows the discharge ports and rotor are in good condition, with very light scratching from wear debris after 1000-hours with ATJ/JP-8 fuel with 24-ppm CI/LI at temperature.

Figure 53 and Figure 54 is the Pre-Test and Post-Test conditions of the fuel injection pump SN:16756536 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure 53. Figure 54 reveals mild wear scars on the roller shoe from the leaf spring contact, heavy burnishing of the rollers, and some scuffing on one roller. The rollers tend to discolor when combination rolling-sliding action occurs as the rollers follow the injection cam profile. Figure 55 and Figure 56 show the relatively mild wear scar due to 1000-hours operation on the roller shoe plunger contact. The injection pump cam ring shown in Figure 57 and Figure 58 reveals polishing and scratching wear on the cam lobes with the 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI blend.

The governor thrust washer condition before and after 1000-hours is seen in Figure 59 and Figure 60. The polishing wear seen on the thrust washer in Figure 60 is typical for the 1000-hour operating interval. Polishing and light scoring wear seen on the advance piston suggests the fuel pressure fluctuations in that area of the fuel injection pump housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The light wear on these components is normal considering the 1000-hour duration of testing. The wear on the thrust washer, the advance piston wear, and the metering valve did have an effect on pump operation.

Figure 61 and Figure 62 illustrates the level of wear seen in the transfer pump section of fuel injection pump SN:16756536. Figure 61 shows the surface condition of the transfer pump liner prior to testing and Figure 62 shows the surface with heavy 95% circumferential scarring after 1000-hours of operation on the 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI. Also illustrative of the transfer pump section wear are the transfer pump blade conditions shown in Figure 63 through Figure 66. The edge wear shown in Figure 63 and Figure 64 corresponds to the surface on the transfer pump blades that contact the transfer pump liner, and they reveal heavy scoring. The side polishing shown in Figure 65 and Figure 66 reflect wear from the transfer pump blade slots on the injection pump rotor. The transfer pump component conditions suggest the test fuel has marginal fuel lubricity.

Figure 67 and Figure 68 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure 68 reveals a wear scar that indicates backlash and timing were likely altered with the 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI blend after 1000-hours at elevated 77°C fuel inlet temperature. This was confirmed by the inability of the pump to be operated on the calibration stand.

Table 20. Pump SN:16756536 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-5079	**SN : 16756536**
Test condition : 1000 hours @ FIT 77°C and 1700 RPM	**TEST : AF8902-25-C3ATJ2-77-1000**
Fuel : 25% ATJ/75% JP8, 22-ppm CI/LI, AF-8902	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Wear at rotor slots and liner contact	3
BLADE SPRINGS	Normal wear	1
LINER	95% Scarring	4
TRANSFER PUMP REGULATOR	Polishing wear from blades and rotor	2
REGULATOR PISTON	Polishing wear and light scuffing	2.5
ROTOR	Light wear marks at distributor ports	1.5
ROTOR RETAINERS	Wear from rotor contact.	2
DELIVERY VALVE	Polishing wear	1.5
PLUNGERS	Polishing wear	2
SHOES	Light scarring from rollers. Light wear from leaf spring and plunger contact.	2.5
ROLLERS	Right roller, heavy scar. Left roller, light scar.	3
LEAF SPRING	Wear from shoe contact	2
CAM RING	Wear scars from rollers.	3
THRUST WASHER	Polishing wear from weights	2
THRUST SLEEVE	Normal	1
GOVERNOR WEIGHTS	Light wear from thrust washer contact.	2.5
LINK HOOK	Wear on fingers and hoook connection, dimple on pivot.	2
METERING VAVLE	Polishing wear	2
DRIVE SHAFT TANG	Wear from rotor contact.	3
DRIVE SHAFT SEALS	Normal	1
CAM PIN	Normal, in specification.	1
ADVANCE PISTON	Light polishing and scuffing.	2.5
HOUSING	Normal	1
	AVERAGE DEMERIT RATINGS	2.09

Figure 51. Pump SN:16756536 Distributor Rotor before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 52. Pump SN:16756536 Distributor Rotor with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 53. Pump SN:16756536 Rollers and Shoe before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 54. Pump SN:16756536 Rollers and Shoe with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 55. Pump SN:16756536 Roller Shoe before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 56. Pump SN:16756536 Roller Shoe with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 57. Pump SN:16756536 Cam Ring before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 58. Pump SN:16756536 Cam Ring with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 59. Pump SN:16756536 Thrust Washer before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 60. Pump SN:16756536 Thrust Washer with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 61. Pump SN:16756536 Transfer Pump Liner before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 62. Pump SN:16756536 Transfer Pump Liner with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 63. Pump SN:16756536 Transfer Pump Blade Edges before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 64. Pump SN:16756536 Transfer Pump Blade Edges with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

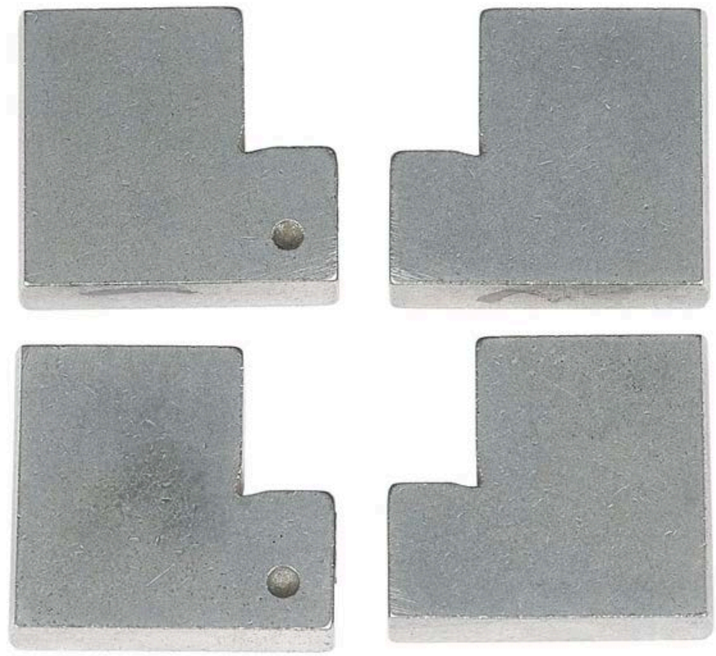


Figure 65. Pump SN:16756536 Transfer Pump Blade Sides before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

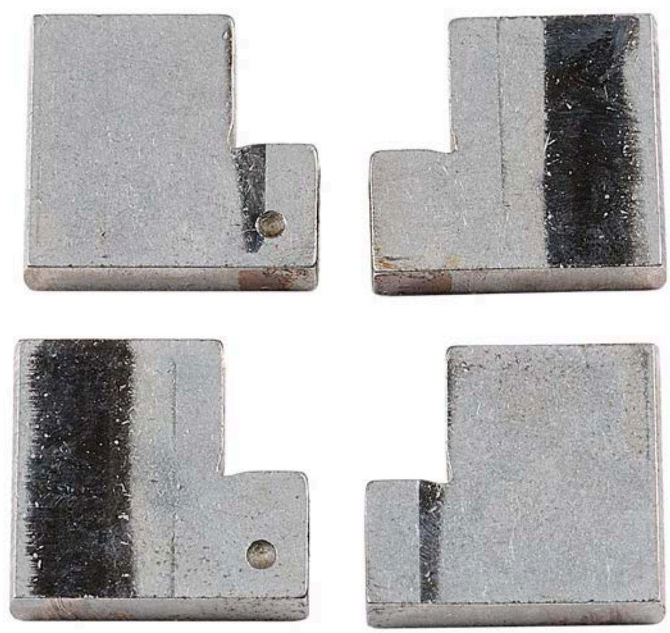


Figure 66. Pump SN:16756536 Transfer Pump Blade Sides with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 67. Pump SN:16756536 Driveshaft Drive Tang Sides before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 68. Pump SN:16756536 Driveshaft Drive Tang with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

5.6.4 25/75 ATJ/JP-8 with 24-ppm CI/LI Fuel Blend at 77 °C – Pump SN:16756538

The parts conditions and subjective wear ratings for fuel injection pump SN:16756538 are summarized in Table 21. Images of the wear seen on the components of fuel injection pump SN:16756538 are shown in Figure 69 through Figure 86. Figure 69 and Figure 70 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure 70 shows the discharge ports and rotor with light scratches and wear near the rotor discharge ports, from wear debris, after the 1000-hours of operation. The rotor condition with the ATJ/JP-8 blend with 24-ppm CI/LI has slightly more distress than the rotor condition seen with JP-8 with 22.5-ppm CI/LI at 1000-hours and elevated temperature [1].

Figure 71 and Figure 72 is the Pre-Test and Post-Test conditions of fuel injection pump SN:16756538 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure 71. Figure 72 reveals light wear scars on the roller shoe from the leaf spring contact; burnishing of the rollers, and scoring on one roller. The rollers tend to discolor when combination rolling-sliding action occurs as the rollers follow the injection cam profile. Figure 73 and Figure 74 show the relatively moderate wear scar due to 1000-hours operation at the roller shoe plunger contact. The wear seen in Figure 74 is typical for a marginal lubricity fuel.

The injection pump cam ring shown in Figure 75 and Figure 76 does reveal some polishing and scoring wear on the cam lobes from 1000-hours operation with the ATJ/JP-8 fuel blend and some flattening of the cam lobes from the distressed rollers. The roller distress with the ATJ/JP-8 blend with 24-ppm CI/LI is more severe than typically seen with JP-8 with 22.5-ppm CI/LI after 1000-hours with 77°C fuel inlet temperature.

The governor thrust washer conditions before and after 1000-hours are seen in Figure 77 and Figure 78. The polishing wear seen on the thrust washer in Figure 78 appears more severe than typical for a 1000-hour operation with a nominal lubricity fuel. Polishing and light scoring wear seen on the advance piston suggests the fuel pressure fluctuations in that area of the fuel injection pump housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The light wear on these components is normal considering the 1000-hour duration of testing. The wear on the thrust washer, the advance piston wear, and the metering valve may have affected the governor cut-off operation.

Figure 79 through Figure 84 illustrate the level of wear seen in the transfer pump section of fuel injection pump SN:16756538. Figure 79 shows the surface condition of the transfer pump liner prior to testing and Figure 80 shows the surface with 90% circumferential scoring after 1000-hours of operation on the ATJ/JP-8 fuel with 24-ppm CI/LI. Also illustrative of the transfer pump section wear are the transfer pump blade conditions shown in Figure 81 through Figure 84. The edge wear shown in Figure 81 and Figure 82 corresponds to the surface on the transfer pump blades that contact the transfer pump liner and are typical for 1000-hours operation with a marginal lubricity fuel. The side polishing shown in Figure 83 and Figure 84 reflect wear from the transfer pump blade slots on the injection pump rotor. The wear seen on the transfer pump components of pump SN:16756538 are more severe than an elevated temperature JP-8 test. The transfer pump component conditions suggest the test fuel has marginal fuel lubricity, also evidenced by the variation of transfer pump pressures noted during testing.

Figure 85 and Figure 86 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure 86 reveals a substantial wear scar that indicates backlash and timing were altered with the ATJ/JP-8 fuel with 24-pm CI/LI after 1000-hours. For both pumps that utilized the ATJ/JP-8 with 24-ppm CI/LI fuel, the significantly worn components that impacted the injection pump performance degradation were the drive tang wear, roller and cam contact, and the transfer pump wear. Both pumps exhibited erratic performance after 1000-hours at elevated temperature with the 25/75 ATJ/JP-8 fuel with 24-ppm CI/LI. Pump performance degradation at 1000-hours was more severe than seen with a JP-8 with 22.5-ppm CI/LI at elevated temperature.

Table 21. Pump SN:16756538 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-5079	SN : 16756538
Test condition : 1000 hours @ FIT 77°C and 1700 RPM	TEST : AF8902-25-C3ATJ2-77-1000
Fuel : 25% ATJ/75% JP8, 22-ppm CI/LI, AF-8902	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Wear at rotor slots and liner contact	3
BLADE SPRINGS	Rubbing wear	2
LINER	90% wear	3
TRANSFER PUMP REGULATOR	Polishing wear from blades	2
REGULATOR PISTON	Polishing and scuffing wear	2.5
ROTOR	Polishing wear and marks at distributor ports	1.5
ROTOR RETAINERS	Wear from rotor	2.5
DELIVERY VALVE	Heavy polishing wear and discolored (heat)	3.5
PLUNGERS	Polishing wear and discoloration	2.5
SHOES	Scarring wear from rollers weight. Dimples from plungers.	3
ROLLERS	Discoloration, burnishing, scarring, and chipping.	4
LEAF SPRING	Wear from shoe contact	2
CAM RING	Wear and scarring from rollers.	3
THRUST WASHER	Wear from weights and sleeve.	2.5
THRUST SLEEVE	Wear from linkage hook fingers.	1.5
GOVERNOR WEIGHTS	Wear from thrust washer contact. Weight cage is loose and worn at rotor contact.	2.5
LINK HOOK	Wear on fingers, hook connection, dimple on pivot.	2
METERING VAVLE	Polishing wear, light	1
DRIVE SHAFT TANG	Heavy wear from rotor slot contact	4
DRIVE SHAFT SEALS	Normal	1
CAM PIN	Normal in specification	1
ADVANCE PISTON	Light scuffing and polishng	2.5
HOUSING	Normal	1
	AVERAGE DEMERIT RATINGS	2.33

Figure 69. Pump SN:16756538 Distributor Rotor before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 70. Pump SN:16756538 Distributor Rotor with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 71. Pump SN:16756538 Rollers and Shoe before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 72 Pump SN:16756538 Rollers and Shoe with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 73. Pump SN:16756538 Roller Shoe before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 74. Pump SN:16756538 Roller Shoe with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 75. Pump SN:16756538 Cam Ring before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 76. Pump SN:16756538 Cam Ring with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

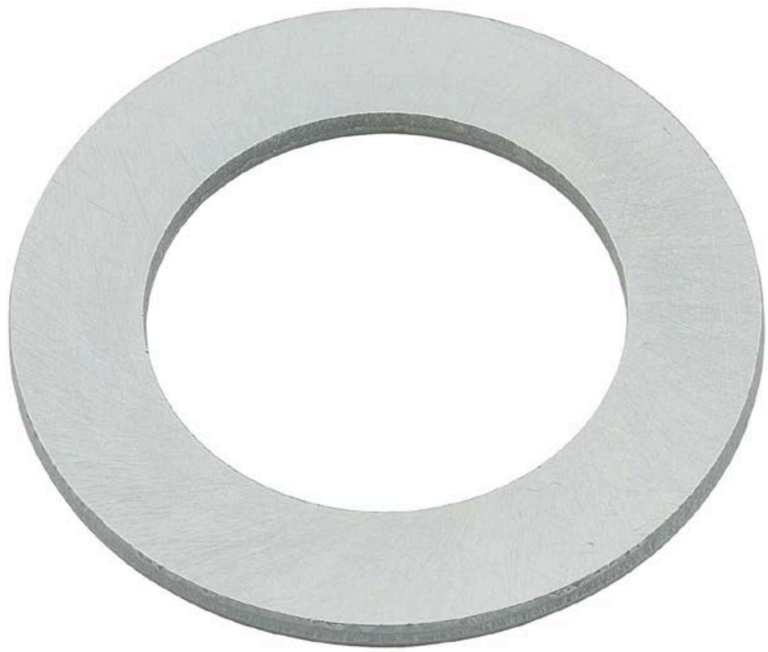


Figure 77. Pump SN:16756538 Thrust Washer before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 78. Pump SN:16756538 Thrust Washer with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 79. Pump SN:16756538 Transfer Pump Liner before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 80. Pump SN:16756538 Transfer Pump Liner with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 81. Pump SN:16756538 Transfer Pump Blade Edges before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 82. Pump SN:16756538 Transfer Pump Blade Edges with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

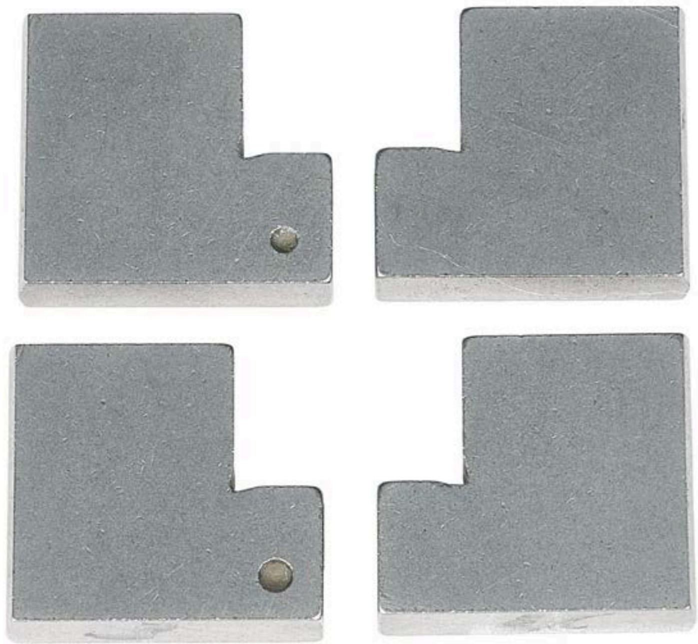


Figure 83. Pump SN:16756538 Transfer Pump Blade Sides before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 84. Pump SN:16756538 Transfer Pump Blade Sides with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 85. Pump SN:16756538 Driveshaft Drive Tang before Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

Figure 86. Pump SN:16756538 Driveshaft Drive Tang with 1000-Hours Testing with 25/75 ATJ/JP-8 Fuel with 24-ppm CI/LI

6.0 DISCUSSION OF RESULTS

In a prior study [2] the effect of synthetic fuel on the durability of the Stanadyne arctic rotary fuel injection pump that contains hardened parts was examined. This fuel injection pump is found on the HMMWV. In conducting the pump stand test with neat synthetic fuel, it was found that the tests had to be stopped prematurely due to fuel injection performance issues that ultimately could affect the operation of an engine.

Comparison results from various synthetic fuel programs were reviewed [2,3]. The comparisons of synthetic fuels performance in rotary fuel injection pumps discussed, suggested that synthetic kerosene fuels, when utilized neat, resulted in premature component wear. On a positive note, reference 3 also performed tests with CI/LI additives in synthetic fuel that showed a substantial improvement of rotary fuel injection pump durability with additive treated synthetic fuel.

A study [4] was performed to determine the impacts of a QPL-25017 CI/LI additive on fuel injection pump durability with synthetic fuel. A CI/LI additive was used at the maximum permitted 24-ppm concentration in a synthetic fuel and in a 50/50-percent blend of synthetic/Jet-A fuel. In conducting the pump stand tests at 40 °C with the two fuels, it was found that both tests had completed 1000-hours of operation with minimal impact on the performance or durability of the diesel engine fuel injection systems that included the fuel injection pump and fuel injectors.

A recent study [5] was performed to determine the impact of minimal QPL-25017 CI/LI additive levels on fuel injection pump durability with a synthetic fuel. The minimal additive levels were determined by the additive concentration that resulted in an ASTM D 5001 BOCLE wear scar in the synthetic fuel of 0.75-mm (8.5-ppm CI/LI additive) and 0.83-mm (2.75-ppm CI/LI additive). Both additive concentrations evaluated were below the QPL-25017 minimum effective concentration for the CI/LI additive used. Both additive levels evaluated were considered inadequate for rotary fuel injection pump protection.

A US ARMY study looked at CI/LI additive concentrations in synthetic and petroleum aviation kerosene fuels at elevated temperatures [1]. The results concluded that the maximum allowable level of CI/LI was required to maintain fuel injection pump durability at elevated temperature. One QPL-25017 CI/LI product appeared to result in improved component conditions over the other products evaluated. The study looked at only the addition of CI/LI in Jet-A or SPK fuel, and did not look at the other MIL-DTL-83133H additives that make JP-8.

The ATJ/JP-8 blend had an ASTM D5001 lubricity of 0.563-mm wear scar when treated with 9-ppm of the CI/LI additive DCI-4A. The ASTM D6079 wear scar diameter result for the same blend was 670-µm. The ATJ/JP-8 blend when treated with 24-ppm of the CI/LI additive DCI-4A, had an ASTM D5001 lubricity of 0.504-mm wear scar. The ASTM D6079 wear scar diameter result for the same blend was 729-µm.

The testing with the 25/75 ATJ/JP-8 fuel with 9-ppm CI/LI, the minimum effective treat rate of the additive, indicated insufficient fuel lubricity for operation at 77 °C fuel inlet temperature. Relatively short time failures, severe component wear, and excessive drive shaft wear resulted in either a seizure or erratic pump performance.

Although the 25/75 ATJ/JP-8 fuel with 24-ppm CI/LI permitted completion of the 1000-hours in the rotary diesel fuel injection pump test, one fuel injection pump's performance could not be measured due to erratic operation. One fuel injection pump would not allow idle operation if it was installed on an engine and the engine would be low on power. Component inspections suggest the transfer pump and drive tang wear was excessive and the cam ring and roller interface wear was high for both pumps. As seen in previous work (1,3,4), the maximum effective concentration of CI/LI additive is suggested for synthetic fuel blends in order to offer adequate rotary diesel fuel injection pump wear protection, but at elevated temperature even the maximum treatment levels appear inadequate for ATJ/JP-8 blends.

7.0 CONCLUSIONS

The following conclusions can be made from the cumulative knowledge of utilizing JP-8, synthetic aviation kerosene fuel blends, and 25/75 ATJ/JP-8 in diesel rotary fuel injection pumps at elevated temperature:

- For elevated fuel inlet temperature operation, even with petroleum JP-8 at 77 °C, the maximum effective CI/LI concentration is required to provide adequate wear protection.
- For elevated fuel inlet temperature operation, with 25/75 ATJ/JP-8 at 77 °C, the minimum effective CI/LI concentration is inadequate.
- A 25/75 blend of ATJ/JP-8 with 24-ppm CI/LI operated at 77 °C fuel inlet temperature will allow 1000-hours of rotary pump operation. However the performance degradation of the fuel injection pumps at 1000-hours would impact engine operation, and component inspections suggested excessive wear.

8.0 RECOMMENDATIONS

The technical feasibility of using ATJ/JP-8 fuel at elevated temperatures in rotary fuel injection equipment when blended with a CI/LI additive has been investigated:

- 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.
- 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.
- Based on these limited set of test results, at elevated fuel inlet temperatures, even the use of maximum concentration CI/LI in an ATJ/JP-8 fuel blend appears to result in accelerated wear in fuel-lubricated rotary fuel injection pumps.

9.0 REFERENCES

1. "Effectiveness Of Additives In Improving Fuel Lubricity And Preventing Pump Failure At High Temperature", Interim Report TFLRF No. 437, D.M. Yost, A.C. Brandt, and R.A. Alvarez, U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI), Southwest Research Institute, January 2013.

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5. Final Report for Southwest Research Institute® Project No. 08.16246.03, "*Advanced Propulsion Fuels Research And Development Support To Afrl/Rzpf Task Order 0011: Rapid Response Research And Development (R&R) For Propulsion Directorate*", Bessee, et al, November 2012, Appendix C in AFRL-RQ-WP-TM-2013-0010.