EVALUATION OF MILITARY FUELS USING A FORD 6.7L POWERSTROKE DIESEL ENGINE

INTERIM REPORT
TFLRF No. 415

by
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San Antonio, TX

for
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14. ABSTRACT

A Ford 6.7L diesel engine utilizing a fuel lubricated high pressure common rail (HPCR) fuel system was evaluated using ULSD, JP-8, 50/50 synthetic paraffinic kerosene (SPK), and 100% SPK to determine the compatibility of modern HPCR fuel systems with military fuels. The engine was operated following the 210hr U.S. Army Tactical Wheeled Vehicle Engine Endurance Cycle (TWVC) to determine fuel system endurance and performance degradation associated with each tested fuel. Pre and post-test powercurves and emissions were completed to monitor and record engine performance, and to determine any power degradation present across the test duration. New fuel system components were installed on the engine prior to each test. After completion, fuel system components were removed and disassembled to determine internal wear present in the high pressure pump and fuel injector assemblies. All components were compared to each other as well as a new unused set of hardware to determine the wear associated with each tested fuels use.

15. SUBJECT TERMS

Military Fuels, Diesel, ULSD, Jet-A, JP-8, 50/50, Synthetic, Synthetic Paraffinic Kerosene, SPK, High Pressure Common Rail, Piezo-Electric, Lubricity

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EXECUTIVE SUMMARY

A large number of current Commercial Off-The-Shelf (COTS) diesel engines available to the U.S. Military employ High Pressure Common Rail (HPCR) fuel injection systems. Overall performance and endurance of these HPCR systems has the potential to vary with use of military or alternative fuels due to critical chemical and physical property differences compared to standard diesel fuels. Fuel systems are typically designed and optimized for use with Ultra Low Sulfur Diesel (ULSD) for on-highway compatibility, and thus assume a standard range of fuel properties as specified by the regulation of ULSD. Of the critical property differences between ULSD and military fuels, changes in fuel viscosity and lubricity are of particular interest. Many modern HPCR systems utilize fuel lubricated high pressure pumps, and can generate upwards of 2000bar fuel rail pressures placing large demands on the fuel to adequately lubricate and protect internal components. In addition, changes in fuel viscosity can have large impacts on internal leakage and filling rates, and have adverse effects on engine performance.

To better understand these critical fuel related impacts, performance and endurance testing was conducted using a fired engine equipped with a modern fuel lubricated HPCR fuel system with the following test fuels: diesel (ULSD), JP-8, 50/50% volumetric blend of JP-8 and Synthetic Paraffinic Kerosene (SPK), and 100% SPK. A sample of the test fuel chemical and physical analysis results can be seen in Exhibit A showing the large variation in physical properties tested. Testing was completed using a Ford 6.7L V8 turbocharged diesel engine. It was chosen for its recent introduction into the market at the time of testing, as well as expected entrance into several flight line vehicles used by the U.S. Air Force. The engine used was tested in its “export” configuration, which does not utilize Exhaust Gas Recirculation (EGR) or exhaust aftertreatment systems. This is consistent with the types of engines that would be purchased and used by the military. Testing was completed following a modified version of the U.S. Army 210-hr Tactical Wheeled Vehicle Cycle (TWVC). Modifications were made to the test cycle to accelerate the test schedule from 14hrs of operation daily to 21hrs daily in an effort to reduce overall test time. Each test was completed on the same engine utilizing new fuel system components to maintain test consistency. At the completion of each test, fuel injection pumps and injectors were removed and disassembled for inspection and comparison. In addition to comparisons of components

between tests, a new unused set of fuel system components were also disassembled to serve as a baseline comparison for all tests in determining wear as a function of the fuels tested. Engine power curves and emissions were taken at the start and end of testing, and used to document any engine performance degradation incurred over the test duration. Results provided a direct comparison between the tested fuels and their impacts on: fuel system operation, internal fuel system wear, engine power output across test duration, and engine out emissions.

Exhibit A - Test Fuel Chemical and Physical Properties

Property	Units	Method	Results			
			ULSD	JP-8	50/50	SPK
Density @ 15°C	g/mL	D4052	0.858	0.802	0.796	0.736
Flashpoint	°F	D56	154	127	115	111
Kinematic @ 40°C	cSt	D445	3.0	1.2	1.0	0.9
Cetane Number		D613	47.2	42.2	53.7	64
Heat of Comb.	BTU/lb	D240	19460	19769	20038	20364
Sulfur	ppm	<10	<10	<10	<10	<10
HFRR	mm	D6079	0.444	0.675	0.695	0.840
BOCLE	mm	D5001	0.46	0.69	0.72	0.76

All tested fuels were successfully operated over the test duration without experiencing any unusual fuel related operational conditions or hardware failures, despite large variations in military fuels viscosity and lubricity from standard ULSD. Even at the minimum lubricity enhancing treat rates, the tested JP-8 and synthetic based fuels provided adequate component protection and system performance compared to the ULSD baseline test. Post-test fuel injection system inspection found tested components to be in similar condition throughout all tests, despite the large differences in fuel lubricity from the baseline to SPK tests. Results from testing support the compatibility of the fuel lubricated HPCR fuel system utilized on the Ford 6.7L with military specified fuels at normal ambient conditions.

FOREWORD/ACKNOWLEDGMENTS

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

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ACRONYMS AND ABBREVIATIONS

AFR – air fuel ratio
BP – boiling point
CN – cetane number
CO – carbon monoxide
CO2 – carbon dioxide
COEI – carbon monoxide emissions index
COTS – commercial off the shelf
EGR – exhaust gas recirculation
EI – emissions index
FIP – fuel injection pump
HC – hydrocarbon
HCEI – hydrocarbon emissions index
HofC – heat of combustion
HPCR – high pressure common rail
IQT – ignition quality test
NOx – oxides of nitrogen
NOxEI – oxides of nitrogen emissions index
O2 – oxygen
PCM – powertrain control module
PCV – pressure control valve
SPK – synthetic paraffinic kerosene
SwRI – Southwest Research Institute
TARDEC – Tank Automotive Research, Development, and Engineering Center
TFLRF – TARDEC Fuels & Lubricants Research Facility
TWV – Tactical Wheeled Vehicle
TWVC – Tactical Wheeled Vehicle Cycle
ULSD – ultra-low sulfur diesel
VCV – volume control valve

1.0 INTRODUCTION & BACKGROUND

A large number of current Commercial Off-The-Shelf (COTS) diesel engines available to the U.S. Military employ High Pressure Common Rail (HPCR) fuel injection systems. Life cycle performance and endurance of these HPCR fuel systems has the potential to be impacted by critical chemical and physical property differences between military specification fuels and commercially available diesel fuels. Although these critical factors can include many different properties, primary concerns lie with typically lower lubricity and viscosity values for military fuels, as these can have major interactions with fuel system hardware. Many HPCR Fuel Injection Pumps (FIP) are fuel lubricated and depend on lubricity specific fuel properties to provide adequate hardware protection during use. Modern HPCR FIPs can generate upwards of 2000 bar fuel pressure which can result in tremendous loading on internal components, placing even further demands on the fuel to protect fuel system hardware. Fuel viscosity effects can dramatically alter internal leakage and filling rates and change the overall efficiency of the fuel injection system, potentially impacting engine out performance. With the large in-flux of HPCR technology into the diesel engine market, many questions have arisen on whether modern HPCR systems will maintain adequate performance and durability using current and future (synthetic based) military fuels.

2.0 OBJECTIVE & APPROACH

The purpose of this project was to evaluate the performance and durability of a modern HPCR fuel system when using diesel and military fuels in a fired engine endurance test. Evaluation of engine and fuel systems performance and durability included: fuel and fuel system hardware interactions, engine performance changes, engine out emissions changes, and engine idle noise evaluations. The Ford Motor Company 6.7L “Scorpion” Powerstroke diesel engine was chosen as a representative modern diesel engine utilizing the latest HPCR fuel injection technology. The Ford 6.7L engine is currently an all new design entering the diesel engine market, and was expected to be the best representation of a modern HPCR fuel injection system. In addition, the Ford 6.7L engine is expected to be equipped in upcoming U.S. Air Force flight line equipment. Engine fuel system testing was completed by operating the engine on a modified version of the

U.S. Army 210hr Tactical Wheeled Vehicle (TWV) engine endurance cycle. The Tactical Wheeled Vehicle Cycle (TWVC) was developed by the military to evaluate fuel and lubricant performance and compatibility with military hardware. To fully ascertain the impact of varying fuel properties on HPCR fuel systems, a matrix of four different fuels were evaluated. These included: a baseline Ultra-Low Sulfur Diesel (ULSD), JP-8, 50/50% volumetric blend of JP-8 and Synthetic Paraffinic Kerosene (SPK), and 100% SPK. Each tested fuel completed an engine run-in routine, the 210hr test duration, and pre and post-test engine powercurve evaluations at ambient (nominally 95°F) and desert-like (nominally 120°F) inlet fuel temperatures. Engine out emissions were sampled and recorded during powercurve testing to document emissions changes between each fuel, and to determine if any engine operation changes were experienced over the test duration. After testing for each fuel was completed, fuel system hardware components were removed from the engine and disassembled for an internal inspection. All components were compared between each test, and to a new un-used set of hardware to determine wear experienced by the use of each fuel.

2.1 TEST CYCLE

Fuel system evaluations were completed following a modified version of the 210hr Tactical Wheeled Vehicle Cycle (TWVC) [1]. Modifications were made to the test cycle to accelerate the testing schedule to compensate for delays incurred early in the program due to engine and hardware availability. The primary modification was the reduction of engine soak time from 10hrs to 3hrs, resulting in an increase of daily run time from 14hrs to 21hrs. This allowed for total days required for testing to be reduced by 5 days. The original soak period included into the TWVC was primarily used for lubricant evaluations, to allow time for chemical reactions to take place in the oil sump. This results in an acceleration of lubricant degradation and helps determine an oil's overall endurance. As this adds no benefit for fuels compatibility testing, it was reduced to decrease the time required to complete each test. Table 1 below outlines the arrangement of daily engine operating conditions. Slight increases in duration for the rated speed and load steps for the first 6 daily cycles were made to keep the proportion of total rated to idle hours on the accelerated test cycle consistent with the standard 210hr TWVC procedure.

Table 1 - Modified 210hr Tactical Wheeled Vehicle Cycle Description

Cycle	Duration	Description
1	2hr 10min	Rated Speed & Load
	1hr	Idle
2	2hr 10min	Rated Speed & Load
	1hr	Idle
3	2hr 10min	Rated Speed & Load
	1hr	Idle
4	2hr 10min	Rated Speed & Load
	1hr	Idle
5	2hr 10min	Rated Speed & Load
	1hr	Idle
6	2hr 10min	Rated Speed & Load
	1hr	Idle
7	2hr	Rated Speed & Load
Soak	3hr	Engine Off

Throughout testing, critical engine parameters were monitored and controlled to engine manufacturer's recommendations and test procedure specifications. Primary specifications adopted from Ford for testing were the desired temperatures for the primary engine coolant loop and secondary auxiliary coolant loop. These temperatures (seen below in Table 2) were maintained to ensure engine integrity over the test duration, and proper charge air cooler operation. Precise control of these critical parameters allowed for an increase in test consistency, and reduced any potential influence from outside variables.

Table 2 - Test Cycle Operation Parameters

Parameter	Units	Rated Speed	Idle
Engine Speed	rpm	2800 +/- 25	NC
High Temp Coolant Loop	°F	203 +/- 3	NC
Low Temp Coolant Loop	°F	100 +/- 3	NC
Oil Sump	°F	NC	NC
*NC = not controlled			

(Note – Engine idle speed was controlled by PCM at approximately 600 RPM with 0% actuation of the engine throttle pedal. Temperature controllers for engine coolant remained at rated speed set points for idle conditions, but were not met due to lack of heat generation in the system. Due to this, temperatures were allowed to reach their natural steady state values during idle testing steps. Engine oil cooler plumbing was factory integrated to the engine water jacket, thus not directly controlled for both rated and idle segments during testing. Oil temperatures were allowed to meet their own steady state temperature based on water jacket temperature and engine load/speed throughout testing.)

The following list outlines the general test stand set-up in regards to the engine installation, and ancillary equipment used during testing.

- The engine was fully instrumented to monitor various engine parameters, temperatures, and pressures throughout testing. An SwRI developed data acquisition and controls system (PRISM) was used to display and log real time engine data during testing.
- Engine speed was controlled by an absorption eddy current dynamometer. Engine load was controlled using a PRISM controller and actuator to manipulate the drive-by-wire throttle pedal attached to the engine's dyno harness.
- Coolant temperature (engine water jacket and secondary coolant loop) was controlled by PRISM using the building supplied process water and appropriately sized heat exchangers in place of the engines' radiators.
- The engine was supplied with fuel by using a "day tank" at ambient temperature and pressure conditions. The day tank allows the engine to feed and return fuel as required during operation. Fuel in the day tank is kept at a constant level by a secondary fuel pump that replenishes the tank supply as necessary from bulk fuel storage. The make-up fuel flow rate into the day tank is the resulting fuel used by the engine, and is measured by a Micromotion Coriolis flowmeter and logged with PRISM as the engine fuel consumption rate.
- Fuel from the day tank was supplied to the engine's diesel fuel condition module (DFCM) at ambient temperature and pressure. The DFCM houses the primary fuel filter and low pressure lift pump for the engine. The DFCM also contains a temperature controlled recirculation device that re-routes engine return fuel to the engine supply until a desired fuel temperature is met. To not interfere with the DFCM operation, the inlet fuel to the DFCM was not conditioned in any way.
- Inlet air was drawn in at ambient conditions from the test cell through a radiator core into the engine air box. The radiator core is supplied building process water to prevent extreme heat buildup in the test cell from elevating inlet air temperatures.
- Engine exhaust is drawn from the engine by the buildings exhaust handling system and discharged outside to the atmosphere. A butterfly valve was used to regulate engine exhaust backpressure to the Ford recommended 11psi specification.

- Emissions were directly sampled from an exhaust probe installed between the engine and exhaust system backpressure valve. Emissions were measured using a Horiba MEXA-1600D Motor Exhaust Gas Analyzer. Exhaust sample handling was carried out by the Horiba systems heated filter and line routed into the emission bench sample conditioning unit.
- Crankcase blowby gasses were recirculated into the turbo compressor inlet via the factory blowby control devices.
- The engine was lubricated with a commercially available full synthetic CJ-4 SAE 5W40 engine oil per Ford specifications for heavy duty applications.MIL-PRF-2104 lubricants were not utilized as it was expected there would not be any impact on fuel injection system hardware durability or wear due to the engine lubricant. It is assumed any anticipated use of MIL-PRF-2140 lubricants in the Ford 6.7L would not alter the substantive fuel lubricity impact results on the fuel injection system components determined in this study.
- Used oil samples were collected from the engine daily to monitor engine and oil condition, and to determine oil change intervals needed during testing.

2.2 TEST ENGINE

The Ford 6.7L engine is a V8, direct injected, turbo-charged, air-to-water intercooled engine, employing a fuel lubricated high pressure common rail injection pump, and piezo-electric fuel injectors. The 6.7L engine used for testing was produced by Ford as an “export” version, intended for sale outside of U.S. borders or for non-emissions regulated military applications. In the export configuration, the engine does not come equipped with exhaust aftertreatment or Exhaust Gas Recirculation (EGR) systems. The 6.7L export engine tested is rated at approximately 320hp (238kW) at 2800rpm, and produces approximately 700 lb*ft (950 Nm) of torque at 1800rpm when using diesel fuel. Figure 1 on the following page shows the 6.7L test installation.

Figure 1 - Ford 6.7L Test Engine Installation

2.3 FUEL SYSTEM DESCRIPTION

The fuel injection system on the Ford 6.7L engine utilizes a fuel lubricated high pressure pump supplying two pressure controlled fuel rails and 8 piezo-electric actuated fuel injectors. The FIP is mounted at the front of the engine valley and gear driven at 1:1 engine speed. The FIP is a two piston design and utilizes a two lobe cam providing four pulses per engine/pump revolution. Fuel management is controlled via the Powertrain Control Module (PCM) through the use of a FIP mounted Volume Control Valve (VCV), and a fuel rail mounted Pressure Control Valve (PCV). The engine primarily operates in what Ford refers to as a VCV mode, in which the VCV regulates the amount of fuel entering the high pressure portion of the FIP based on engine demands. The PCM uses the PCV to regulate total fuel rail pressure and adjust quickly as engine demands change. This operation arrangement is primarily utilized to increase the efficiency of the fuel injection system, as only the fuel required for engine operation is compressed by the pump, and to give the PCM the ability to quickly adapt to changing engine conditions. Figure 2 shows the fuel injection pump, fuel rail, and fuel injector used by the 6.7L engine.

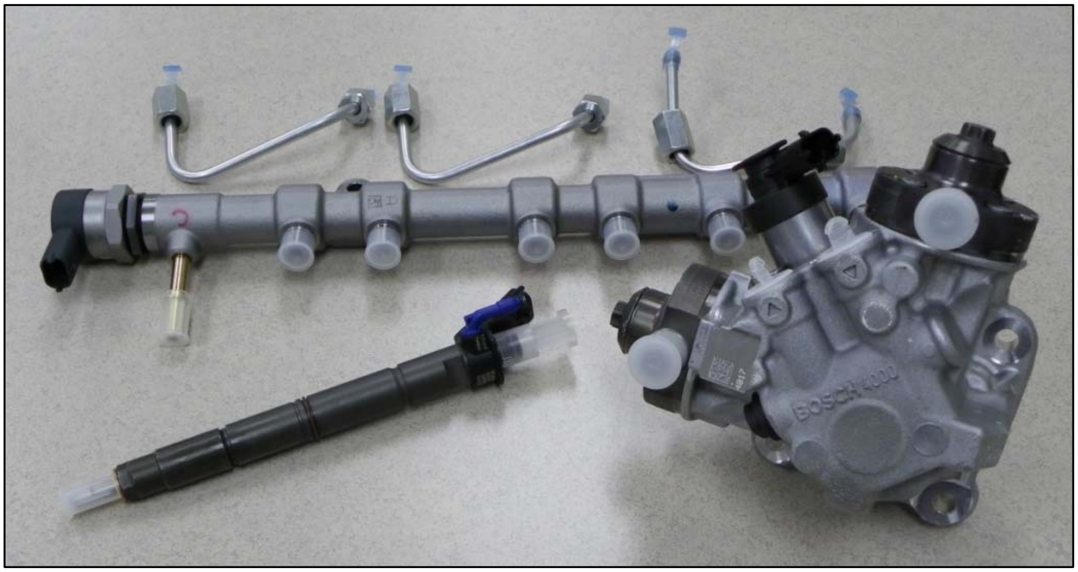


Figure 2 - Ford 6.7L Fuel Injection Pump, Rail, & Injector

The high pressure portion of the FIP consists of a plunger and barrel assembly that is actuated by a roller follower driven from the FIP camshaft. Regulated fuel from the VCV is drawn into the barrel on the downward stroke, and then compressed to the specified rail pressure upon plunger ascent. High pressure fuel exits the barrel through a spring loaded check ball into high pressure fuel lines that supply each fuel rail.

Figure 3 on the following page shows the orientation of high pressure pumping assembly. Critical wear points for these components can include: roller and shoe surface wear, scuffing on the follower and follower bore surfaces, plunger and barrel surface wear and scuffing, wear between high pressure plunger head and shoe assembly, as well as fuel check valve and seat wear.

Figure 3 - Camshaft Follower & High Pressure Plunger & Barrel Assembly

The fuel injector utilized by the 6.7L engine is a piezo-electric actuated fuel injector to directly inject fuel into the combustion chamber. In this application, the fuel injector couples the piezo-stack against one piston (upper) of an internal hydraulic coupler (Figure 5) filled with fuel from the low pressure lift pump portion of the fuel system. The hydraulic coupler translates the small linear movement of the piezo-stack to a larger movement by the difference in piston diameters within the hydraulic coupler. The second piston (lower) of the hydraulic coupler acts against the injector control valve (Figure 6) which regulates the pressure on the top of the injector needle thus controlling needle lift. When the control valve is forced down, the high pressure fuel passage is blocked from the upper portion of the injector needle causing a pressure imbalance. The high pressure fuel acting on the lower surface of the needle then causes needle lift and fuel is injected into the combustion chamber. Figure 4 below shows a parts break-out of an entire disassembled fuel injector. Figure 5 and Figure 6 show larger views of the hydraulic coupler and control valve assemblies. Critical wear points for these components can include:

control valve and seat wear, wear and scuffing on needle surface from guide, needle seat wear, wear and scuffing on the hydraulic coupler pistons, and deposit formation on nozzle.

Figure 4 - Fuel Injector Component Break-Out

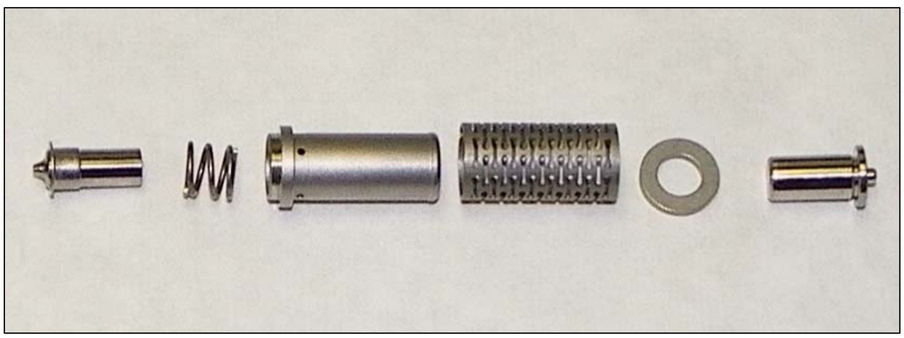


Figure 5 - Fuel Injector Hydraulic Coupler

Figure 6 - Fuel Injector Control Valve Assembly

2.4 TEST FUEL PROPERTIES

The baseline diesel (ULSD) test was intended to provide a "known good" reference to compare overall performance and post-test fuel system wear to the tested military and synthetic fuels, while the JP-8 fuel was intended to be representative of fuels currently fielded and used by the U.S. Military in all tactical and combat ground vehicles. The ULSD utilized during testing was a certification fuel purchased from a commercial supplier. The JP-8 used during the JP-8 and 50/50 testing was blended at location from commercially available Jet-A. JP-8 is normally made by blending military additives into Jet A-1, a lower freeze point specification than Jet A. The Jet A used for this testing would also have met the Jet A-1 specification because the freeze point specification was met. The SPK fuel used for testing was supplied by the test sponsors. As received, both the Jet-A and SPK fuels were considered neat, or containing no additives. Due to this, additization was required prior to testing to meet acceptable standards. Since testing was primarily focused on fuel lubricity related issues, only lubricity enhancer/corrosion inhibitor additive was added to the Jet-A and SPK fuels. The remaining two additives typically found in JP-8 fuels (anti-static and anti-icing) have little impact on the test objectives of this program. The lubricity enhancer used for blending was Innospec Fuel Specialties DCI-4A. Per QPL-25017, the minimum effective treat rate of DCI-4A required an additive concentration level of 9ppm in the final fuel blend. This minimum effective treat rate is determined through procedures outlined in MIL-PRF-25017H. In an effort to determine fuel system impact in a "worst case" scenario, the test fuel was treated only at the 9ppm minimum effective treat rate. After blending, a 1-gallon fuel sample was pulled from each bulk tank to analyze and document the fuels chemical and physical properties. Table 3 shows the fuel analysis results for each fuel tested.

Table 3 - Test Fuel Chemical & Physical Analysis

Property	Units	Method	Results			
			ULSD	JP-8	50/50	SPK
Density @15°C	g/mL	D4052	0.858	0.802	0.769	0.736
Specific Gravity @15°C		D4052	0.859	0.803	0.770	0.737
API Gravity @15°C		D4052	33.3	44.8	52.3	60.6
Flashpoint	°F	D56	154	127	115	111
	°C	D93	70	51	46	43
	°F	D3828	158	126	112	109
Kinematic Viscosity @-20°C	cSt	D445	24.9	3.6	3.0	2.5
Kinematic Viscosity @40°C	cSt	D445	3.0	1.2	1.0	0.9
Hydrocarbon Content						
Carbon	wt%	D5291	86.96	86.05	84.76	83.94
Hydrogen	wt%		13.02	13.80	14.44	16.46
Calculated Cetane Index		D976	45.3	37.6	46.3	57.2
Calculated Cetane Index		D4737	44.3	39.7	51.2	66.8
Cetane Number		D613	47.2	42.2	53.7	64.0
IQT	DCN	D6890	42.8	40.1	49.0	58.5
Heat of Combustion (Gross)	BTU/lb	D240	19469.1	19768.8	20038.1	20364.4
Total Acid Number	mg KOH/g	D3242	0.007	0.005	0.015	0.011
Hydrocarbon Type						
Aromatics	%mass	D5186	28.5	19.1	10.0	0.3
Hydrocarbon Type						
Aromatics	%vol	D1319	29.0	16.2	8.0	0.4
Olefins			4.0	1.4	1.0	0.5
Saturates			67.0	82.4	91.0	99.1
Sulfur	ppm	D5453	<10	<10	<10	<10
Nitrogen	wt%	D3228	<0.030	<0.030	<0.030	<0.030
HFRR	mm	D6079	0.444	0.675	0.695	0.840
BOCLE	mm	D5001	0.46	0.69	0.72	0.76
Bulk Modulus @30°C	psi	by Speed of Sound	223924	183851	167527	152749
Distillation						
IBP	°C	D86	194.2	140.3	136.0	152.5
10%			217.7	174.4	165.8	161.5
20%			233.9	177.4	167.7	162.7
50%			271.9	186.7	176.1	168.8
90%			326.8	216.0	202.4	186.0
End Pt			348.1	238.9	228.0	203.0

3.0 DISCUSSION & RESULTS

The following sections discuss the results found during testing. Results are broken down into the following subgroups: Overall Test Performance, Pre & Post-Test Powercurves and Emissions, Engine Noise Evaluations, and Post-Test Fuel Injection Hardware Inspection. Full detailed results for each individual test can be seen in the individual test reports attached as appendices to this report.

3.1 OVERALL TEST PERFORMANCE

All four test fuels completed the 210hr test cycle with satisfactory performance. No fuel related hardware failures or unusual operating conditions were experienced in any of the individual tests. Table 4 below lists the average values of various engine operating parameters over the full load rated speed test segments for the entire test matrix of fuels. This shows the consistency achieved between each tested fuel. Full load power variation for the JP-8 and SPK fuels remained below 5% deviation from the baseline ULSD test. This demonstrates that the engine remained in good condition throughout each test and did not experience any degradation that could potentially bias results.

Table 4 - Rated Segment Engine Operating Summary (Full Matrix)

Perameter:	Units:	ULSD Average	JP-8 Average	50/50 JP-8/SPK Average	SPK Average
Engine Speed	RPM	2800.02	2799.98	2800.01	2799.99
Torque*	ft*lb	601.86	594.10	575.37	580.89
Fuel Flow	lb/hr	131.83	128.67	124.81	122.65
Power*	bhp	320.87	316.73	306.75	309.69
BSFC*	lb/bhp*hr	0.411	0.406	0.407	0.396
Temperatures:					
High Temperature Loop Coolant In	°F	185.08	185.44	184.91	185.34
High Temperature Loop Coolant Out	°F	203.00	203.00	203.00	203.00
Low Temperature Loop Coolant In	°F	100.02	100.06	100.01	100.10
Low Temperature Loop Coolant Out	°F	125.70	123.34	121.40	124.28
Oil Sump	°F	239.55	243.66	246.24	247.30
Fuel In	°F	89.47	84.69	90.90	92.89
Fuel Pump Drain	°F	106.44	101.92	107.78	109.22
Fuel Return	°F	101.97	99.95	101.39	102.37
Intake Air Before Compressor	°F	75.55	75.38	76.39	77.56
Intake Air After Compressor	°F	350.14	334.08	326.45	333.16
Intake Air After Charge Cooler	°F	109.44	106.88	105.68	107.01
Cylinder 1 Exhaust	°F	1416.98	1423.18	1470.48	1390.12
Cylinder 2 Exhaust	°F	1364.12	1370.15	1416.01	1323.56
Cylinder 3 Exhaust	°F	1387.31	1401.47	1429.61	1353.50
Cylinder 4 Exhaust	°F	1368.84	1388.66	1424.16	1356.49
Cylinder 5 Exhaust	°F	1394.05	1406.34	1451.84	1352.27
Cylinder 6 Exhaust	°F	1414.47	1436.30	1491.75	1388.84
Cylinder 7 Exhaust	°F	1401.15	1409.89	1464.71	1346.72
Cylinder 8 Exhaust	°F	1394.43	1402.12	1467.54	1354.35
Exhaust, Left Manifold Exit	°F	**	**	**	1326.09
Exhaust, Right Manifold Exit	°F	**	**	**	1345.11
Exhaust After Turbo	°F	1156.47	1179.12	**	1117.57
Pressures:					
Oil Galley	psi	56.08	54.93	54.61	52.91
Ambient Pressure	psiA	14.34	14.37	14.26	14.23
Intake Restriction	psi	0.53	0.51	0.41	0.48
Exhaust Restriction	psi	10.71	10.52	10.29	10.71
Boost Pressure	psi	20.30	18.73	16.76	19.41
Fuel Rail Pressure	psi	19345.69	19399.39	19381.76	19406.54

* Non-corrected Values

Used oil samples were sampled daily for analysis to determine oil change intervals and to provide an indicator of engine condition that could be easily compared across all four tests. No unusual wear metal accumulations were noted during any of the tests. Iron (Fe) accumulation rates changed from the first test to the following three, consistent with what would be expected during engine break-in. No other significant accumulations of typical wear metals were noted. Figure 7 shows four typical engine wear metal accumulations over the life of the engine and test program. This supports that no adverse engine degradation was experienced that could potentially bias test results.

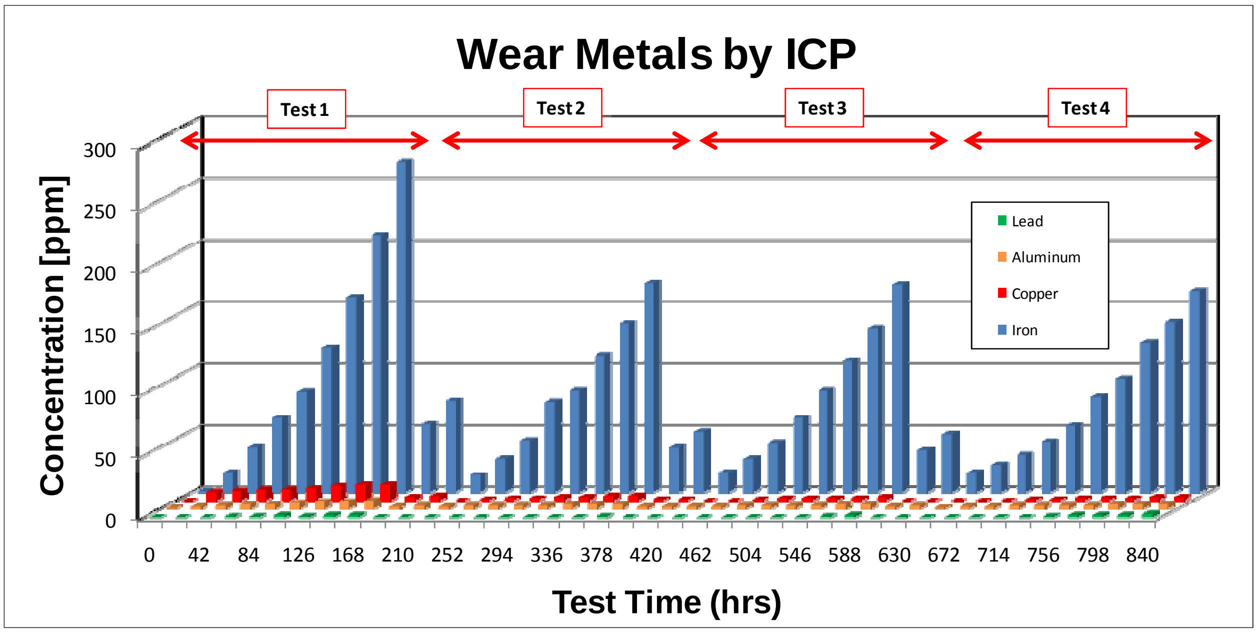


Figure 7 - Accumulated Wear Metals Over 840hr Engine Testing Duration

3.2 PRE & POST-TEST ENGINE POWERCURVES & EMISSIONS

Pre-test and post-test engine powercurves were completed at 95°F and 120°F fuel inlet temperatures for each individual fuel tested. This was done to monitor fuel effects on engine power degradation, and to document changes in engine out emissions between each test. Engine degradation experienced during testing could be attributed to overall engine wear, or negative fuel injection system impacts from the tested fuels.

Unfortunately, during the ULSD, JP-8, and 50/50 test, the 6.7L engine experienced a steady decrease in engine boost pressure resulting in a loss of engine power output across each test duration. This was noted in the pre and post-test powercurves for each of the first three tests. During investigation into these trends, no other causes were identified for the documented power loss. Engine power spot checks were completed using ULSD at the completion of testing on both post-test hardware and newly installed hardware to determine if the fuel system components had experienced wear during testing resulting in the engines performance change or variation. These spot checks did not yield any significant change in engine output between the used and new fuel system hardware, thus ruling out fuel system degradation as a possible cause. At the completion of the 50/50 test, engine output had decreased to more than 5% below new engine output, and it was determined that a replacement turbocharger assembly be installed to avoid any further engine boost degradation or PCM commanded engine de-rates due to insufficient boost pressure. After installation of the replacement turbocharger assembly, the engine power output returned within approximately 1% of new engine output and testing continued. Despite this steady loss in power over the first three tests, engine fuel consumption rates remained consistent across each test, thus not invalidating the overall test goals. As a consequence of the consistent fueling coupled with the reduction in mass air flow through the engine, the measured Air Fuel Ratio (AFR) gradually enriched throughout the effected tests and could be seen as an increase in exhaust port temperatures throughout each of the first three tests. As expected, the AFR of the final test was corrected with the replacement turbocharger assembly, and exhaust port temperatures returned back to expected values, further supporting the turbocharger as culprit of the engine power degradation.

3.2.1 Engine Powercurves

Composite full load engine pre and post-test powercurves can be seen below for each fuel. Regardless of fuel type, all high fuel inlet test powercurves produced higher engine output than their ambient temperature counterparts. This is attributable to the viscosity effect of the fuel on the 6.7L common rail fuel injection system. Given a common fuel rail supply maintained at a constant pressure and a fixed on-time (open time) of an injector, a lower viscosity fluid can have a higher volumetric flowrate resulting in a increase of injected fuel (i.e., energy increase) yielding a higher engine output. Thus, when tested under high temperature conditions, engine output was increased over ambient temperature conditions for each of the individual powercurves. In addition, this phenomenon also explains the ability of the JP-8 (and other lower viscosity fuels) to achieve similar power ratings as produced by ULSD despite their reduced volumetric energy content. Table 5 shows calculations between ULSD and JP-8 showing the engines change in volumetric consumption, and the energy adjustment based off of the fuels density. From this chart we can see that the actual reduction in energy consumed correlates to the difference in engine output power production.

Table 5 – Engine Output Power Comparison

	units	**ULSD**	**JP8**
Max Power	bhp	320.87	316.73
Fuel Flow @ Max Power	lb/hr	131.83	128.67
Density	g/mL	0.858	0.802
Viscosity	cSt	3.0	1.2
Heat of Combustion	BTU/lb	19469.1	19768.8
		Calculations	
Volumetric Flow	gal/hr	18.16	18.96
Volumetric Energy	BTU/gal	141345.7	134154.1
Energy Consumed	BTU/hr	2566648.2	2543698.8
Energy Consumed	BTU/hr	2566648.2	2543698.8
Percent Reduction in Energy Consumption from ULSD			0.89%
Percent Reduction in Max Power from ULSD			1.29%

Test 1 – Diesel

Figure 8 below shows the pre and post-test full load powercurve testing for ULSD. The engine experienced a respective 1.8% and 1.9% power loss over the test duration at ambient and elevated fuel inlet temperatures.

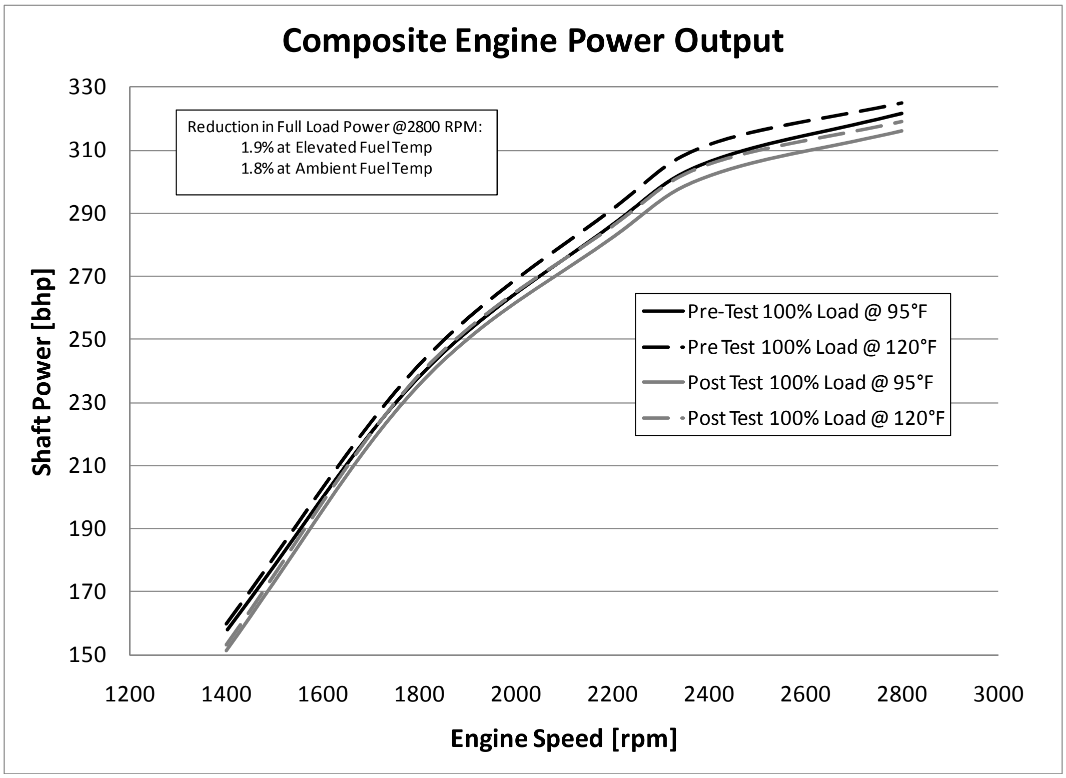


Figure 8 - Ford 6.7L, ULSD, Pre & Post-Test Full Load Powercurve

Test 2 – JP-8

Figure 9 below shows the pre and post-test full load powercurve testing for JP-8. The engine experienced a respective 2.8% and 3.0% power loss over the test duration at ambient and elevated fuel inlet temperatures.

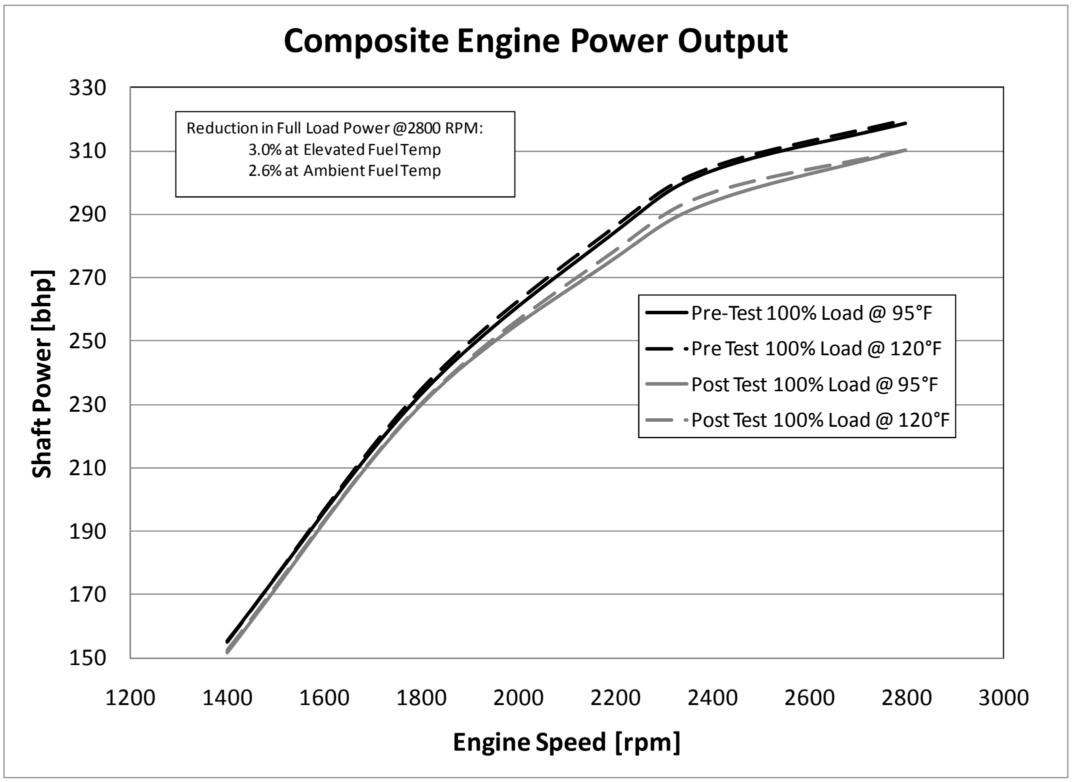


Figure 9 - Ford 6.7L, JP-8, Pre & Post-Test Full Load Powercurve

Test 3 – 50/50% JP-8/SPK

Figure 10 below shows the pre and post-test full load powercurve testing for 50/50 JP-8/SPK. The engine experienced a respective 2.2% and 1.7% power loss over the test duration at ambient and elevated fuel inlet temperatures.

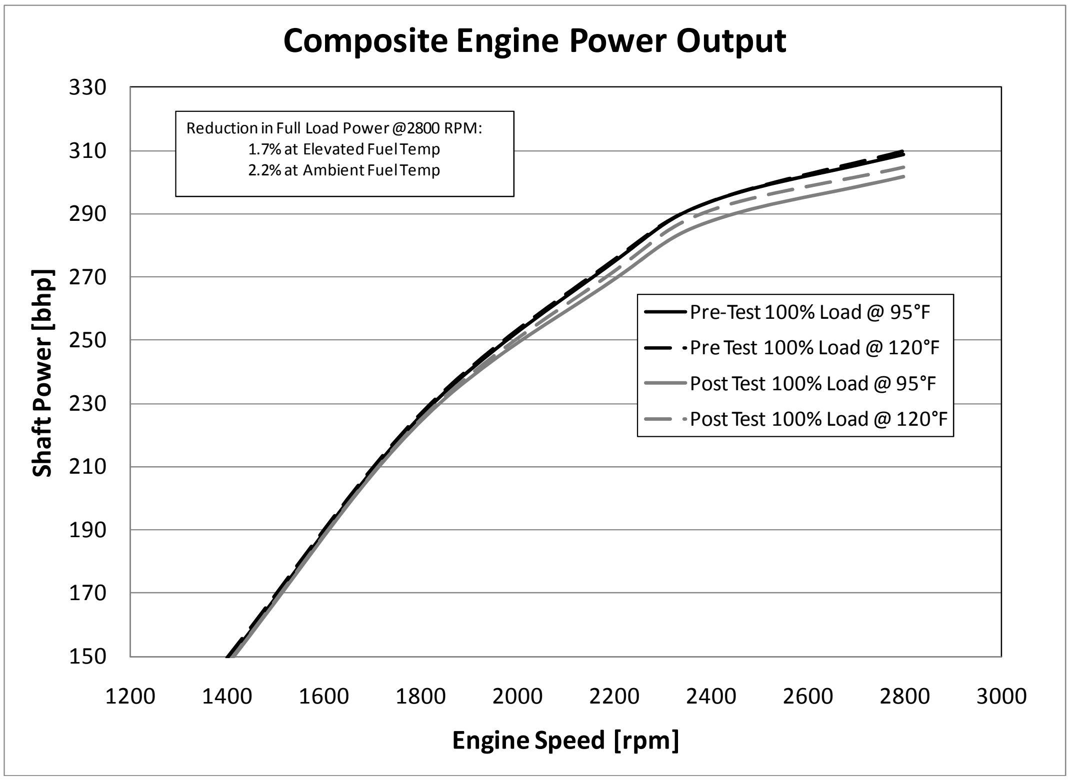


Figure 10 - Ford 6.7L, 50/50 JP-8/SPK, Pre & Post-Test Full Load Powercurve

Test 4 – 100% SPK

Figure 11 below shows the pre and post-test full load powercurve testing for SPK. The engine experienced a respective 1.2% and 1.4% power loss over the test duration at ambient and elevated fuel inlet temperatures.

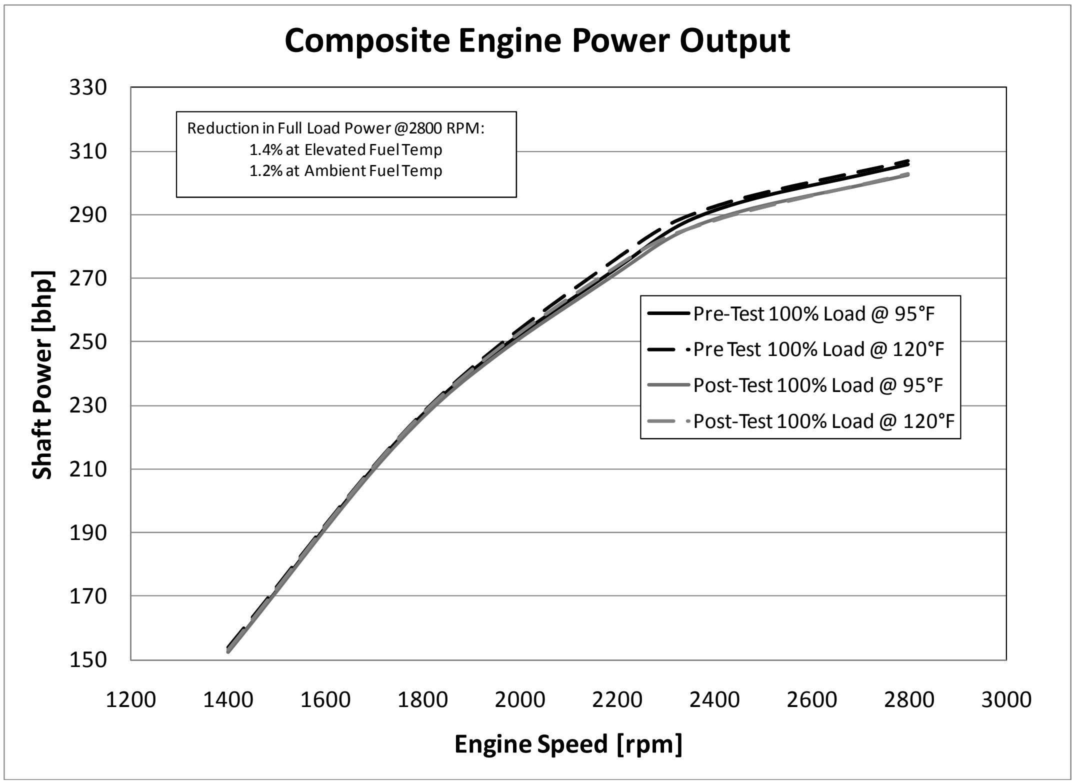


Figure 11 - Ford 6.7L, SPK, Pre & Post-Test Full Load Powercurve

3.2.2 Engine Out Emissions

The engine out exhaust emissions for the Ford 6.7L engine were measured as raw emissions downstream of the turbocharger outlet. The emissions instrumentation was a Horiba MEXA-1600D Motor Exhaust Gas Analyzer measurement system calibrated for detecting unburned hydrocarbon (HC), carbon monoxide (CO), carbon dioxide, oxygen, and oxides of nitrogen (NOx) species in the exhaust. The raw emission measurements were converted to a brake specific mass emission basis utilizing the procedures outlined in CFR 40, Part 86, and Sub-part D. Due to subtle differences in fuel consumption and engine load between the four tests fuels the brake specific mass emissions were converted to an Emission Index value. The

Emission Index is calculated by dividing the brake specific mass emissions by the brake specific mass fuel consumption, resulting in a value reflecting the mass of emission generated per mass of fuel burned. Except for the ULSD fuel, emissions presented are the average of the regulated emission species (HC, CO, NOx) measured pre and post of the 210-hr test.

Test 1 – Diesel

Due to an emission bench calibration gas availability early in the program, the pre-test emission measurements were not made in order meet the test scheduling with the engine. ULSD data shown in this report is only for the emission measurements made following the 210-hr durability test. Subsequent testing with the other test fuels indicated very little deviation between pre-test and post-test emission measurements, suggesting a good comparison can be made with only the ULSD post-test emission results. Figure 12 shows the HC Emissions Index (HCEI), grams HC/lb fuel, for ULSD over the performance matrices performed at two fuel temperatures. The 25% load points show higher HC, even though the Air/Fuel Ratio (AFR) is lean, likely due to lower in-cylinder temperatures. The 50% and 75% load points show similar HCEI response. At all engine loads the HCEI increases with increasing engine speed, due to shorter time available for combustion to go to completion. The HCEI impact of the ULSD fuels higher density and viscosity, and lower volatility is seen at full load, rich AFR, and high engine speeds.

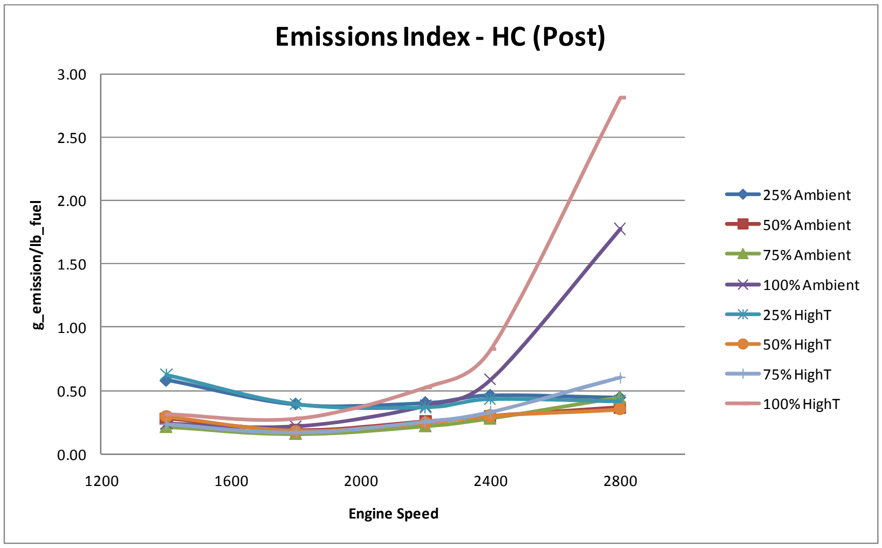


Figure 12 - Ford 6.7L, ULSD, Post-Test HC Emissions

Figure 13 shows the CO Emissions Index (COEI), grams CO/lb fuel, for ULSD over the performance matrices performed at two fuel temperatures. The 25% load points reveal significantly higher CO due to lower in-cylinder temperatures, and incomplete combustion at lean Air/Fuel Ratios. The 50%, 75%, and 100% load points show similar COEI results at the two lowest engine speeds, but at higher engine speeds the 50% load points exhibit more incomplete combustion. The 75% and 100% load points have very similar COEI response. At all engine loads the COEI increases with increasing engine speed, due to shorter time available for combustion to go to completion.

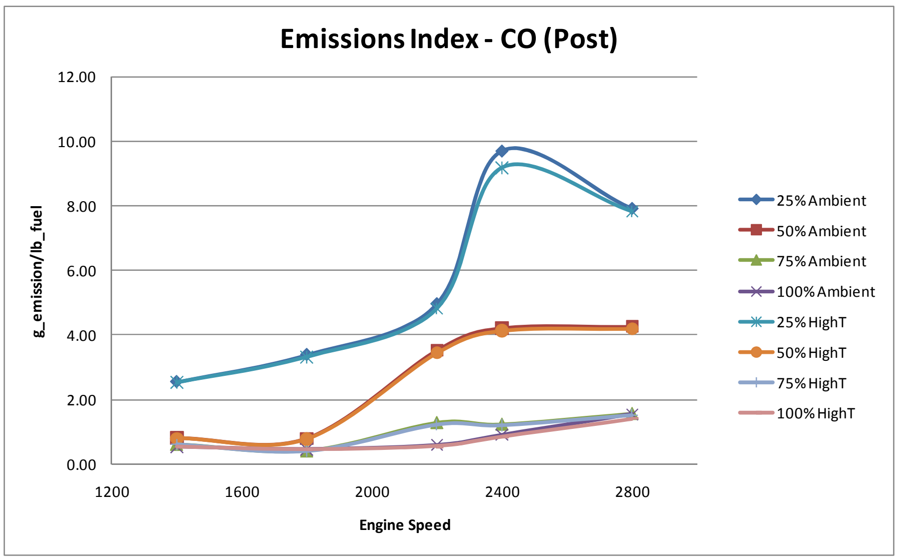


Figure 13 - Ford 6.7L, ULSD, Post-Test CO Emissions

Figure 14 shows the NOx Emissions Index (NOxEI), grams NOx/lb fuel, for ULSD over the performance matrices performed at two fuel temperatures. The 25% and 50% load points show the highest NOxEI, suggesting a greater portion of premixed burning during the heat release event. The 6.7L engine uses pilot fuel injection to control NOx and noise, the pilot parameters (timing and relative injection quantity) at the lower loads likely result in a slightly greater ratio of premixed to diffusion combustion. As the engine load increases, the pilot fuel injection parameters are relatively more effective in rate-shaping the combustion event, and the relative amount of NOx formed decreases. The decrease of NOxEI with increasing engine speed may be attributed to less premixed fuel from less physical time available for evaporation and mixing during the ignition delay period.

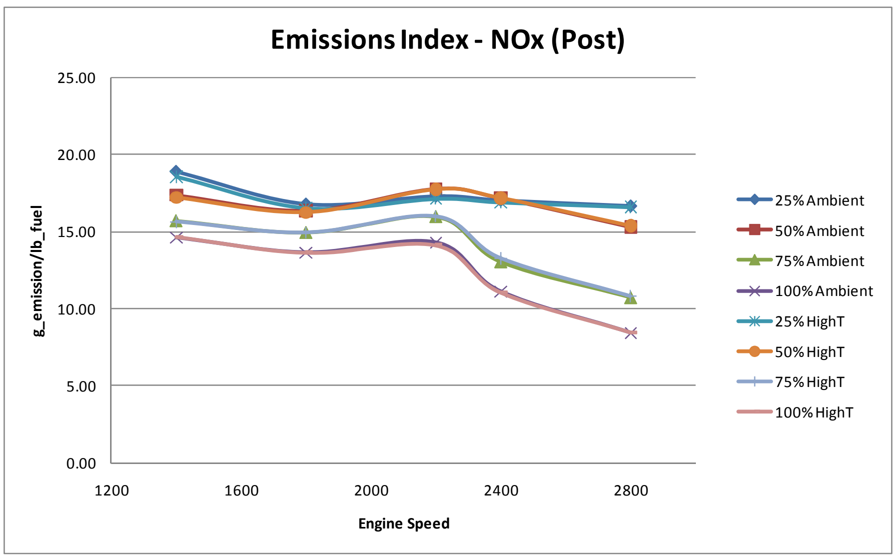


Figure 14 - Ford 6.7L, ULSD, Post-Test NOx Emissions

Test 2 – JP-8

Data shown from the JP-8 tests are the average of the emission measurements made prior-to and after the 210-hr durability test. There was a slight deviation between pre-test and post-test emission measurements, suggesting both the engine and fuel system integrity did not vary due to the durability cycle. Figure 15 shows the HC Emissions Index (HCEI), grams HC/lb fuel, for JP-8 over the performance matrices performed at the two fuel temperatures. As with ULSD, the 25% load points on JP-8 show slightly higher HC, even though the Air/Fuel Ratio (AFR) is lean, due to lower in-cylinder temperatures. The 50%, 75%, and 100% load points show similar HCEI response at the three lowest engine speeds. At the highest engine speeds and richest AFR (100% load), the HCEI increases dramatically. The full load HCEI for JP-8 increases, but is lower than with the ULSD fuel, likely due to better fuel/air mixing with JP-8 from its lower viscosity and higher volatility. At all engine loads, the HCEI increases with increasing engine speed due to shorter time available for combustion.

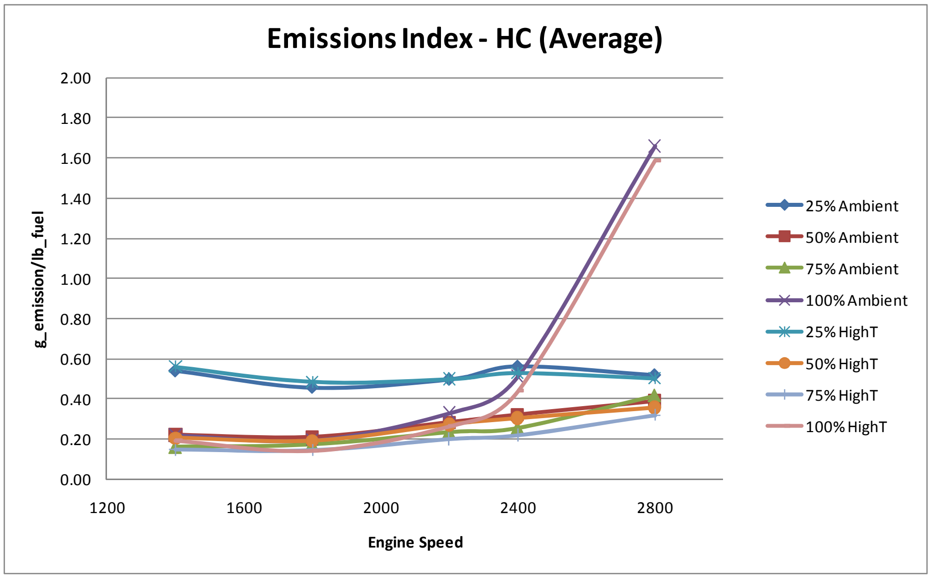


Figure 15 - Ford 6.7L, JP-8, Average Pre & Post-Test HC Emissions

Figure 16 shows the CO Emissions Index (COEI), grams CO/lb fuel, for JP-8 over the performance matrices performed at two fuel temperatures. The 25% load points reveal significantly higher CO due to lower in-cylinder temperatures, and incomplete combustion at lean Air/Fuel Ratios. The 50%, 75%, and 100% load points show similar COEI results at the two lowest engine speeds, but at higher engine speeds the 50% load points exhibit more incomplete combustion. Overall COEI is lower with JP-8 than ULSD fuel at light loads. The 75% and 100% load points have very similar COEI response. At all engine loads the COEI increases with increasing engine speed due to shorter time available for combustion completion.

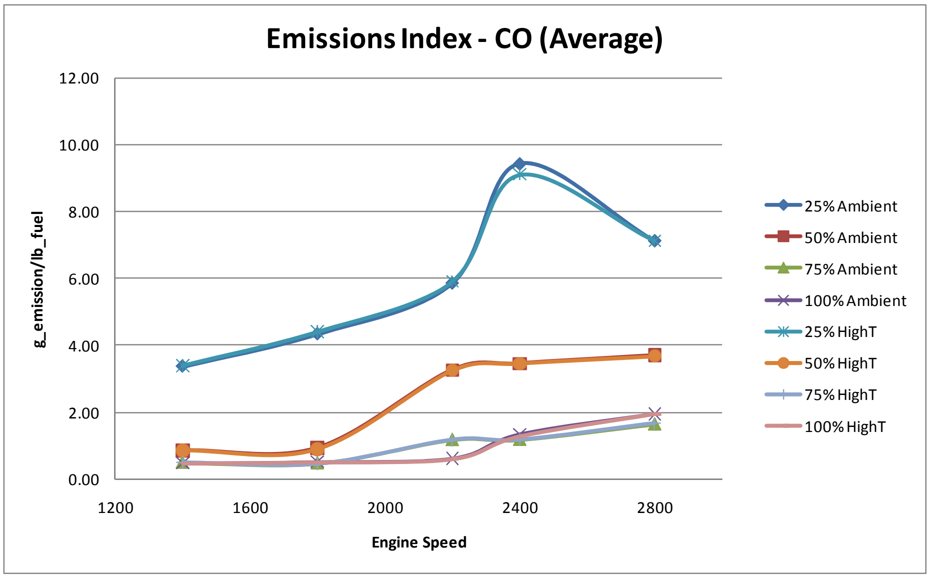


Figure 16 - Ford 6.7L, JP-8, Average Pre & Post-Test CO Emissions

Figure 17 shows the NOx Emissions Index (NOxEI), grams NOx/lb fuel, for JP-8 over the performance matrices performed at two fuel temperatures. The 25% and 50% load points show the highest NOxEI, suggesting a greater portion of premixed burning during the heat release event. The 6.7L engine uses pilot fuel injection to control NOx and noise, and the pilot parameters (timing and relative injection quantity) at the lower loads likely result in a larger fraction of premixed to diffusion combustion. It had been anticipated that the lower cetane number (CN) of JP-8 would result in more premixed fraction as a result of a longer ignition delay period, and produce more NOx. As the engine load increases the pilot fuel injection parameters are relatively more effective in rate-shaping the combustion event and the relative amount of NOx formed decreases. The decrease of NOxEI with increasing engine speed may be attributed to less premixed fuel from less physical time available for evaporation and mixing during the ignition delay period. With respect to ULSD the NOxEI with JP-8 is slightly lower overall.

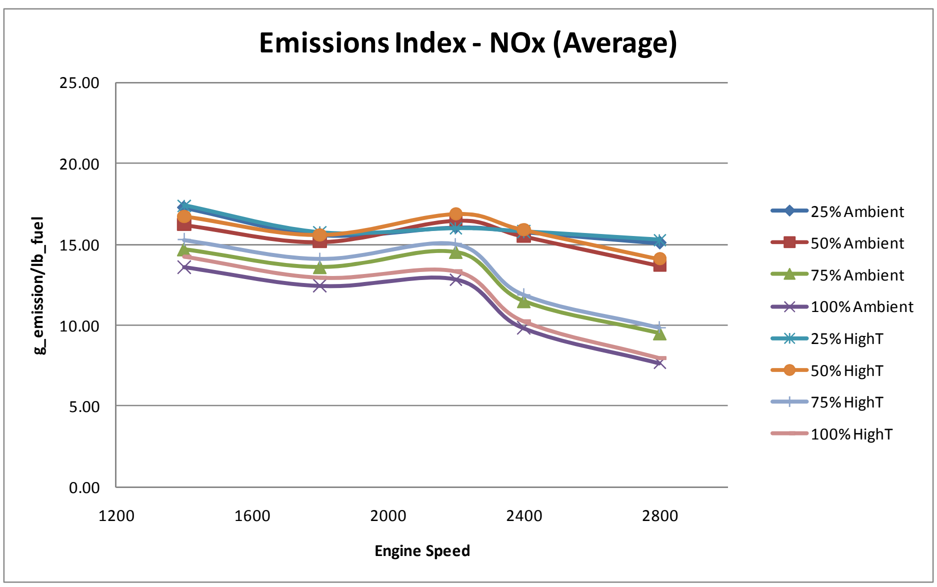


Figure 17 - Ford 6.7L, JP-8, Average Pre & Post-Test NOx Emissions

Test 3 – 50/50% JP-8/SPK

Data shown from the 50/50% JP-8/SPK blend is the average of the emission measurements made prior-to and after the 210-hr durability test. As seen during the JP-8 testing, there was little deviation between pre-test and post-test emission measurements suggesting that both the engine and fuel system integrity did not vary due to the durability cycle. Figure 18 shows the HC Emissions Index (HCEI), grams HC/lb fuel, for the blend over the performance matrices performed at the two fuel temperatures. As with the other fuels, the 25% load points on the JP-8/SPK blend show slightly higher HC at the lean Air/Fuel Ratio, due to lower in-cylinder temperatures. The HCEI at 50% load was slightly elevated on the JP-8/SPK blend with respect to the ULSD and JP-8 results. The 75% and 100% load points show similar HCEI response at the four lowest engine speeds. At the highest engine speed and richest AFR (100% load), the HCEI increases dramatically. The full load HCEI for the JP-8/SPK blend increases, but is lower than either the ULSD or JP-8 fuels. At all engine loads the HCEI increases with increasing engine speed, due to shorter time available for the combustion to complete.

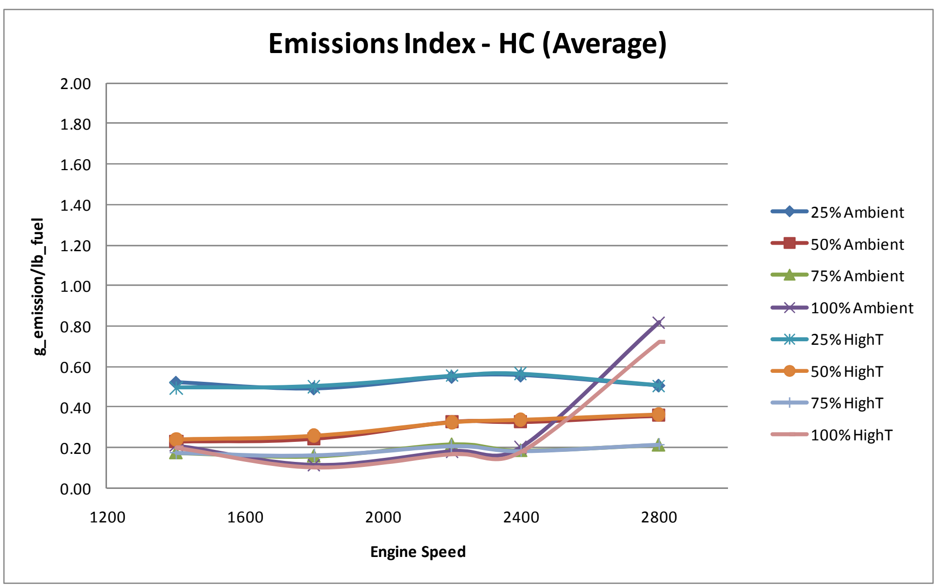


Figure 18 - Ford 6.7L, 50/50 JP-8/SPK, Average Pre & Post-Test HC Emissions

Figure 19 shows the CO Emissions Index (COEI), grams CO/lb fuel, for the JP-8/SPK blend over the performance matrices performed at two fuel temperatures. The 25% load points reveal significantly higher CO due to lower in-cylinder temperatures, and incomplete combustion at lean Air/Fuel Ratios. However, the COEI with the JP-8/SPK blend is lower than both ULSD and JP-8 at light loads. The 50%, 75%, and 100% load points show similar COEI results at the two lowest engine speeds, but at higher engine speeds the 50% load points exhibit more incomplete combustion. The 75% and 100% load points have very similar COEI response with the JP-8/SPK blend as seen during the ULSD and JP-8 test fuels. At all engine loads the COEI increases with increasing engine speed, due to shorter time available for combustion completion.

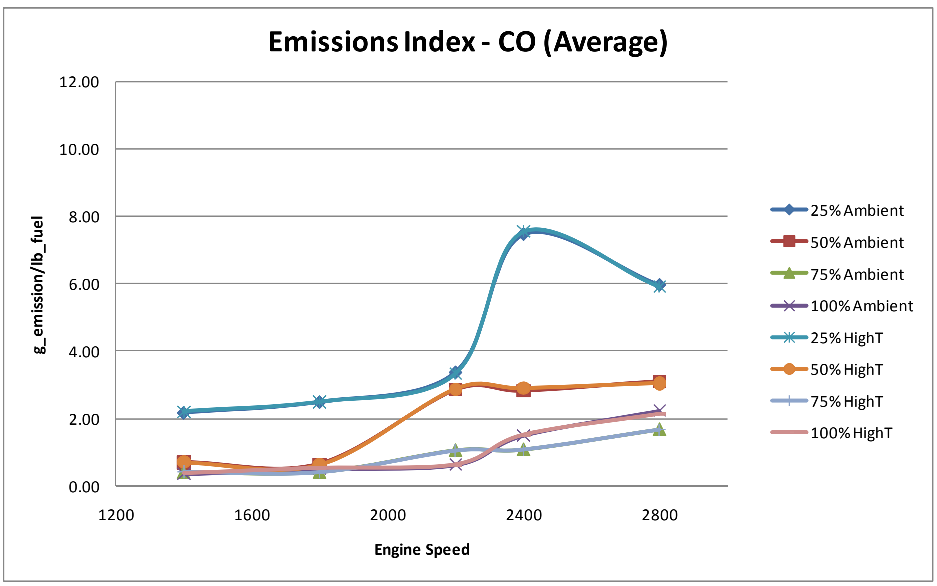


Figure 19 - Ford 6.7L, 50/50 JP-8/SPK, Average Pre & Post-Test CO Emissions

Figure 20 shows the NOx Emissions Index (NOxEI), grams NOx/lb fuel, for JP-8/SPK blend over the performance matrices performed at two fuel temperatures. The 25% and 50% load points show the highest NOxEI, suggesting a greater portion of premixed burning during the heat release event. As the engine load increases, the pilot fuel injection parameters are relatively more effective in rate-shaping the combustion event and the relative amount of NOx formed decreases. The decrease of NOxEI with increasing engine speed may be attributed to less premixed fuel from less physical time available for evaporation and mixing during the ignition delay period. The JP-8/SPK blends NOxEI responses is similar to JP-8, and overall lower than ULSD, likely due to better fuel/air mixing from viscosity and volatility effects.

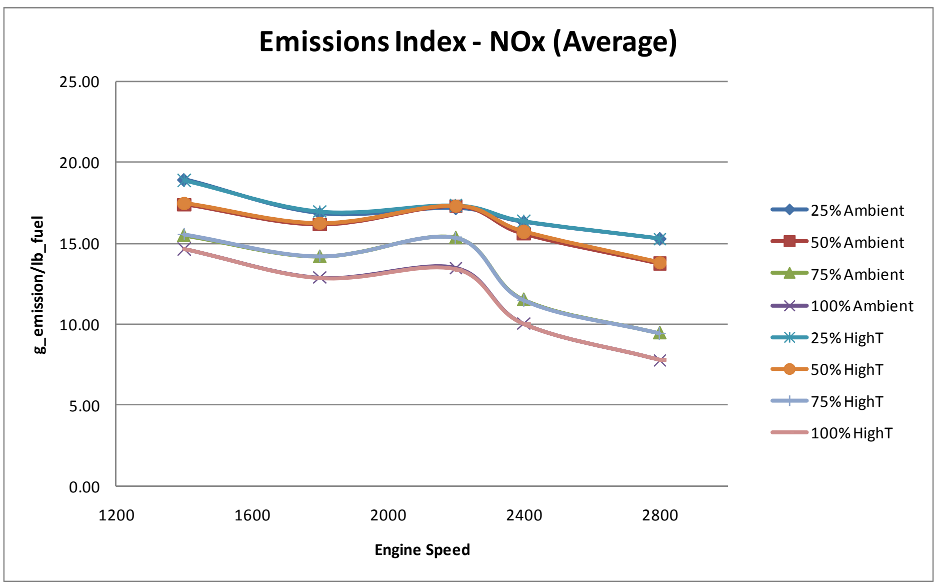


Figure 20 - Ford 6.7L, 50/50 JP-8/SPK, Average Pre & Post-Test NOx Emissions

Test 4 – 100% SPK

Data shown from the SPK tests are again the average of the emission measurements made prior-to and after the 210-hr durability test. In this case, there was some deviation between pre-test and post-test emission measurements, attributed to turbocharger oil seal leakage. Other than the turbocharger seal, the engine and fuel system integrity did not appear to vary due to the durability cycle. Figure 21 shows the HC Emissions Index (HCEI), grams HC/lb fuel, for SPK over the performance matrices performed at the two fuel temperatures. As with ULSD, JP-8, and JP-8/SPK blend, the 25% load points on SPK show higher HC due to lower in-cylinder temperatures at the leanest Air/Fuel Ratio. The 50%, 75%, and 100% load points show similar HCEI response at the three lowest engine speeds. At the highest engine speeds and richest AFR (100% load), the HCEI increases dramatically. The HCEI for the SPK fuel is influenced by the turbocharger seal leakage, and is overall elevated with respect to the other fuels. At engine loads above 25%, the HCEI increases with increasing engine speed, due to shorter time available for combustion completion.

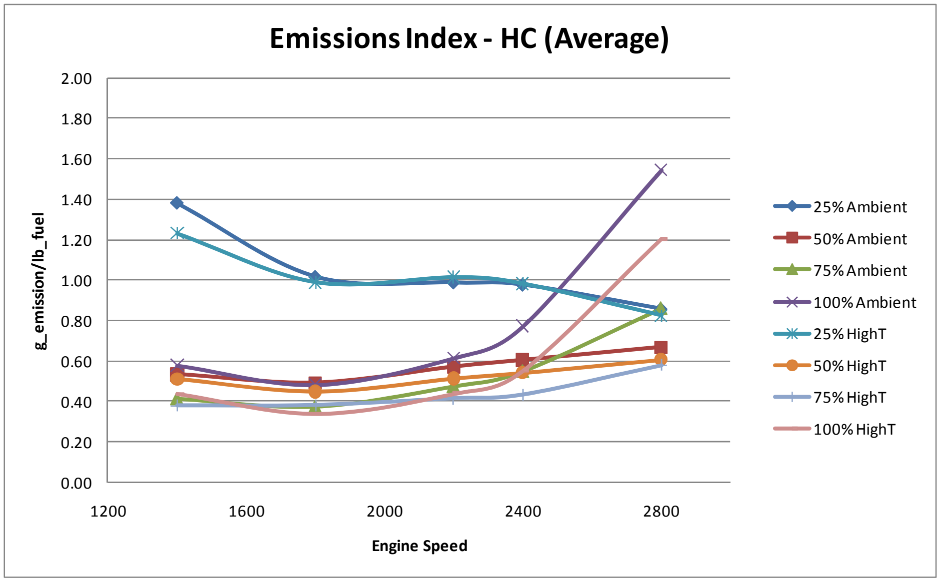


Figure 21 - Ford 6.7L, SPK, Average Pre & Post-Test HC Emissions

Figure 22 shows the CO Emissions Index (COEI), grams CO/lb fuel, for SPK over the performance matrices performed at two fuel temperatures. The 25% load points reveal significantly higher CO due to lower in-cylinder temperatures, and incomplete combustion at lean Air/Fuel Ratios. The 50%, 75%, and 100% load points show similar COEI results at the two lowest engine speeds, but at higher engine speeds the 50% load points exhibit more incomplete combustion. The 75% and 100% load points have very similar COEI response. At all engine loads the COEI increases with increasing engine speed due to shorter time available for combustion completion. Overall the SPK fuel exhibits similar COEI response as JP-8, except at 25% load where the COEI response is lower with SPK.

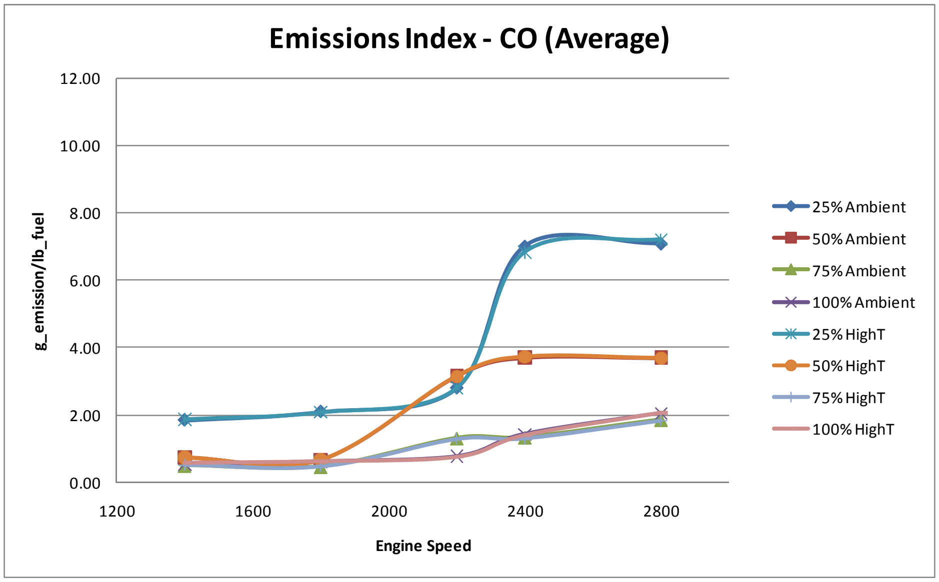


Figure 22 - Ford 6.7L, SPK, Average Pre & Post-Test CO Emissions

Figure 23 shows the NOx Emissions Index (NOxEI), grams NOx/lb fuel, for SPK over the performance matrices performed at two fuel temperatures. The 25% and 50% load points show the highest NOxEI, suggesting a greater portion of premixed burning during the heat release event. The 6.7L engine uses pilot fuel injection to control NOx and noise, and as the engine load increases, the pilot fuel injection parameters are relatively more effective in rate-shaping the combustion event resulting in a decrease in NOx formation. The SPK fuel had the highest Cetane Number (CN), thus the most reactive fuel, and generally had slightly lower NOxEI than the other fuels. The decrease of NOxEI with increasing engine speed may be attributed to less premixed fuel from less physical time available for evaporation and mixing during the shortened ignition delay period, resulting from the high SPK Cetane Number.

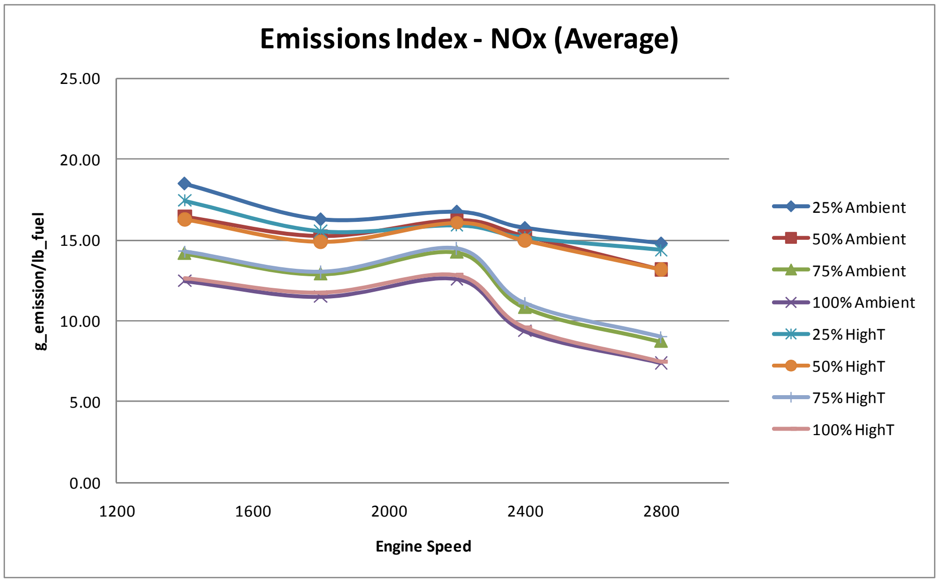


Figure 23 - Ford 6.7L, SPK, Average Pre & Post-Test NOx Emissions

3.2.3 Fuels Emissions Comparison

The emission index results were lump averaged for all the data sets, the pre-test and post-test data at the two fuel temperatures, for each of the test fuels. The results for each test fuel were normalized by the ULSD fuel, and are shown as deviations in Figure 13. The Hydrocarbon (HCEI) and Carbon Monoxide Index (COEI) emissions generally represent a measure of inefficiency. The impact of the turbocharger seal oil leakage during the SPK test is apparent from the overall averaged results. The JP-8/SPK blend data suggest that the SPK fuel should have resulted in lower HC had the turbocharger seal not leaked. The COEI data suggest the SPK fuel effectively lowers CO, both in the blend and when used neat.

The oxides of nitrogen or NOx emissions in a diesel engine are a measure of premixed combustion, which can be affected by fuel Cetane Number, and by fuel injection strategies such as pilot-injection. With increased premixed burn fraction, the temperatures in-cylinder will start at a higher temperature during the diffusion-burning phase of combustion. About 80% of the fuel energy is released during diffusion burning. Thus, if the temperature at the start of diffusion-burning is higher, the maximum temperature will also increase. NOx formation is considered proportional to the time that at temperatures are above the NOx formation threshold. The average NOx emissions indices for the test fuels are also shown in Figure 24. With respect to ULSD, the JP-8, JP-8/SPK, and SPK test fuels revealed a reduced NOxEI when averaged over all the test points.

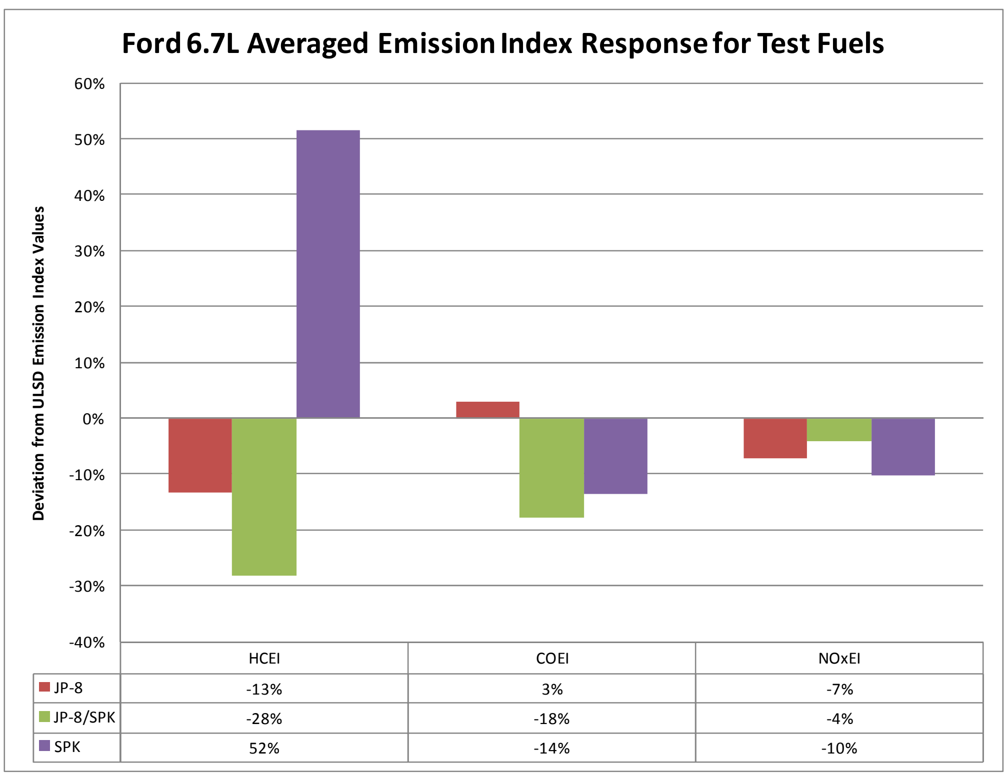


Figure 24 - Fuel Specific Averaged Emission Indices

To understand the impact of fuel property variations on the Ford 6.7L engine emissions, correlation coefficients were determined for several averaged emission data sets and are shown in Table 6 for all fuels. These averaged emission data sets were the overall average (HCEI, COEI, NOxEI), the 100% load emission data (100HCEI, 100COEI, 100NOxEI), the 50% load emission data (50HCEI, 50COEI, 50NOxEI), and the 25% load emission data (25HCEI, 25COEI, 25NOxEI). Due to the turbocharger oil leak with the SPK fuel, correlation coefficients were also evaluated with the HCEI values for the SPK fuel removed from the data set. The bold and highlighted values in Table 6 represent +/-0.9 or greater correlation coefficients. The cross-correlation coefficients for the fuel property variables for the test fuels are shown in Table 7, with highlighted values representing +/-0.95 or greater correlation coefficients.

In Table 6, it can be seen that removing the SPK HCEI data set significantly changed the correlation coefficients for the HCEI with respect to the various fuel properties, and for the engine average and all the load averaged data sets. Fuel density directly impacts the HCEI at the averaged 100% and 75% conditions, while inversely impacting the 50% and 25% load conditions. An effect common for the fuel properties in Table 6 is the high load conditions (100% and 75%) often show emission response coefficients inversely proportional to the light load conditions (50% and 25%). Fuel density shows an inverse relationship with COEI at 100% load, and a direct relationship with NOxEI at 100% and 75% loads. The kinetic viscosity at 40°C effects the 75% load HCEI proportionately and the 25% HCEI and 100% COEI inversely.

Fuel ignition quality is determined by the fuel property variables Cetane Number (CN) and the Ignition Quality Test Derived Cetane Number (DCN). The CN compares the ignition of a test fuel when bracketed by reference fuel blends in a special test engine that operates at fixed speed and injection timing, with the compression ratio altered for ignition at Top Dead Center. The procedure is specified in the ASTM D-613 test method, with units specified as Cetane Number (CN). The IQT method correlates the measured ignition delay characteristics of a fuel with a cetane number correlation defined by primary reference fuels blends and a data-base of test fuels in a combustion bomb. The procedure is specified in the ASTM D-6890 test method, with units specified as Derived Cetane Number (DCN). It is noted that CN and DCN are highly correlated, as they are both defined by reference fuel blends. A higher CN and DCN indicate a fuel that is more reactive, and will more readily ignite at compression ignition engine cylinder conditions of temperature and pressure at the time of injection. The HCEI at 50% load increases with increasing CN, whilst the COEI at 25% load decreases with increasing CN. The multiple fuel injection event strategies used by the 6.7L engine may mask some of the expected ignition quality effects on emissions.

Several different fuel variables are a measure of fuel structure, those being the hydrogen/carbon atom ratio (H/C), the aromatics content (mass and volume), olefins content, and saturates content. Table 7 suggests that H/C and saturates are highly correlated with each other, and inversely proportional to the aromatics and olefins content. Data from Table 6 suggest the emissions responses follows this relationship as well. The 100% load point reveals good correlations with the structure variables for all emission species, as HCEI and NOxEI decrease and COEI increases. At 75 % load the HCEI and NOxEI also decrease with an H/C and saturate increase. At 25% load the HCEI emission response is inverse of the high load conditions with respect to fuel structure. Of interest is the apparent correlation between emissions and the measures of fuel lubricity; however fuel lubricity has been shown to correlate with fuel structure, as seen in Table 7. Thus it is the relationship that exists between lubricity and structure that manifests the lubricity correlation with emissions. The heat of combustion (HofC) is correlated with fuel structure (H/C ratio and hydrocarbon type) and inversely with density; this is reflected in the emission index response correlation for HofC is very similar to the H/C response for emission index.

The fuel Bulk Modulus is a measure of fuel compressibility and affects fuel injection dynamics. As the saturate content of a fuel increases, there are more highly branched molecule chains making the fuel more compressible, and the measured Bulk Modulus would be lower. The emission index response for fuel Bulk Modulus is inversely proportional to the response seen with H/C ratio and saturates. With feedback control for rail pressure, it is likely the apparent Bulk Modulus effect on emission index is due to the correlation with other fuel variables, specifically fuel structure. However, the fuel injectors use the fuel’s incompressibility as a hydraulic link to amplify the movement of the piezo-stack actuator; it is feasible changes in Bulk Modulus could have had an impact on fuel injection and subsequently emissions.

The test fuels boiling point data is a measure of fuel volatility; higher boiling point temperatures indicate a less volatile fuel. The HCEI data for the engine average 100% and 75% load points indicate HCEI emission increase as the fuels become less volatile. At the 25% load conditions, greater volatility results in higher HCEI. The COEI results at full-rack (100% loads) indicate a decrease in COEI with lower volatility fuels. The NOxEI at most conditions was mostly affected by the backend volatility of the test fuels 90% Boiling Point and End Point, higher temperatures result in increased NOxEI.

Except where noted due to turbocharger oil leakage, the SPK and SPK blend result in emissions similar to JP-8 and slightly lower than ULSD overall. The SPK fuels do not appear to significantly alter the gaseous emission performance of the 6.7L engine.

Table 6 - Correlation Coefficients of Fuel Properties with Respect to Emission Indices

Fuel Property Correlation Coefficients with Engine Emission Index
With SPK HCEI Data and SPK HCEI Data Removed due to Turbocharger Oil leakage (r>0.9 highlighted)

	Density	K.Vis, 40C	H/C	CN	IQT, DCN	HofC	Aromatics, Mass	Aromatics, Volume	Olefins, Volume	Saturates, Volume	HFRR	BOCLE	Bulk Modulus	IBP	10% BP	20% BP	50% BP	90% BP	End Pt
HCEI	-0.4374	-0.1135	0.5545	0.7197	0.7337	0.5469	-0.5301	-0.4367	-0.2365	0.4162	0.4732	0.2205	-0.3527	0.2155	-0.1780	-0.1652	-0.1538	-0.2006	-0.2547
HCEI w/o SPK	***0.9847***	0.8815	***-0.9990***	-0.5859	-0.6991	***-0.9983***	***0.9993***	***0.9883***	***0.9099***	***-0.9821***	-0.8874	***-0.9025***	***0.9649***	0.8849	***0.9228***	***0.9152***	***0.9006***	***0.9000***	0.8922
COEI	0.7438	0.5319	-0.7640	-0.7973	-0.7842	-0.7625	0.7758	0.7539	0.6015	-0.7404	-0.5858	-0.5871	0.7071	0.4337	0.6155	0.5999	0.5724	0.5798	0.5757
NOxEI	0.8559	0.8441	-0.8342	-0.5271	-0.5986	-0.8371	0.8273	0.8483	0.8772	-0.8559	***-0.9437***	-0.8760	0.8652	0.6519	0.8470	0.8471	0.8515	0.8702	0.8933
100HCEI	0.4135	0.6214	-0.2937	0.0185	0.0023	-0.3022	0.3215	0.4158	0.5516	-0.4334	-0.3365	-0.5594	0.4847	0.8019	0.6031	0.6076	0.6065	0.5726	0.5273
100HCEI w/o SPK	***0.9847***	0.8815	***-0.9990***	-0.5859	-0.6990	***-0.9983***	***0.9993***	***0.9883***	***0.9099***	***-0.9821***	-0.8874	***-0.9026***	***0.9649***	0.8849	***0.9228***	***0.9152***	***0.9006***	***0.9000***	0.8922
100COEI	***-0.9794***	***-0.9679***	***0.9338***	0.6255	0.6787	***0.9380***	***-0.9407***	***-0.9776***	***-0.9927***	***0.9843***	***0.9719***	***0.9897***	***-0.9963***	-0.8513	***-0.9903***	***-0.9870***	***-0.9813***	***-0.9872***	***-0.9892***
100NOxEI	***0.9081***	0.8222	***-0.9083***	-0.6711	-0.7326	***-0.9096***	***0.9008***	***0.9029***	0.8779	***-0.9047***	***-0.9650***	-0.8725	0.8991	0.5972	0.8460	0.8420	0.8401	0.8637	0.8904
75HCEI	-0.7527	-0.4440	0.8404	***0.9034***	***0.9256***	0.8350	-0.8247	-0.7537	-0.5643	0.7360	0.7482	0.5476	-0.6808	-0.1274	-0.5189	-0.5046	-0.4883	-0.5293	-0.5729
75HCEI w/o SPK	***1.0000***	***0.9498***	***-0.9918***	-0.4370	-0.5650	***-0.9933***	***0.9906***	***0.9998***	***0.9679***	***-0.9999***	***-0.9537***	***-0.9634***	***0.9958***	***0.9521***	***0.9755***	***0.9711***	***0.9621***	***0.9618***	***0.9568***
75COEI	-0.2870	-0.0193	0.3964	0.5373	0.5574	0.3895	-0.3692	-0.2835	-0.1250	0.2669	0.3648	0.1126	-0.2130	0.2892	-0.0626	-0.0538	-0.0494	-0.0945	-0.1499
75NOxEI	***0.9305***	0.8727	***-0.9174***	-0.6465	-0.7099	***-0.9196***	***0.9126***	***0.9254***	***0.9190***	***-0.9293***	***-0.9832***	***-0.9148***	***0.9301***	0.6702	0.8923	0.8892	0.8879	***0.9076***	***0.9295***
50HCEI	-0.7527	-0.4440	0.8404	***0.9034***	***0.9256***	0.8350	-0.8247	-0.7537	-0.5643	0.7360	0.7482	0.5476	-0.6808	-0.1274	-0.5189	-0.5046	-0.4883	-0.5293	-0.5729
50HCEI w/o SPK	-0.7554	-0.5140	0.8339	***0.9188***	***0.9670***	0.8269	-0.8388	-0.7699	-0.5679	0.7462	0.5249	0.5534	-0.6932	-0.5203	-0.5940	-0.5785	-0.5496	-0.5486	-0.5337
50COEI	0.6717	0.7566	-0.5856	-0.3197	-0.3376	-0.5918	0.6092	0.6756	0.7317	-0.6854	-0.5750	-0.7327	0.7143	0.8327	0.7705	0.7688	0.7597	0.7394	0.7074
50NOxEI	0.8654	0.8637	-0.8386	-0.5191	-0.5911	-0.8419	0.8328	0.8578	0.8934	-0.8662	***-0.9508***	-0.8926	0.8779	0.6804	0.8653	0.8658	0.8702	0.8874	***0.9086***
25HCEI	-0.7848	-0.5104	0.8600	0.8712	***0.9017***	0.8556	-0.8446	-0.7844	-0.6217	0.7699	0.7967	0.6068	-0.7223	-0.2003	-0.5763	-0.5638	-0.5504	-0.5897	-0.6323
25HCEI w/o SPK	***-0.9671***	***-0.9983***	***0.9260***	0.1920	0.3347	***0.9306***	***-0.9225***	***-0.9611***	***-1.0000***	***0.9705***	***0.9989***	***0.9999***	***-0.9861***	***-0.9987***	***-0.9993***	***-0.9998***	***-0.9999***	***-0.9998***	***-0.9994***
25COEI	0.7853	0.5049	-0.8343	***-0.9161***	***-0.9053***	-0.8310	0.8396	0.7949	0.6004	-0.7768	-0.6430	-0.5828	0.7292	0.3354	0.5997	0.5818	0.5529	0.5711	0.5801
25NOxEI	0.6025	0.7152	-0.5550	-0.1784	-0.2612	-0.5598	0.5459	0.5901	0.7086	-0.6066	-0.7576	-0.7150	0.6384	0.5833	0.6772	0.6851	0.7023	0.7140	0.7343

Table 7 - Fuel Property Cross-Correlation Matrix for All Test Fuels

Fuel Property Cross-Correlation Matrix (r>0.95 highlighted)

	Density	K.Vis, 40C	H/C	CN	IQT, DCN	HofC	Aromatics, Mass	Aromatics, Volume	Olefins, Volume	Saturates, Volume	HFRR	BOCLE	Bulk Modulus	IBP	10% BP	20% BP	50% BP	90% BP	End Pt
Density	**1.0000**																		
K.Vis, 40C	0.8998	**1.0000**																	
H/C	**-0.9868**	-0.8189	**1.0000**																
CN	-0.7669	-0.4108	0.8568	**1.0000**															
IQT, DCN	-0.8116	-0.4755	0.8936	**0.9962**	**1.0000**														
HofC	**-0.9887**	-0.8257	**0.9999**	0.8508	0.8883	**1.0000**													
Aromatics, Mass	**0.9897**	0.8284	**-0.9996**	-0.8500	-0.8867	**-0.9997**	**1.0000**												
Aromatics, Volume	**0.9999**	0.8952	**-0.9880**	-0.7741	-0.8176	**-0.9897**	**0.9910**	**1.0000**											
Olefins, Volume	**0.9532**	**0.9893**	-0.8936	-0.5371	-0.5976	-0.8989	0.9006	0.9497	**1.0000**										
Saturates, Volume	**-0.9997**	-0.9104	**0.9823**	0.7511	0.7967	**0.9844**	**-0.9858**	**-0.9994**	**-0.9602**	**1.0000**									
HFRR	**-0.9774**	-0.9264	**0.9536**	0.6731	0.7316	**0.9565**	**-0.9537**	**-0.9740**	**-0.9679**	**0.9783**	**1.0000**								
BOCLE	-0.9457	**-0.9924**	0.8827	0.5166	0.5783	0.8882	-0.8899	-0.9419	**-0.9997**	**0.9532**	**0.9635**	**1.0000**							
Bulk Modulus	**0.9930**	0.9449	**-0.9609**	-0.6865	-0.7371	**-0.9641**	**0.9659**	**0.9917**	**0.9819**	**-0.9957**	**-0.9815**	**-0.9770**	**1.0000**						
IBP	0.7282	0.9447	-0.6078	-0.1409	-0.2024	-0.6171	0.6246	0.7232	0.8906	-0.7459	-0.7518	-0.8997	0.8029	**1.0000**					
10% BP	0.9425	**0.9932**	-0.8763	-0.5112	-0.5704	-0.8819	0.8851	0.9392	**0.9980**	**-0.9507**	**-0.9509**	**-0.9984**	**0.9754**	0.9127	**1.0000**				
20% BP	0.9351	**0.9956**	-0.8659	-0.4920	-0.5523	-0.8718	0.8748	0.9316	**0.9973**	-0.9438	-0.9470	**-0.9982**	**0.9704**	0.9200	**0.9997**	**1.0000**			
50% BP	0.9243	**0.9982**	-0.8514	-0.4649	-0.5272	-0.8576	0.8603	0.9203	**0.9959**	-0.9336	-0.9428	**-0.9976**	**0.9629**	0.9278	**0.9984**	**0.9994**	**1.0000**		
90% BP	0.9388	**0.9948**	-0.8726	-0.4991	-0.5612	-0.8783	0.8803	0.9349	**0.9990**	-0.9469	**-0.9577**	**-0.9998**	**0.9726**	0.9090	**0.9987**	**0.9990**	**0.9989**	**1.0000**	
End Pt	0.9499	**0.9887**	-0.8907	-0.5294	-0.5919	-0.8960	0.8969	0.9459	**0.9993**	**-0.9568**	**-0.9720**	**-0.9993**	**0.9789**	0.8856	**0.9955**	**0.9952**	**0.9947**	**0.9984**	**1.0000**

3.3 ENGINE NOISE EVALUATION

Engine idle noise was measured for each test fuel to determine if any engine noise variation was present due to combustion effects between each fuel. Noise measurements were taken at engine idle speed in an effort to reduce any effects present from other ancillary test equipment. It was found that at engine rated speed, excessive noise was generated in the test cell and small changes in engine noise levels were masked. During engine idle conditions, running ancillary test equipment could be reduced to a minimum to more accurately evaluate noise emitted from the engine without interference. Since the engine was designed and calibrated around the characteristics of diesel fuel, there was a potential for changes in combustion to occur that could be detectible through changes in audible engine noise. This would act as a good indicator of any large combustion changes occurring within the engine due to the variation in chemical properties of the tested military fuels. Table 8 below lists the engine idle noise measurements taken during testing. Overall, no major engine noise variation was observed. All measurements fell within the same repeatability range for an individual location for each fuel.

Table 8 - Ford 6.7L Engine Idle Noise Measurements

Engine Idle Noise [dB]						Average	Std Dev
	ULSD						
	Front	90.0	97.4			93.7	5.23
	Top	86.8	87.9			87.4	0.78
	Left	86.5	86.6			86.6	0.07
	Right	86.4	86.6			86.5	0.14
	JP-8						
	Front	90.1	93.0	91.4		91.5	1.45
	Top	86.6	88.5	87.2		87.4	0.97
	Left	86.4	89.4	87.9		87.9	1.50
	Right	86.4	87.4	88.3		87.4	0.95
	50/50						
	Front	92.4	90.2	90.1		90.9	1.30
	Top	87.3	85.8	86.7		86.6	0.75
	Left	87.1	86.7	86.8		86.9	0.21
	Right	87.4	87.5	87.2		87.4	0.15
	SPK						
	Front	90.4	92.0	90.3		90.9	0.95
	Top	86.8	87.2	87.8		87.3	0.50
	Left	86.5	87.0	87.0		86.8	0.29
	Right	87.0	87.9	87.4		87.4	0.45

3.4 POST-TEST FUEL SYSTEM HARDWARE INSPECTION

After each test was completed, fuel system components were removed from the engine and disassembled for inspection. The following sections review the visual inspection and photographs of the high pressure fuel pump and fuel injectors for each test.

3.4.1 Fuel Injection Pump

As previously stated, the fuel injection pump can be broken down into four critical areas for evaluation: the interface of the fuel pump body bore and cam follower, cam and roller interface, cam and bushing (bearing) interface, and high pressure plunger and barrel. A visual inspection and description of each of these components can be seen below in Table 9, followed by discussion of wear present, and representative pictures. Photos of all components for each test can be seen in the attached appendix test reports.

Table 9 - Fuel Injection Hardware Inspection

Part	New	ULSD	JP-8	JP-8/SPK	SPK
Volume Control Valve	New	As new	As new	As new	As new
Pump Body	Very light polish of bores	Very light polish of bores, top & bottom	Very light polish of bores, top & bottom	Light polish & light scuff of bores, top & bottom	Light polish & very light scuff of bores, top & bottom
Pump Bushings	Both new	Both as new	Both as new	Both as new	Both as new
Cam	Visible light grinding marks	Light polish, not measureable, seal contact wear	Light polish & very light burnish, not measureable, seal contact wear	Polish & light burnish, not measureable, seal contact wear, journals V.L. burnish	Light polish & very light burnish, not measureable, seal contact wear
Roller - Left	New, bright & shiny	Light polish	Very light burnish & polish	Light burnish & polish, Heavy roller end wear against follower	Very light burnish & polish
Roller - Right	New, bright & shiny	Light polish	Very light burnish & polish	Light burnish & polish	Very light burnish & polish
Roller Shoe - L	New	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button
Roller Shoe - R	New	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button
Follower - L	New	Very light polish	Polish, very light scuff, top & bottom	Polish, light scuff, top & bottom	Polish, very light scuff, top & bottom
Follower - R	New	Very light polish	Polish, very light scuff, top & bottom	Polish, light scuff, top & bottom	Polish, very light scuff, top & bottom

Table 9- Fuel Injection Hardware Inspection (continued)

Part	New	ULSD	JP-8	JP-8/SPK	SPK
Plunger - L	New	As new, very light polish on plunger button, more than right	As new, light polish on plunger button, more than right	As new, light polish on plunger button, more than right, more polish than JP-8	As new, light polish on plunger button, more than right
Plunger - R	New	As new, very light polish on plunger button	As new, light polish on plunger button	As new, light polish on plunger button	As new, light polish on plunger button
Barrel - L	New	As new	As new	As new	As new
Barrel - R	New	As new	As new	As new	As new
Inlet Check - L	New	As new	As new	As new	As new
Inlet Check -R	New	As new	As new	As new	As new

The wear present on the pump body bore and cam follower surfaces were found to be similar in each tests, with slightly more wear present on the 50/50 JP-8/SPK components. The bores in each of the pumps showed some polishing on their surface from interactions with the cam follower. Markings tended to be present primarily at the top and bottom of the travel area of the follower, which is consistent with areas of largest side loading present on the follower from the forces applied by the pumps camshaft and plunger return spring. The new unused pump also showed similar but smaller markings likely produced at end of line testing during manufacturing. The 50/50 JP-8/SPK and 100% SPK test showed a tendency to have very light scuffing present on the surface in addition to the typical polishing. Although this is undesirable, the scuffing marks were very minimal and did not affect pump performance during testing. After comparison of all new and tested components, the polishing of the pump body bore in each test appeared to be normal. Figure 25 and Figure 26 shows polishing present on the post-test ULSD pump SPK pump respectively.

Figure 25 – Post-Test ULSD Pump Body Bore Polish

Figure 26 – Post-Test SPK Pump Body Bore Polish (Light Scuffing)

All follower surfaces showed polishing and slight scuffing on their surfaces consistent with the polishing found on the pump bore surface. This again corresponded with areas that typically experience the greatest side load forces. Although the ULSD follower showed some minor scuffing, the JP-8, 50/50 JP-8/SPK and SPK components typically contained a slightly larger scuffed area. This is attributed to the reduction in lubricity of the military fuels when compared to the ULSD. The follower assembly from the 50/50 JP-8/SPK test experienced the greatest percentage of scuffed area, and is likely related to an unusual wear pattern found only on the left hand roller from this test (discussed further below). Figure 27 shows a representative photo of a roller from each test for comparison. With the exception of the 50/50 test, wear present on the follower surfaces did not appear to be severe overall.

Figure 27 - Follower Surface Scuffing

Left to right, top to bottom: ULSD, JP-8, 50/50 JP-8/SPK, SPK

During inspection of the roller/follower used in the 50/50 JP-8/SPK test, heavy wear at the end of the roller into the body of the follower was observed on the left hand assembly. This wear was not present on the right hand roller, or any other rollers of the remaining tests. It is possible that this could be an isolated problem inherent of a manufacturing flaw within this particular pump. Several different scenarios could potentially cause the roller to preload into the follower wall, such as: slight variation in diameter across the length of the roller resulting in a slight taper on the roller surface, camshaft machining that creates a surface not perpendicular to the roller interface, or bore machining variation resulting in a slightly canted bore. As would be expected, it appears that the extra friction at this location potentially caused higher than normal fuel temperatures in this area lowering the fuel viscosity and contributing to the increased scuffing observed on the left hand follower. Figure 28 and Figure 29 show the roller end wear into the follower assembly.

Figure 28 - Roller Wear Into Follower (1), Left Follower, 50/50 JP-8/SPK

Figure 29 - Roller Wear Into Follower (2), Left Follower, 50/50 JP-8/SPK

Pump camshaft and roller surfaces showed some slight variation during the component inspection. Roller surfaces for the non-diesel fuels showed a minor burnishing on the surface when compared to the baseline diesel rollers. Apart from the previously mentioned roller end wear on the 50/50 JP-8/SPK test, no other unusual wear was found on any of the roller surfaces. Figure 30 shows a comparative shot of all four test rollers.

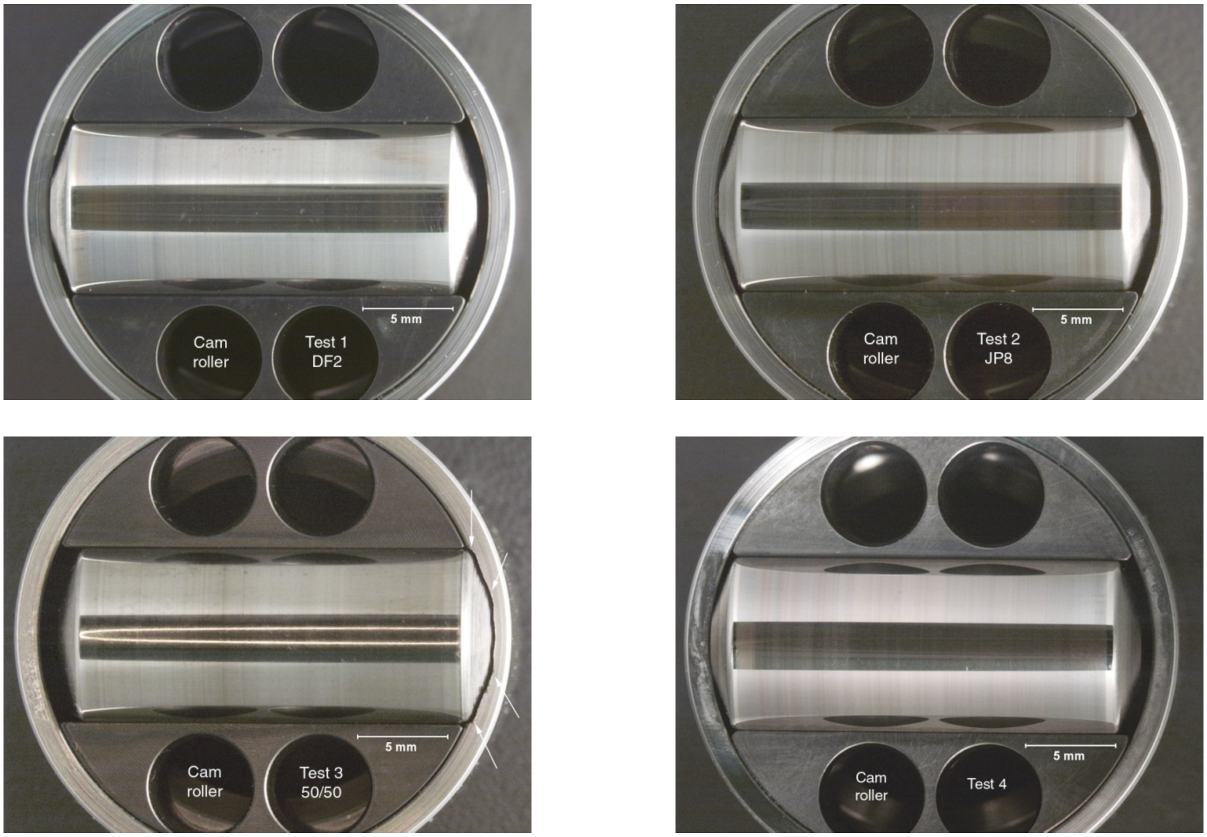


Figure 30 - Roller Assemblies

Left to right, top to bottom: ULSD, JP-8, 50/50 JP-8/SPK, SPK

Camshaft surfaces showed similar trends as the rollers. Figure 31 shows the camshaft removed from the ULSD tested pump, while Figure 32 shows the camshaft from the 50/50 JP-8/SPK test. Note the slight burnishing (discoloration) of the lobe and journal bearing surfaces. Camshafts were dimensionally measured across the peak of the camshaft lobe for each test to determine if any wear patterns could be determined. The measurements of the post-test camshafts showed no greater variation in surface condition than that of the new unused pump.

Figure 31 - Camshaft, ULSD

Figure 32 - Camshaft, 50/50 JP-8/SPK

After the visual inspection and photographs, camshaft lobe surfaces were put under magnification to better quantify wear present on the lobe surface. Figure 33 below shows each cam lobe surface under magnification. With the exception of a slight surface appearance difference in the 50/50 test, no other differences can be seen between each test.

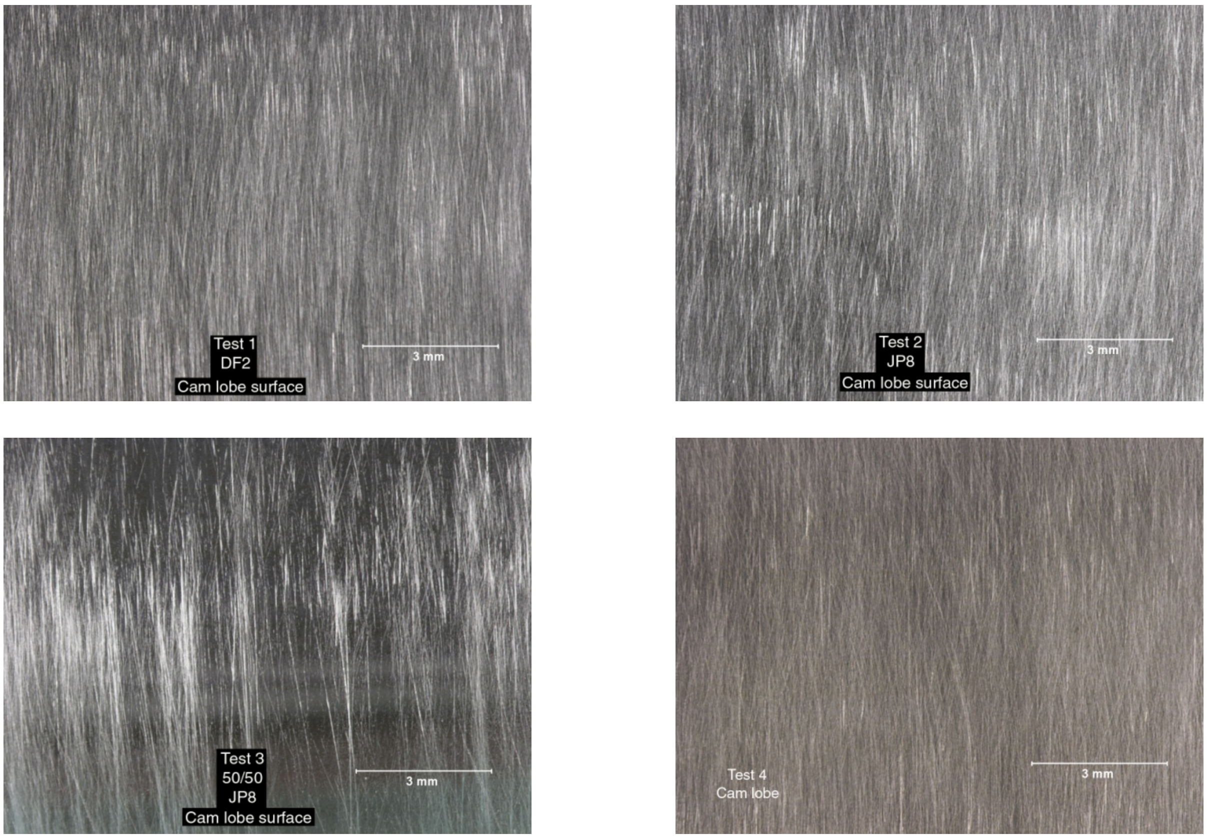


Figure 33 - Roller Assemblies

Left to right, top to bottom: ULSD, JP-8, 50/50 JP-8/SPK, SPK

Pump body camshaft bushings showed no noticeable wear in any of the four tests. Each bushing inspected appeared to be in "as new" condition for each test. Figure 34 and Figure 35 on the following page show the front and rear pump body camshaft bushings for the SPK fuel which had the lowest lubricity value of all tested fuels, and would be expected to experience the highest wear in that location.

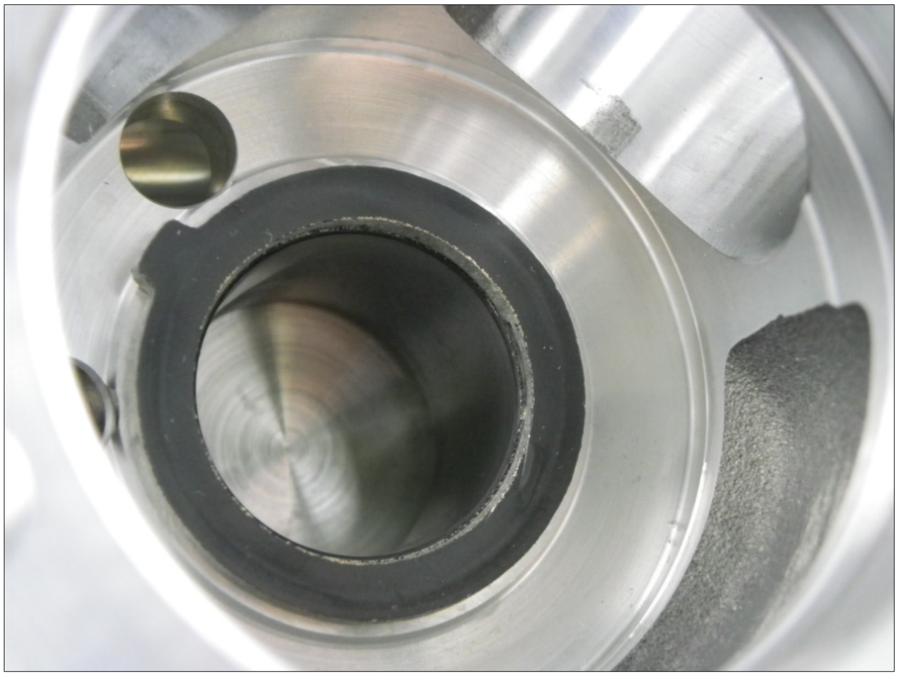


Figure 34 - Rear Pump Body Camshaft Bushing, SPK

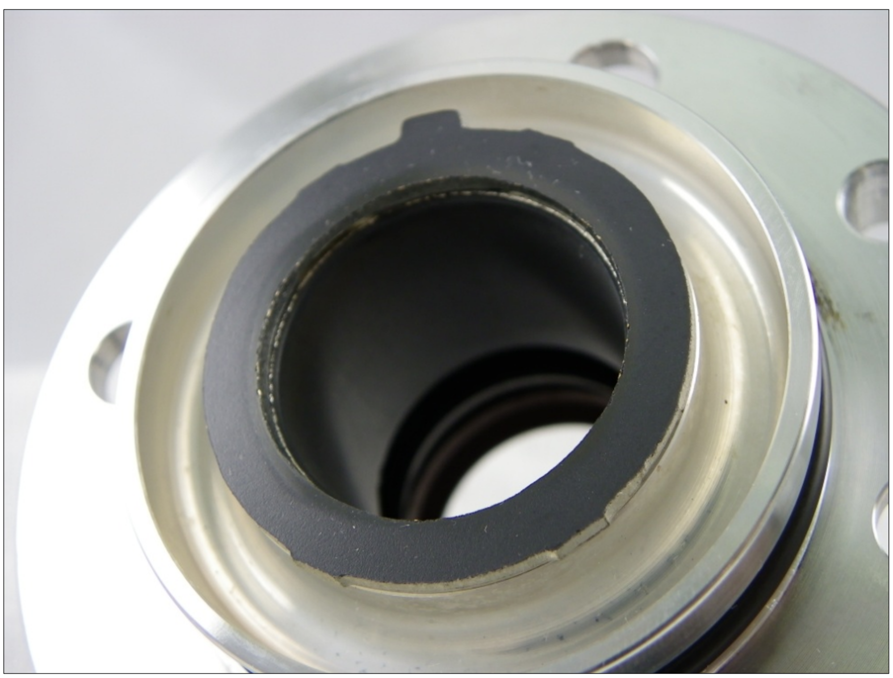


Figure 35 - Font Pump Body Camshaft Bushing, SPK

The barrel and plunger assemblies for each test did not show any wear distinguishing themselves from the new unused components. All surface treating to the high pressure plunger was intact and showed no variation. The inside barrel surfaces also appeared to be smooth and unworn. Figure 36 and Figure 37 below show the high pressure plunger from the new unused pump, and the SPK test respectively.

Figure 36 - High Pressure Plunger, New

Figure 37 - High Pressure Plunger, SPK

3.4.2 Fuel Injectors

Consistent with the high pressure fuel pump inspection, fuel injectors from each test were removed and disassembled for inspection and photographs. Due to the size of the fuel injectors internal components, many photos were taken under magnification to better determine any wear patterns present. Inspections were made to the hydraulic coupler pistons, control valve, control plates, injector needle, and nozzle. With the exception of slight deposition differences between the diesel and military fuels (primarily noticed in coloring), no other differing patterns could be identified between the ULSD test and the JP-8 and SPK tests. From the inspection, the only internal injector components showing any appreciable wear patterns were the upper pistons of the hydraulic coupling. As previously explained, the hydraulic coupler is used to translate the small linear movement of the piezo-stack to a larger linear movement to operate the injector control valve and regulate needle lift. From the inspection, it appeared that the piezo-stack imparted a slight side load on the upper piston causing a reacting wear scar to be formed on the outer piston surface. This wear scar was seen in each of the test fuels, and was found to be overall similar in size and condition between the ULSD and military fuels. Figure 38 below shows the condition of the new/unused injector upper hydraulic coupler piston.

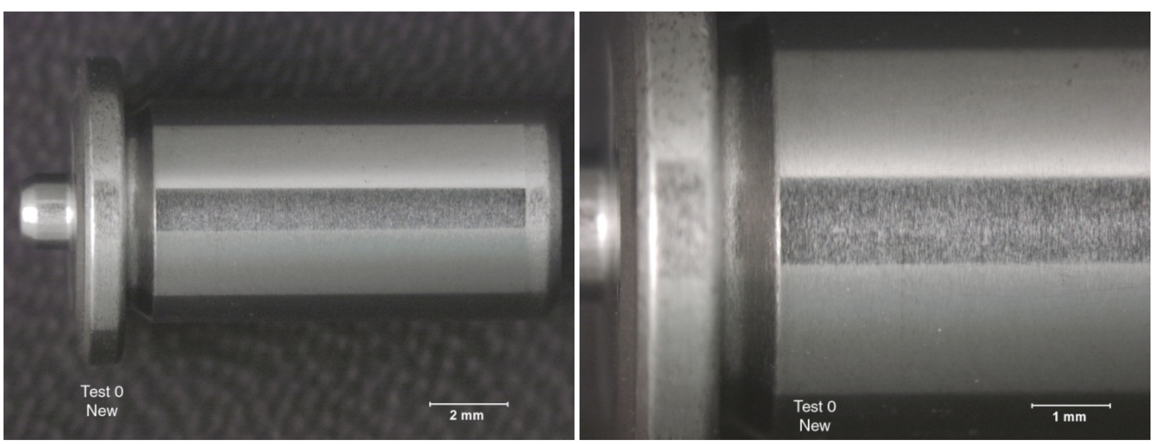


Figure 38 - Upper Piston, Injector Hydraulic Coupling, Unused

Figure 39 shows the condition of the upper piston removed from the post-test ULSD fuel injector. The slight coloration of the wear scar appears to be oxidation formation on the metal surface where the original surface coating has been completely removed.

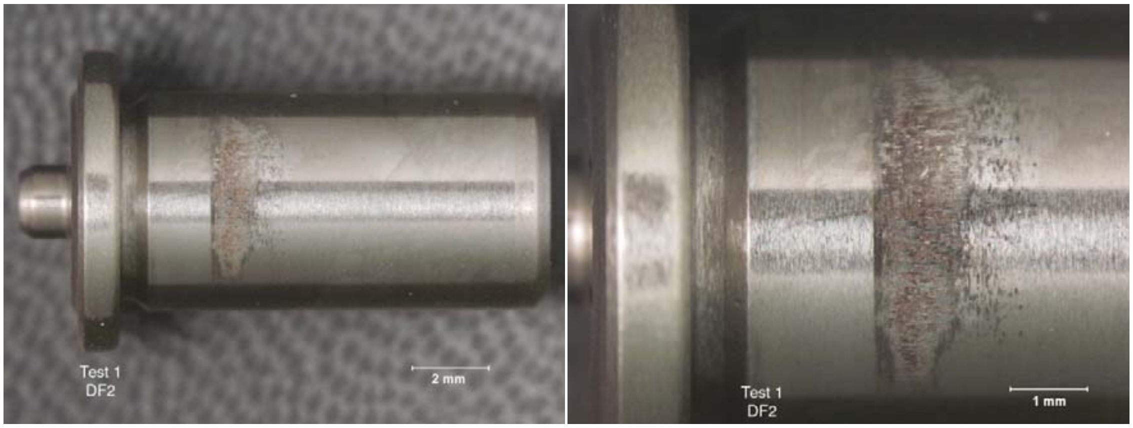


Figure 39 - Upper Piston, Injector Hydraulic Coupling, ULSD

Figure 40, Figure 41, and Figure 42 below show the condition of the upper piston removed from the post-test JP-8, 50/50 JP-8/SPK, and SPK fuel injectors respectively. Note the overall similar wear pattern as seen in the ULSD component. Again, the slight coloration of the wear scar appears to be oxidation formation on the metal surface where the original surface coating has been completely removed.

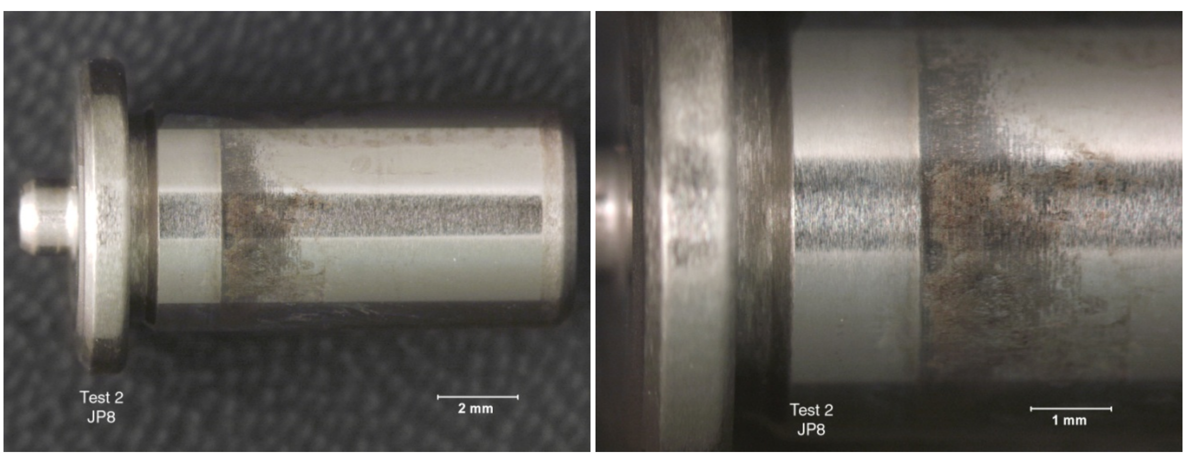


Figure 40 - Upper Piston, Injector Hydraulic Coupling, JP-8

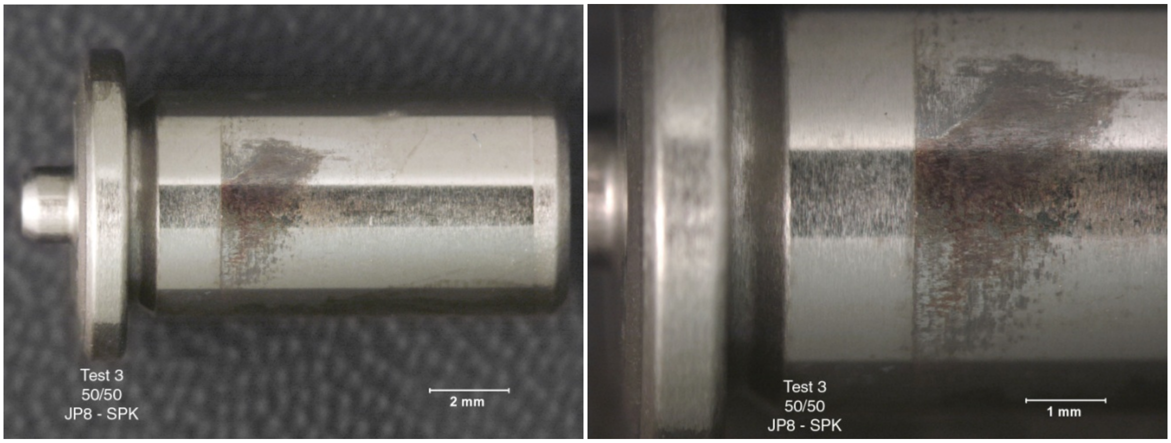


Figure 41 - Upper Piston, Injector Hydraulic Coupling, 50/50 JP-8/SPK

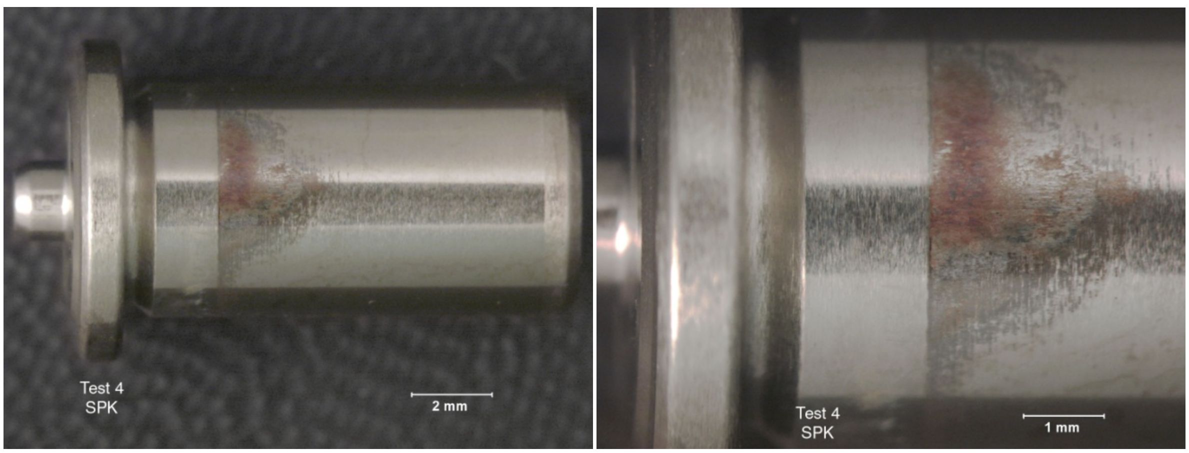


Figure 42 - Upper Piston, Injector Hydraulic Coupling, SPK

Although this wear did not impact the testing at hand, this type of wear is typical of wear that can be detrimental to fuel injector function if continued. Binding or sticking of the hydraulic coupler will impair the action of the control valve which can potentially result in no fuel being injected into the engine, or a constant flow of injected fuel. Either of these occurring during engine operation would require immediate fuel injector replacement to ensure proper engine operation.

4.0 CONCLUSION

Testing conducted supports that the Ford 6.7L fuel lubricated high pressure common rail fuel injection system can be successfully operated using military specified fuels at normal ambient conditions. Even at the minimum lubricity enhancing treat rates, the tested JP-8 and synthetic based fuels provided adequate component protection and system performance compared to ULSD. No unusual fuel related operating conditions were experienced throughout testing, and engine performance remained consistent and satisfactory throughout. Post-test fuel injection system inspection found used components to be in similar condition throughout all tests, despite the large differences in fuel lubricity from the baseline to SPK tests.

5.0 RECOMMENDATIONS

Due to the minimal differences seen in component conditions at the end of testing, TFLRF staff recommends that further testing be considered at more stringent conditions to ensure long term military compatibility. Two key issues to further investigate for military compatibility would be testing at longer durations and higher fuel inlet temperatures. Longer test durations will give better insight into long-term compatibility with low viscosity and lubricity fuels used in military applications. Wear experienced during this testing was minimal overall, but could potentially escalate when operated over a longer time frame. It is unknown at this time whether wear patterns experienced during this testing could worsen to the point of causing operational problems, or will remain benign in terms of engine operation. Testing at elevated fuel inlet temperatures would be beneficial to determine if operation at desert-like conditions would accelerate wear patterns in the fuel system. Ford/Bosch specifies that fuel inlet temperatures are to be maintained below 70°C (158°F) for use. Fuel temperature specifications experienced in desert operation have historically been difficult to accurately predict, but have the potential to elevate above recommended conditions. This could potentially have a dramatic impact on fuel system operation and compatibility.

6.0 REFERENCES

1. Development of Military Fuel/Lubricant/Engine Compatibility Test, CRC Report 406, January 1967.

2. Electronic Code of Federal Regulations, Title 40, Part 86, Subpart D, March 15, 2011

APPENDIX A
ULSD Test Report
(AF7469-67T1-W-210)

Evaluation of ULSD in the Ford 6.7L High Pressure Common Rail Diesel Engine

Project 14734.04

Ford Motor Company 6.7L Diesel

Test Lubricant ID: N/A
Test Lubricant: Full Synthetic, CJ-4, SAE 5W-40
Test Fuel ID: AF7469
Test Fuel: DF2, Halterman Certification USLD
Test Number: AF7469-67T1-W-210
Start of Test Date: December 2, 2010
End of Test Date: December 16, 2010
Test Duration: 210 Hours
Test Procedure: Tactical Wheeled Vehicle

Conducted for
U.S. Army TARDEC
Force Projection Technologies
Warren, MI

Introduction

This test was used to determine the performance and endurance of a modern high pressure common rail diesel fuel injection system when operated on ULSD. Testing was completed following a modified version of the 210hr Tactical Wheeled Vehicle Cycle engine endurance test cycle (CRC Report No.406, Development of Military Fuel/Lubricant/Engine Compatibility Test). This work was completed in support of Project 14734.04, Assessment of Fuels for Military Use, 2010 and Beyond.

Test Engine

The Ford 6.7L diesel engine was chosen for testing as a representative engine utilizing modern high pressure common rail fuel injection technology. The Ford 6.7L engine is a direct injected, turbo-charged, intercooled engine, which employs a fuel lubricated high pressure common rail injection pump and piezo-electric fuel injectors. The test engine was purchased new directly from Ford Motor Company for testing, and all new fuel system hardware present on the engine was used for testing.

Test Stand Configuration

The engine was mounted in a test stand specifically configured for Ford 6.7L engine testing. Engine monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. An appropriately sized absorption dynamometer was used to control engine speed and dissipate load. Engine load was manipulated through the actuation of the engine throttle pedal assembly. Engine coolant temperatures were controlled with the use of liquid-to-liquid heat exchangers utilizing laboratory process water for cooling. Engine intake air was supplied at ambient conditions utilizing the factory engine air box and ducting. Engine exhaust was routed from the test cell through a butterfly valve to control engine exhaust back pressure, and then ducted into the laboratory exhaust blower system for removal. Fuel was supplied to the diesel fuel conditioning module/engine at ambient conditions.

Engine Run-in

Prior to testing, the engine was run-in following the Ford specified engine run-in procedure. Table 1 below outlines the Ford recommended engine run-in procedure.

Table 1 - Ford Recommended Run-In Procedure

Step	Duration	Speed	Load	
		[rpm]	[lb-ft]	[Nm]
1	0:05	650	0	
2	0:30	1000	72	97
3	0:30	1200	103	140
4	0:30	1400	141	191
5	0:30	1500	162	219
6	0:30	1600	184	249
7	0:30	1700	208	282
8	0:30	1800	233	316
9	0:30	2000	287	390
10	0:30	2200	348	472
11	0:30	2400	414	561
12	0:30	2500	449	609
13	0:30	2600	486	659
14	0:30	2700	524	710
15	0:30	2800	563	764

Pre and Post Test Engine Performance Checks

Before and after testing, engine powercurves were completed at varying speeds and loads to determine pre-test engine performance. Engine performance was documented at engine speeds of 1400, 1800, 2200, 2400, and 2800 rpm, with load intervals of 25%, 50%, 75%, and 100% of full load. Powercurves were completed at both ambient (95°F) and desert condition (120°F) inlet fuel temperatures. Exhaust gas emissions were sampled at each point on the curve to document engine out emissions. Powercurve plots can be seen in the Engine Performance Curves section.

Test Cycle

The test cycle followed during fuel system evaluations was a modified version of the 210hr Tactical Wheeled Vehicle Cycle as outlined in CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test. Slight modifications were made to the test cycle to accelerate the testing schedule. The primary modification was the reduction of engine soak time from 10hrs to 3hrs. The engine soak period in the test cycle was originally included for engine lubricant testing, and added no benefit for fuel compatibility testing. Total modified daily runtime was 21hrs per day, 15hrs at rated speed/load and 6hrs at idle, followed by a 3hr engine soak. To keep the modified test cycle rated to idle testing hours consistent with the standard 210hr Tactical Wheeled Vehicle Cycle, the following daily operating arrangement was derived. The engine completed 6 cycles of 2hr 10min at rated speed followed by a 1hr idle step. After the 6 cycles were completed, an additional 2hr rated segment was conducted followed by the 3hr soak. Engine coolant temperatures were maintained at Ford specifications to ensure engine integrity throughout the test. Engine coolant utilized was a 50/50 blend of ethylene glycol antifreeze and deionized water. Engine operating parameters were controlled as specified in Table 2 below.

(Note – Engine idle speed was controlled by PCM at approximately 600 RPM. Temperature controllers remained at rated speed set points for idle conditions, but were not met due to lack of heat generation in the coolant system. Temperatures were allowed to reach their natural steady state value during idle testing steps. Engine oil cooler plumbing was integral to the engine water jacket, thus not directly controlled. Oil temperatures were allowed to meet their own steady state temperature based on water jacket temperature and engine load/speed throughout testing.)

Table 2 - Test Cycle Operation Parameters

Parameter	Rated Speed	Idle
Engine Speed	2800 +/- 25	NC
High Temp Coolant Loop	203 +/- 3	NC
Low Temp Coolant Loop	100 +/- 3	NC
Oil Sump	NC	NC
*NC = not controlled		

Oil Sampling

Four ounces of engine oil was sampled every 21hrs (daily) for used oil analysis. Used oil analysis consisted of the following tests as seen below in Table 3. Engine oil changes were performed on the engine based on used oil condition.

Table 3 - Used Oil Analysis Procedures

Daily Used Oil Analysis		
ASTM	D4739	Total Base Number
ASTM	D664	Total Acid Number
ASTM	D445	Kinematic Viscosity @ 100°C
ASTM	API Gravity	API Gravity
ASTM	D4052	Density
ASTM	TGA SOOT	TGA Soot
ASTM	E168	Oxidation
ASTM	E168	Nitration
ASTM	D5185	Wear Metals by ICP

Used oil analysis results can be seen in the engine oil analysis and engine oil analysis trends section of the report.

Oil Level Checks

Engine oil level was checked daily, and replenished as needed to restore oil level to full mark. This process occurred after the completion of the 3hr soak prior to restarting testing the next day.

Test Fuel Analysis

The test fuel used was certification ULSD purchased from Haltermann Solutions. The fuel was used as purchased without any additizing or blending prior to use. Table 4 summarizes the critical chemical and physical properties of the tested ULSD. Table 5 on the following page shows the certificate of analysis (COA) for the ULSD as received.

Table 4 - Test Fuel Chemical & Physical Analysis

Property	Units	Method	Results
Density @15°C	g/mL	D4052	0.736
Specific Gravity @15°C		D4052	0.737
API Gravity @15°C		D4052	60.6
Flashpoint	°F	D56	111
	°C	D93	43
	°F	D3828	109
Kinematic Viscosity @-20°C	cSt	D445	2.5
Kinematic Viscosity @40°C	cSt	D445	0.9
Hydrocarbon Content			
Carbon	wt%	D5291	83.94
Hydrogen	wt%		16.46
Calculated Cetane Index		D976	57.2
Calculated Cetane Index		D4737	66.8
Cetane Number		D613	64.0
IQT	DCN	D6890-04	58.5
Heat of Combustion (Gross)	BTU/lb	D240	20364.4
Total Acid Number	mg KOH/g	D3242	0.011
Hydrocarbon Type			
Aromatics	%mass	D5186	0.3
Hydrocarbon Type			
Aromatics	%vol	D1319	0.4
Olefins			0.5
Saturates			99.1
Sulfur	ppm	D5453	<10
Nitrogen	wt%	D3228	<0.03
HFRR	mm	D6079	0.840
BOCLE	mm	D5001	0.76
Bulk Modulus @30°C	psi	by Speed of Sound	152749
Distillation			
IBP	°C	D86	152.5
10%			161.5
20%			162.7
50%			168.8
90%			186.0
End Pt			203.0

Table 5 - Haltermann Certification ULSD Certificate of Analysis (COA)

Haltermann
PRODUCTS

Telephone: (800) 969-2542

Product Information

FAX: (281) 457-1469

Johann Haltermann, Ltd.

PRODUCT: 2007 Certification Diesel — Batch No.: YC3021HW10

PRODUCT CODE: HF0582 — Tank No.: 42

Analysis Date: 4/12/2010

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

APPROVED BY: [signature] ANALYST ITK

Endurance Test Cycle Results

The following information summarizes the results of the engine fuel system endurance tests. Data includes: engine operating summary, powercurve analysis, engine out emissions, used oil analysis, post test component inspection, post test component photos, and listing of any problem areas or anomalies experienced during testing.

Engine Operating Conditions Summary

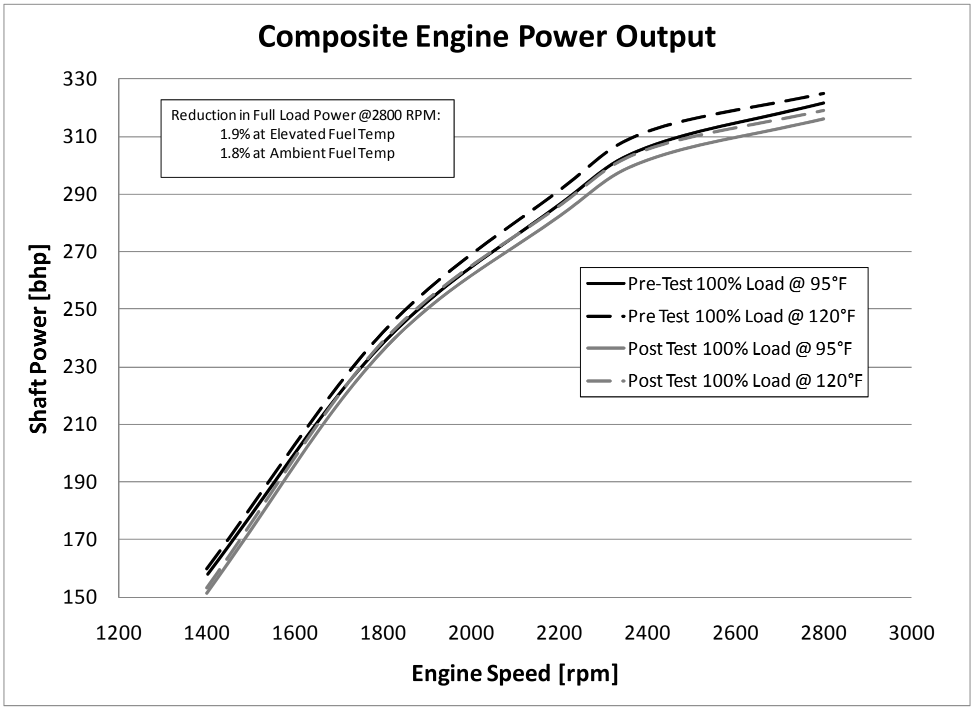
Below is a summary of the engine operating conditions over the 210hr test duration.

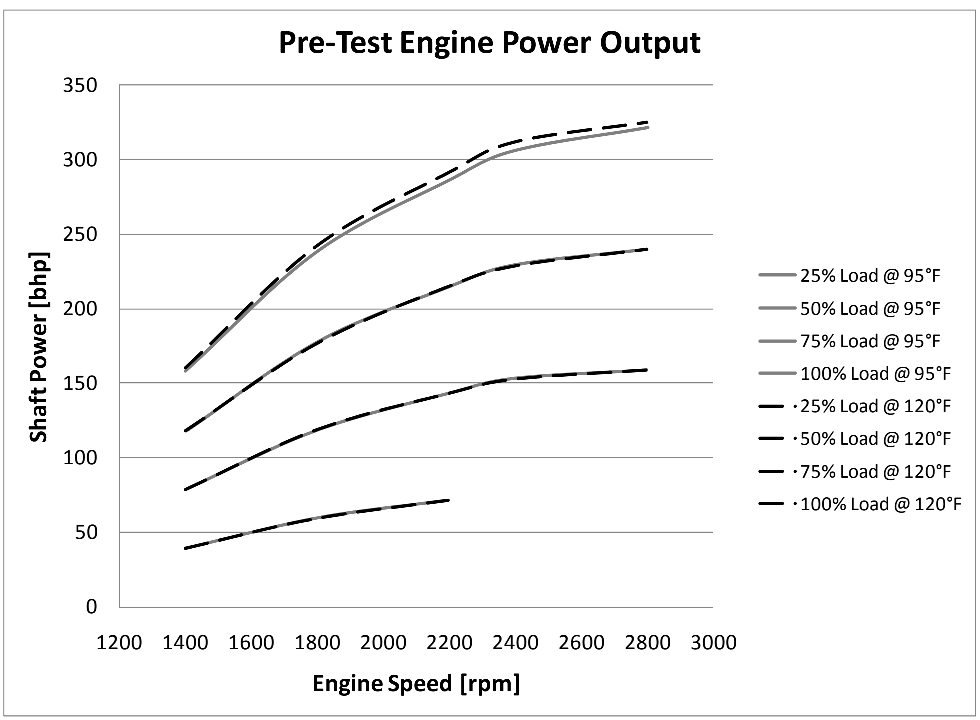
		Rated Conditions (2800 RPM)		Idle Conditions (600 RPM)	
Perameter:	**Units:**	**Average**	**Std. Dev.**	**Average**	**Std. Dev.**
Engine Speed	RPM	2800.02	2.00	601.21	6.00
Torque*	ft*lb	601.86	4.65	48.56	2.31
Fuel Flow	lb/hr	131.83	0.94	1.81	0.77
Power*	bhp	320.87	2.50	5.56	0.30
BSFC*	lb/bhp*hr	0.411	0.004	0.328	0.142
Temperatures:					
High Temperature Loop Coolant In	°F	185.08	0.74	174.34	11.34
High Temperature Loop Coolant Out	°F	203.00	0.52	177.24	11.61
Low Temperature Loop Coolant In	°F	100.02	1.17	85.75	8.20
Low Temperature Loop Coolant Out	°F	125.70	1.45	85.80	8.28
Oil Sump	°F	239.55	4.11	181.34	12.08
Fuel In	°F	89.47	5.61	85.95	8.43
Fuel Pump Drain	°F	106.44	6.36	89.58	8.70
Fuel Return	°F	101.97	2.78	87.18	8.45
Intake Air Before Compressor	°F	75.55	3.10	73.40	4.80
Intake Air After Compressor	°F	350.14	5.06	88.98	5.79
Intake Air After Charge Cooler	°F	109.44	1.15	84.61	8.58
Cylinder 1 Exhaust	°F	1416.98	14.88	287.79	19.01
Cylinder 2 Exhaust	°F	1364.12	16.66	284.01	17.18
Cylinder 3 Exhaust	°F	1387.31	14.72	284.85	13.05
Cylinder 4 Exhaust	°F	1368.84	16.54	265.15	11.62
Cylinder 5 Exhaust	°F	1394.05	13.15	275.59	15.64
Cylinder 6 Exhaust	°F	1414.47	15.42	287.57	13.51
Cylinder 7 Exhaust	°F	1401.15	14.55	273.56	11.13
Cylinder 8 Exhaust	°F	1394.43	15.26	276.95	11.63
Exhaust After Turbo	°F	1156.47	15.23	232.19	16.26
Pressures:					
Oil Galley	psi	56.08	0.67	28.80	1.61
Ambient Pressure	psiA	14.34	0.09	14.33	0.09
Intake Restriction	psi	0.53	0.01	-0.02	0.00
Exhaust Restriction	psi	10.71	0.26	-0.13	0.04
Boost Pressure	psi	20.30	0.30	0.41	0.03
Fuel Rail Pressure	psi	19345.69	24.41	3985.47	63.42

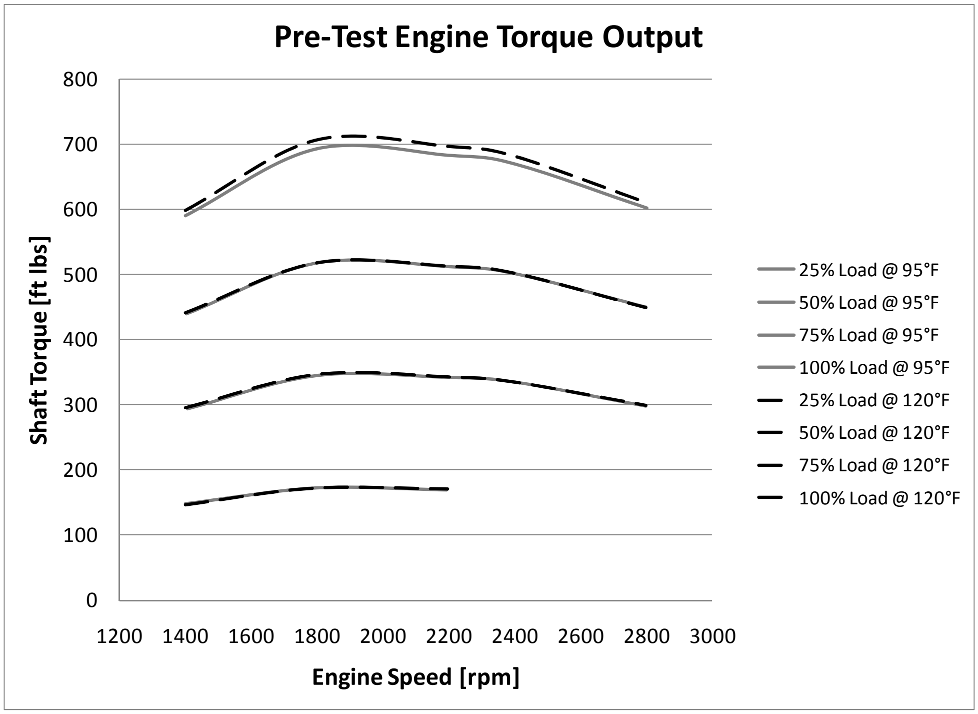
* Non-corrected Values

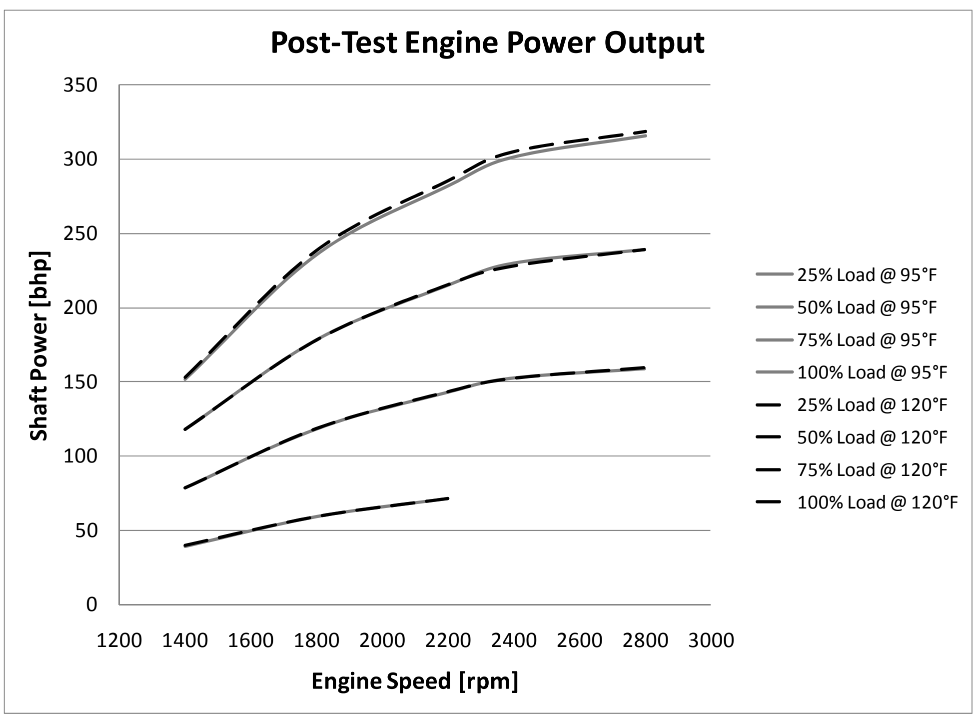
Engine Performance Curves

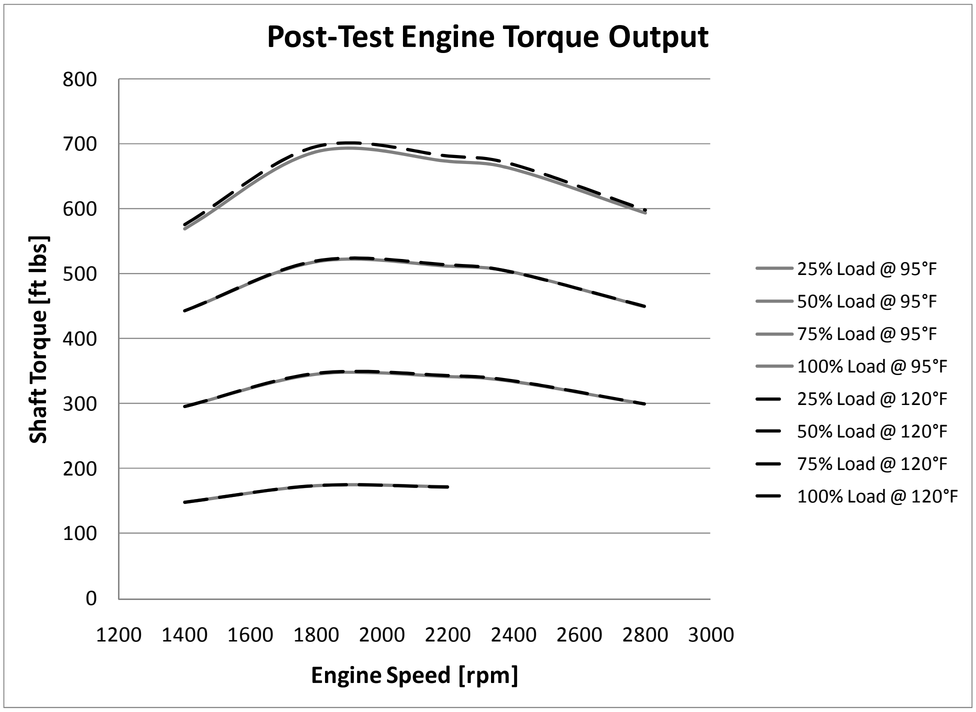
The plots below show the pre and post test engine power curves, as well as a pre and post test composite full load powercurve comparison.






Pre-Test Engine Torque Output
Shaft Torque [ft lbs]
800
700
600
500
400
300
200
100
0
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F


Post-Test Engine Power Output
Shaft Power [bhp]
350
300
250
200
150
100
50
0
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F



Engine Out Emissions

Direct engine out exhaust measurements were taken at the pre and post test powercurve testing segments to document the engines overall condition. In addition, tailpipe emission changes over the test duration could help identify fuel system degradation and engine performance changes. Mass based calculations were determined following methodology outlined in the Code of Federal Regulations, Title 40, Part 86, Subpart D. Final mass based emissions values were then correlated to engine fuel consumption rates to provide direct comparison of emission produced per unit mass of fuel. These values are denoted as the Emissions Index (EI).

In an effort to reduce testing delays, the ULSD test was initiated without completing full pre test emissions evaluations. Emission bench calibration gas delays incurred at the onset of the project would have further delayed testing that had already experienced setbacks due to engine availability. With COR approval, a reduced amount of emissions were sampled (with then available calibration gasses) at the pre-test powercurves and are included in tabular form for reference.

Table 6 - Pre-Test Emissions Measurements (LIMITED)

@ Ambient Temperature (Fuel = 95°F)						*@ Elevated Temperature (Fuel = 120°F)*				
Engine Speed	**Load**	**CO**	**NO/NOx**	**THC**		**Engine Speed**	**Load**	**CO**	**NO/NOx**	**THC**
RPM	**%**	**ppm**	**ppm**	**ppm**		**RPM**	**%**	**ppm**	**ppm**	**ppm**
1400			523	99		1400			624	63
1800			494	66		1800			599	49
2200	25%		455	63		2200	25%		550	51
2400			474	73		2400			567	60
2800			487	78		2800			583	64
1400		80.0	727	60		1400			875	55
1800		72.6	668	55		1800			803	44
2200	50%		683	66		2200	50%		818	52
2400			637	72		2400			766	55
2800			540	77		2800			648	65
1400		77.8	855	71		1400		68.6		58
1800		51.8	787	75		1800		46.1	938	55
2200	75%		734	97		2200	75%		882	69
2400			634	135		2400			754	83
2800			522	212		2800			624	119
1400			984	193		1400		88.9		97
1800		76.2	862	183		1800		57.6		107
2200	100%	59.5	795	218		2200	100%	57.9	939	147
2400		94.1	678	308		2400		82.3	802	207
2800			547	946		2800			643	502
** Note - Empty cells represent readings outside of calibrated range*										

The EI for the post test ULSD powercurves are plotted below:

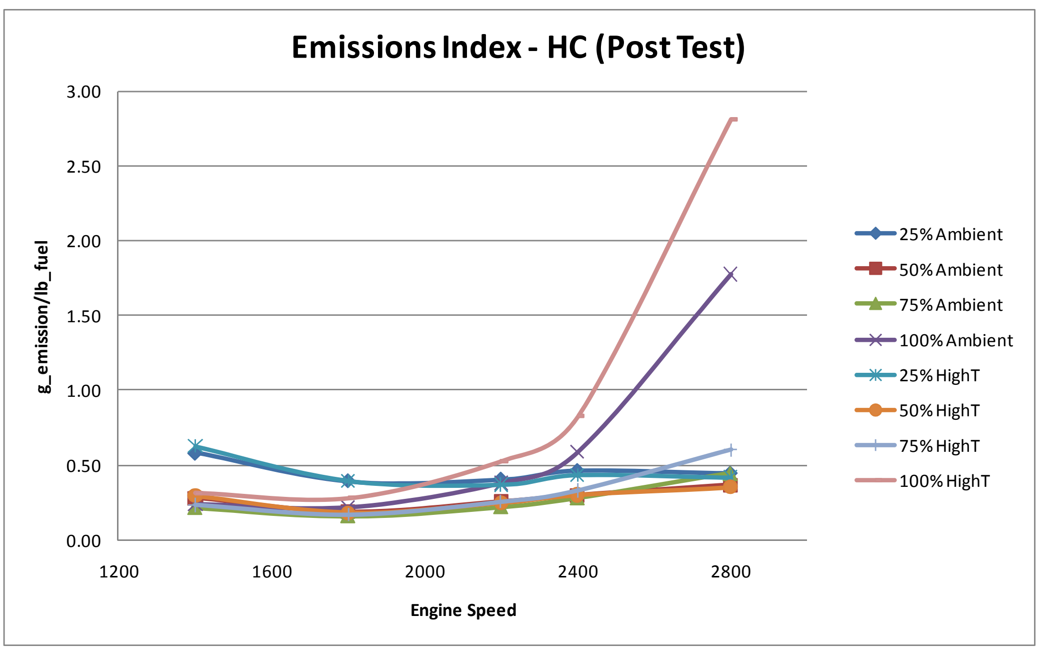


Figure 1 - AF7469 ULSD, Post Test HC Emissions Index

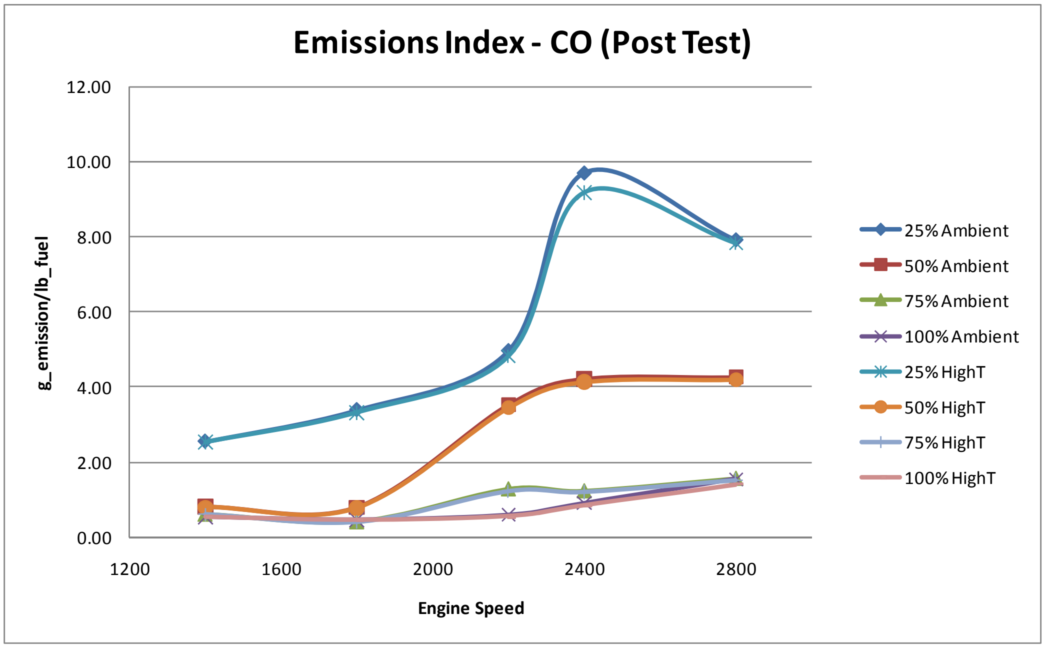


Figure 2 - AF7469 ULSD, Post Test CO Emissions Index

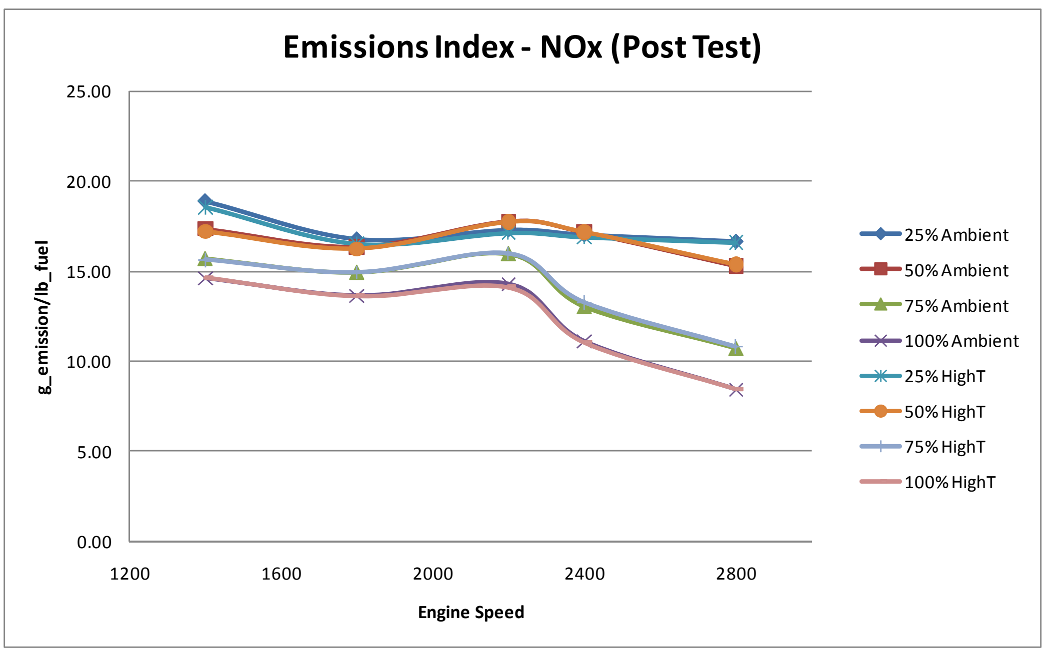


Figure 3 - AF7469 ULSD, Post Test NOx Emissions Index

Engine Noise Evaluation

Engine noise levels were quantified with the use of a handheld dB meter to use as a comparison with follow on testing. Noise measurements were taken at engine idle conditions with test cell cooling fans turned off in an effort to reduce any chance of data effects due to noise emitted from ancillary test equipment. No engine noise measurements were taken at rated speed conditions due to the extreme noise levels present in the test cell.

Fuel: AF7469
Engine Condition: Idle, Approx 600rpm
Date: 12/9/10

Front - 90dB
Top - 86.8dB
Left - 86.5dB
Right - 86.4dB

Fuel: AF7469
Engine Condition: Idle, Approx 600rpm
Date: 12/13/10

Front - 91.4dB
Top - 87.9dB
Left - 86.6dB
Right – 86.6dB

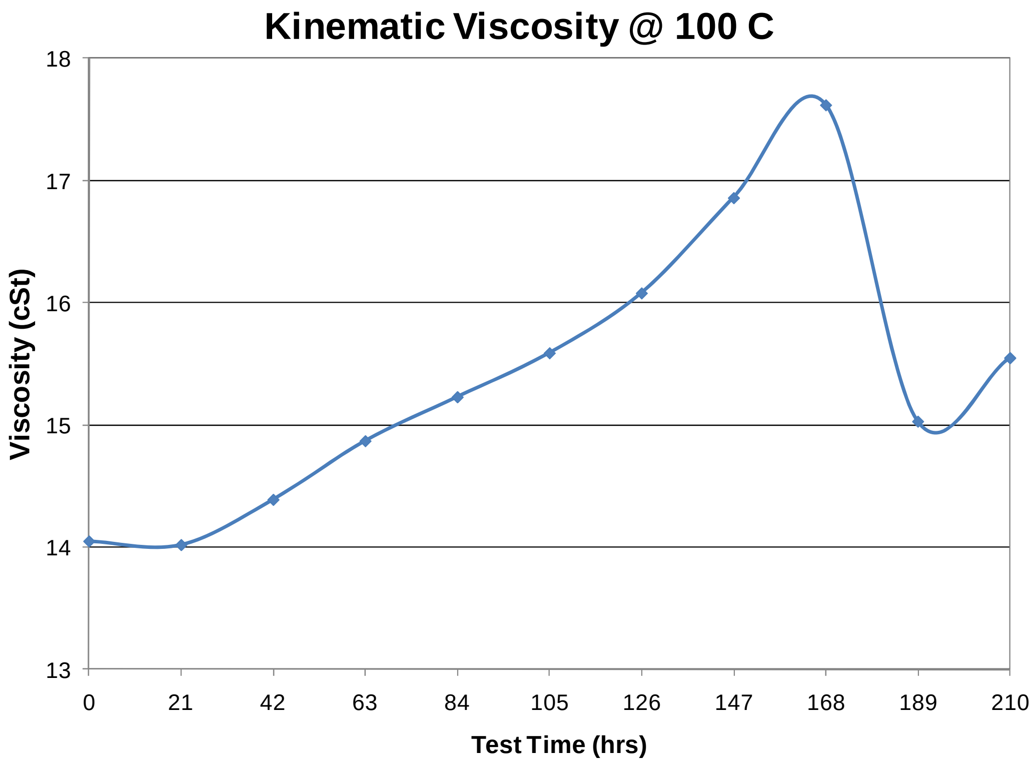
Engine Oil Analysis

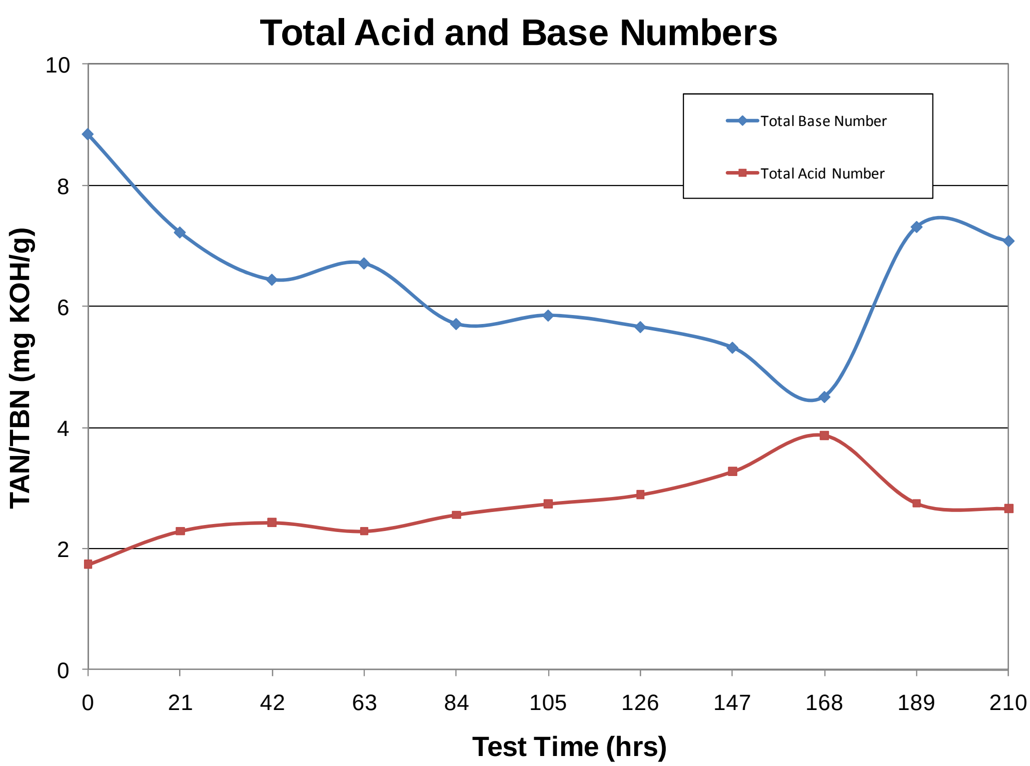
Table 7 below shows the engine used oil analysis over the test duration. An oil change was completed at the completion of 168 testing hours to prevent TAN & TBN cross and acceleration of engine oil degradation. Plots of various used oil property trends are shown below.

Table 7 – Engine Used Oil Analysis Over Test Duration

Property	ASTM Test	Test Hours										
		0	**21**	**42**	**63**	**84**	**105**	**126**	**147**	**168**	**189**	**210**
Density	**D4052**	0.854	0.859	0.863	0.867	0.870	0.873	0.877	0.881	0.885	0.862	0.867
Viscosity @ 100°C (cSt)	**D445**	14.1	14.0	14.4	14.9	15.2	15.6	16.1	16.9	17.6	15.0	15.6
Total Base Number (mg KOH/g)	**D4739**	8.8	7.2	6.4	6.7	5.7	5.9	5.7	5.3	4.5	7.3	7.1
Total Acid Number (mg KOH/g)	**D664**	1.7	2.3	2.4	2.3	2.6	2.7	2.9	3.3	3.9	2.8	2.7
Oxidation (Abs./cm)	**E168 FTNG**	0.0	1.1	1.9	2.9	3.2	4.1	4.5	5.4	5.8	1.5	2.5
Nitration (Abs./cm)	**E168 FTNG**	0.0	0.7	1.2	1.3	1.4	1.4	1.4	1.1	2.3	0.8	1.6
Soot	**Soot**	0.3	0.8	1.7	2.3	3.0	3.5	4.1	4.8	5.6	1.7	2.7
Wear Metals (ppm)	**D5185**											
Al		1	2	3	4	4	5	6	6	7	2	3
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		73	47	38	35	31	31	30	28	28	47	36
Ca		840	1013	1046	1014	1004	1042	1039	1046	1068	888	897
Cr		<1	<1	1	2	2	3	3	3	4	<1	1
Cu		<1	7	8	9	9	10	12	13	13	3	4
Fe		1	16	36	60	81	117	158	208	267	55	74
Pb		<1	<1	<1	1	1	2	1	2	2	<1	<1
Mg		1128	1033	1048	1047	1017	1149	1177	1173	1199	1237	1231
Mn		<1	<1	<1	1	1	2	2	2	3	<1	<1
Mo		66	60	61	62	61	64	65	67	67	68	69
Ni		<1	<1	<1	<1	<1	<1	<1	1	1	<1	<1
P		1104	1067	1074	1026	981	1027	1041	1013	1041	1094	1070
Si		4	6	7	8	9	9	10	11	12	7	8
Ag		<1	2	3	4	4	4	6	7	8	2	2
Na		7	6	9	7	7	8	10	10	10	8	9
Sn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Zn		1254	1230	1276	1227	1209	1292	1335	1351	1354	1292	1259
K		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Sr		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

Engine Oil Analysis Trends





Oil Consumption Data

Average oil consumption per test hour was 0.029 lbs/hr.
[Calculated by: (Total Additions-Total Samples)/210hrs]

Test Time	Samples: Date	Sample + Container Weight, lbs	-	Container Weight,lbs	=	Sample Weight, lbs
21 hr	12/3/10	0.29		0.06		0.23
42 hr	12/4/10	0.29		0.06		0.23
63 hr	12/7/10	0.31		0.06		0.25
84 hr	12/8/10	0.30		0.06		0.24
105 hr	12/9/10	0.30		0.06		0.24
126 hr	12/10/10	0.30		0.06		0.24
147 hr	12/11/10	0.30		0.06		0.24
168 hr	12/14/10	0.30		0.06		0.24
189 hr	12/15/10	0.29		0.06		0.23
210 hr	12/16/10	0.30		0.06		0.24
				Total Samples	=	2.38

Test Time	Additions: Date	Addition + Container Weight, lbs	-	Container Weight,lbs	=	Addition Weight, lbs
21 hr	12/3/11	0		0		0
42 hr	12/6/11	1.57		0.13		1.44
63 hr	12/7/11	1.7		0.13		1.57
84 hr	12/8/11	1.17		0.13		1.04
105 hr	12/9/11	1.3		0.13		1.17
126 hr	12/10/11	1.33		0.13		1.20
147 hr	12/13/11	0.63		0.13		0.50
168 hr	12/14/11			Engine Oil Change		
189 hr	12/15/11	0		0		0
210 hr	12/16/11	1.63		0.13		1.50
				Total Additions	=	8.42

Post Test Fuel Injection Hardware Inspection

Table 8 shown below outlines the visual inspection results from the post test high pressure common rail fuel injection pump, compared to new unused components.

Table 8 – Outline of Visual Inspection Results

Part	New	DF-2
Volume Control Valve	New	As new
Pump Body	Very light polish of bores	Very light polish of bores, top & bottom
Pump Bushings	Both new	Both as new
Cam	Visible light grinding marks	Light polish, not measureable, seal contact wear
Roller - Left	New, bright & shiny	Light polish
Roller - Right	New, bright & shiny	Light polish
Roller Shoe - L	New	New, polish from plunger button
Roller Shoe - R	New	New, polish from plunger button
Follower - L	New	Very light polish
Follower - R	New	Very light polish
Plunger - L	New	As new, very light polish on plunger button, more than right
Plunger - R	New	As new, very light polish on plunger button
Barrel - L	New	As new
Barrel - R	New	As new
Inlet Check - L	New	As new
Inlet Check -R	New	As new

Post Test Fuel Injection Hardware Photos (no magnification)

The following photos document the post test fuel injection hardware condition. Figure 4 and Figure 5 shows a representative photo of the HPCR pump body. Frame of reference for left and right notations are taken from Figure 5 based off of orientation as installed in the engine.

Figure 4 - HPCR Pump Body, Front (Representative Photo)

Figure 5 - HPCR Pump Body, Rear (Representative Photo)

Figure 6 shows the left hand pump body bore, while Figure 7 shows a close up picture of the light polish found on the bore surface from interaction with the cam follower assembly.

Figure 6 - AF749 ULSD, Post Test, Left Pump Bore

Figure 7 - AF7469 ULSD, Post Test, Left Pump Bore Close

Figure 8 shows the right hand pump body bore, while Figure 9 shows a close up picture of the light polish found on the bore surface similar to the left hand bore.

Figure 8 - AF7469 ULSD, Post Test, Right Pump Bore

Figure 9 - AF7469 ULSD, Post Test, Right Pump Bore Close

Figure 10 and Figure 11 shows the pump body rear and front camshaft bushings respectively. The bushings showed no signs of wear.

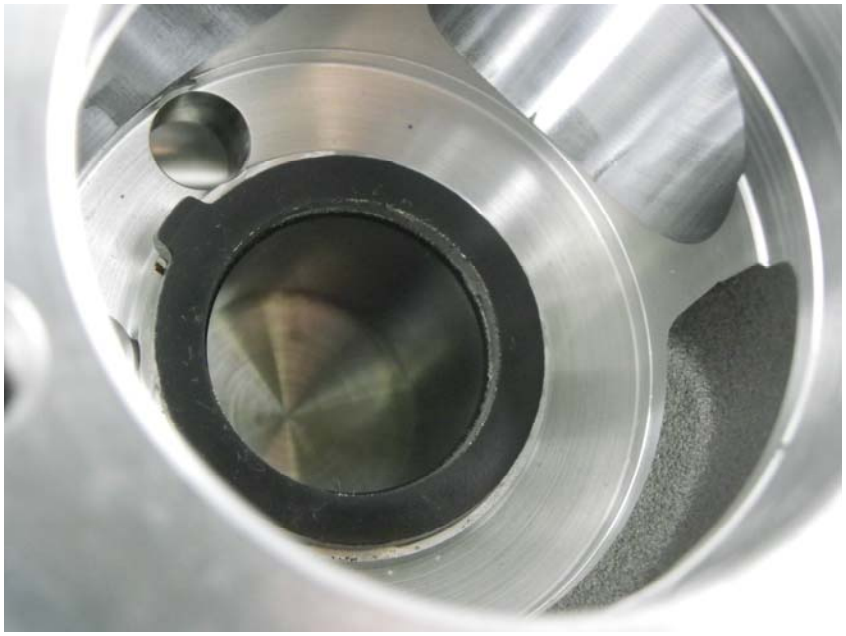


Figure 10 - AF7469 ULSD, Rear Pump Body Camshaft Bushing

Figure 11 - AF7469 ULSD, Front Pump Body Camshaft Bushing

Figure 12 shows the HPCR fuel injection pump camshaft.

Figure 12 - AF7469 ULSD, HPCR Pump Camshaft

Figure 13 shows a close-up of a cam lobe peak. A slight polish can be seen in the contact areas of the cam surface, but no measureable wear is detected.

Figure 13 - AF7469 ULSD, HPCR Pump Camshaft, Lobe Surface Close-up

Figure 14 shows the left bore cam follower and roller assembly. The follower was oriented to show the most severe areas of scuffing present on the follower surface. Figure 15 below shows the left hand roller surface.

Figure 14 - AF7469 ULSD, Left Cam Follower

Figure 15 - AF7469 ULSD, Left Cam Follower Roller

Figure 16 shows the left cam follower undercrown and the contact area with the high pressure piston head. Figure 17 shows the left hand high pressure plunger. Note the similar markings where it contacts the follower undercrown. Polishing at this interface was visible, but no physical wear was tactically distinguishable.

Figure 16 - AF7469 ULSD, Left Cam Follower Undercrown

Figure 17 - AF7469 ULSD, Left High Pressure Plunger

Figure 18 shows the right bore cam follower and roller assembly. Unlike the left hand follower, this follower did now show any scuffing on the follower surface. Figure 19 below shows the right hand roller surface.

Figure 18 - AF7469 ULSD, Right Cam Follower

Figure 19 - AF7469 ULSD, Right Cam Follower Roller

Figure 20 shows the right cam follower undercrown and the contact area with the high pressure piston head. Figure 21 shows the right hand high pressure plunger. Similar to the left hand assembly, polishing at this interface was visible, but no physical wear was tactically distinguishable.

Figure 20 - AF7469 ULSD, Right Cam Follower Undercrown

Figure 21 - AF7469 ULSD, Right High Pressure Plunger

Post Test Fuel Injection High Magnification Photos

The following photos document the post test fuel injector hardware condition. Figure 22 shows the injector nozzle tip. No substantial deposit formations were seen under low magnification. Figure 23 below shows the injector needle tip. No abnormal wear or markings were found on the tapered seat.

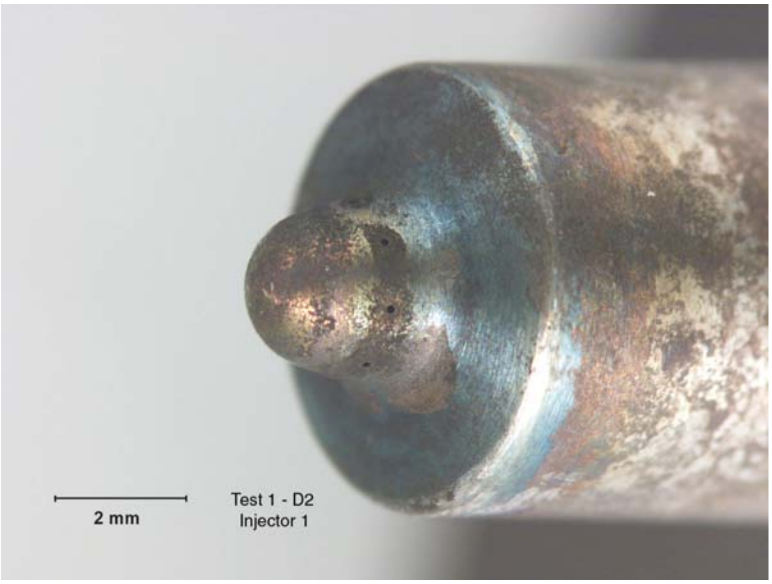


Figure 22 - AF7469 ULSD, Injector Nozzle

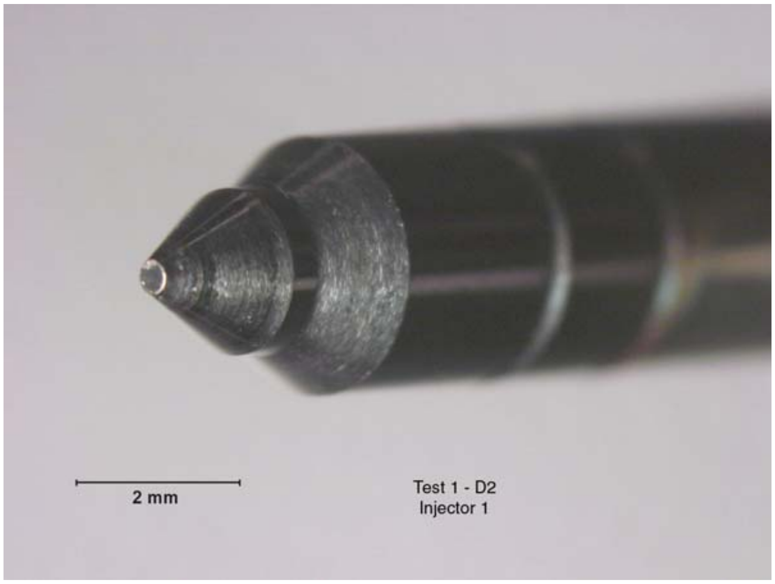


Figure 23 - AF7469 ULSD, Injector Needle

Figure 24 and Figure 25 shows the upper and lower hydraulic coupler pistons respectively. No noticeable wear was seen on the piston surface interface, or at the heads of the piston at the piezo- stack and control valve interface.

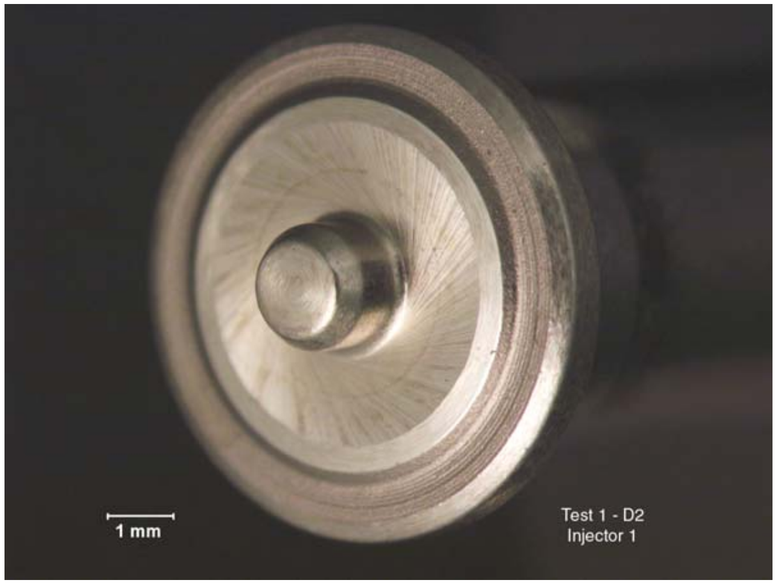


Figure 24 - AF7469 ULSD, Upper Hydraulic Coupler Piston

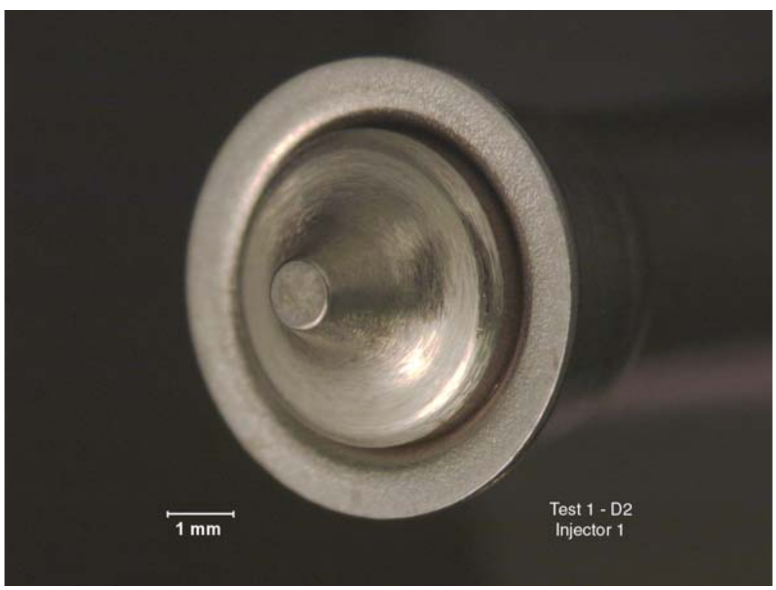


Figure 25 - AF7469 ULSD, Lower Hydraulic Coupler Piston

Figure 24 and Figure 25 shows the side profile of the upper hydraulic coupler piston. A wear scar shows on the surface of the piston consistent with wear expected from being slightly cocked in the bore when depressed by the piezo-stack.

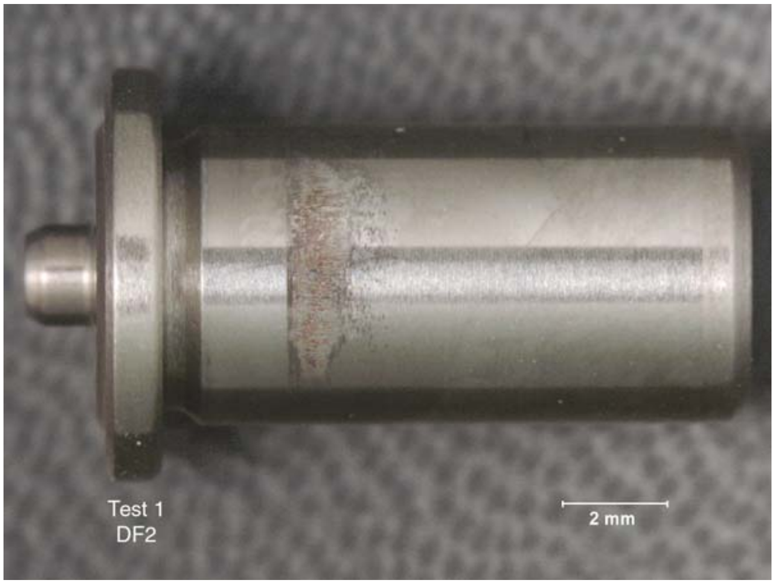


Figure 26 - AF7469 ULSD, Upper Hydraulic Coupler Piston, Profile

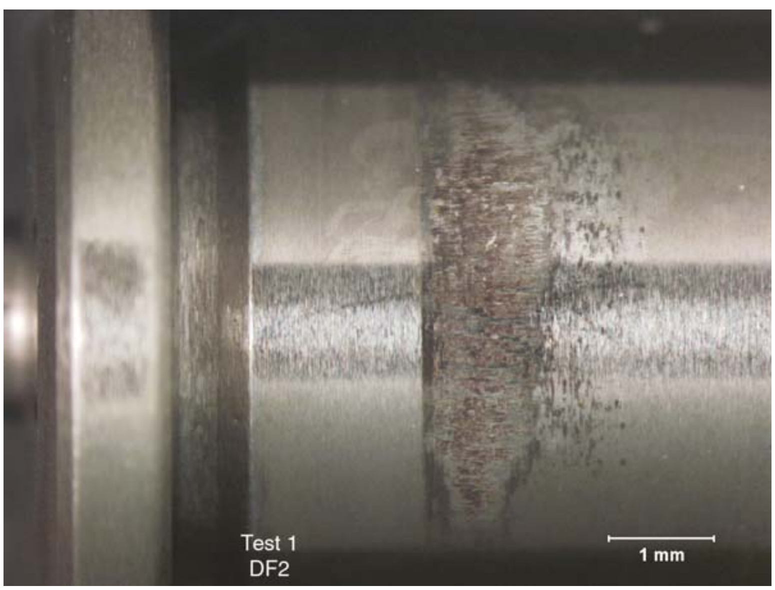


Figure 27 - AF7469 ULSD, Lower Hydraulic Coupler Piston, Wear Scar Close Up

Figure 28 and Figure 29 shows the top and bottom surfaces of the intermediate plate. This plate contains the fuel control passages used to manipulate the needle position.

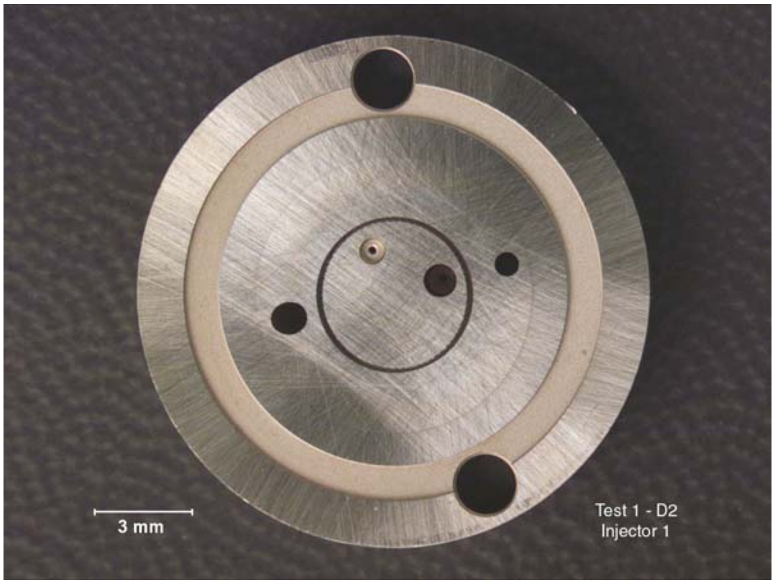


Figure 28 - AF7469 ULSD, Intermediate Plate (Top)

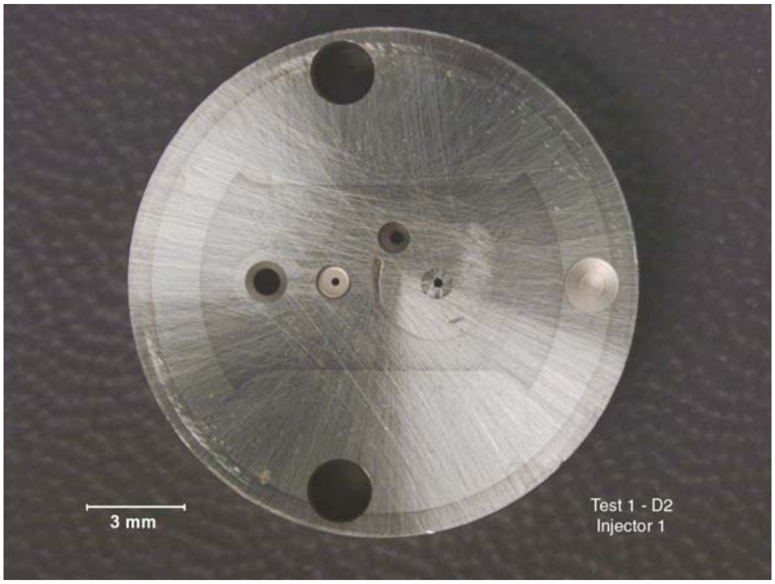


Figure 29 - AF7469 ULSD, Intermediate Plate (Bottom)

Figure 30 and Figure 31 shows the top and bottom of the control valve plate. The control valve sits in the bore shown in Figure 31. The lower piston of the hydraulic coupler operates in the bore shown in Figure 30.

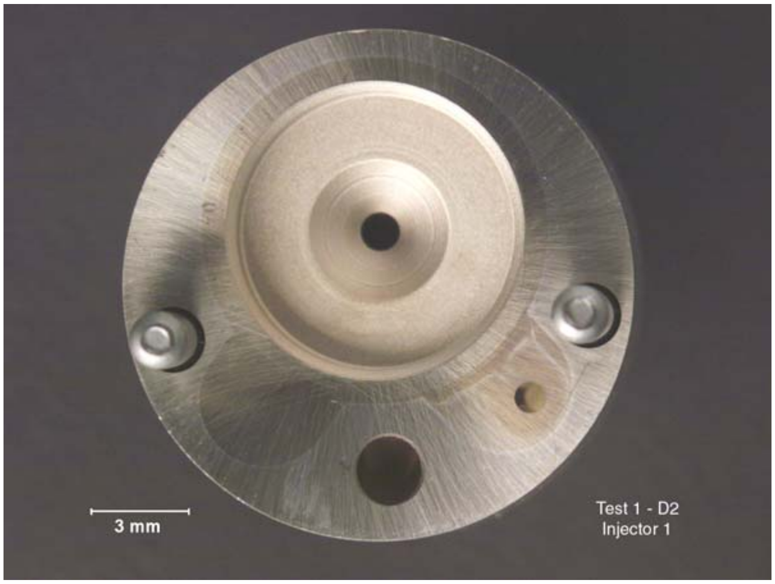


Figure 30 - AF7469 ULSD, Control Valve Plate (Top)

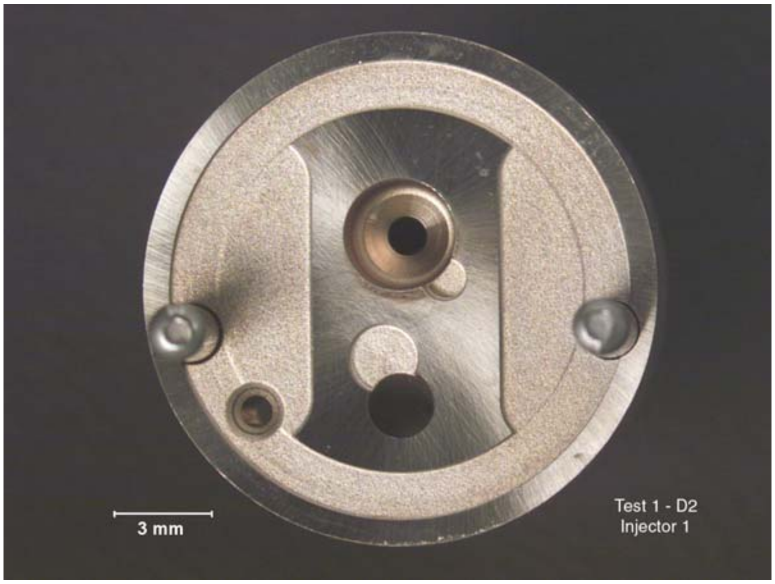


Figure 31 - AF7469 ULSD, Control Valve Plate (Bottom)

Figure 32 shows the control valve which regulates the pressure on top of the injector needle, thus controlling lift. No unusual wear was found on the control valve.

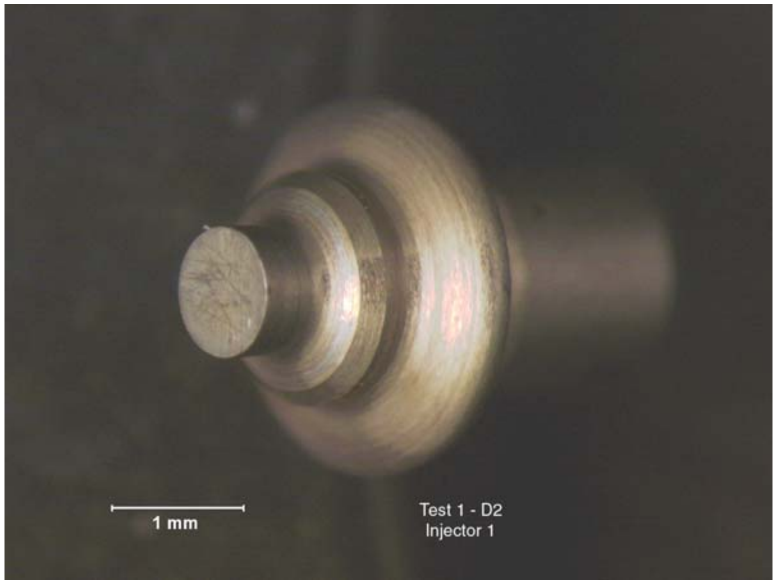


Figure 32 - AF7469 ULSD, Fuel Injector Control Valve

Noted Problem Areas

TFLRF staff noted a consistent drop in engine boost pressure over the ULSD (Test 1) endurance test duration (approximately 4.5% loss from start to finish). As expected, engine mass air flow and other related parameters showed similar losses over testing. Despite this, the engine fuel flow rate did not follow the same reduction, thus the boost pressure reduction did not impact the overall test goals. As a byproduct of the engine mass flow reduction, the engine air fuel ratio (AFR) slightly enriched over testing and resulted in elevating exhaust gas port temperatures (EGT) over the test duration. This trend was also experienced in the JP-8 (Test 2) and 50/50 JP-8/SPK test (Test 3), and resulted in a replacement of the turbocharger assembly prior to the neat SPK test (Test 4).

APPENDIX B

JP-8 Test Report

(AF7801-67T1-W-210)

Evaluation of JP-8 in the Ford 6.7L High Pressure Common Rail Diesel Engine

Project 14734.08

Ford Motor Company 6.7L Diesel

Test Lubricant ID: N/A
Test Lubricant: Full Synthetic, CJ-4, SAE 5W-40
Test Fuel ID: AF7801
Test Fuel: JP8, Blended from Valero Jet-A w/9ppm DCI-4A
Test Number: AF7801-67T1-W-210
Start of Test Date: January 31, 2011
End of Test Date: February 15, 2011
Test Duration: 210 Hours
Test Procedure: Tactical Wheeled Vehicle

Conducted for
Mobility & Vehicles Engineering
United States Air Force WR-ALC
Robins AFB, GA

Introduction

This test was used to determine the performance and endurance of a modern high pressure common rail diesel fuel injection system when operated on JP-8. Testing was completed following a modified version of the 210hr Tactical Wheeled Vehicle Cycle engine endurance test cycle (CRC Report No.406, Development of Military Fuel/Lubricant/Engine Compatibility Test). This work was completed in support of Project 14734.08, Identification of The Effects of Alternative Fuels Utilization on USAF Vehicles and Equipment Powered by Compression Ignition Engines with Common-Rail Fuel Injection.

Test Engine

The Ford 6.7L diesel engine was chosen for testing as a representative engine utilizing modern high pressure common rail fuel injection technology. The Ford 6.7L engine is a direct injected, turbo-charged, intercooled engine, which employs a fuel lubricated high pressure common rail injection pump and piezo-electric fuel injectors. The test engine had approximately 210hrs of previous testing time in support of additional research, but was fitted with a new fuel injection pump and fuel injectors prior to testing to restore the high pressure fuel system to “as new” condition.

Test Stand Configuration

The engine was mounted in a test stand specifically configured for Ford 6.7L engine testing. Engine monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. An appropriately sized absorption dynamometer was used to control engine speed and dissipate load. Engine load was manipulated through the actuation of the engine throttle pedal assembly. Engine coolant temperatures were controlled with the use of liquid-to-liquid heat exchangers utilizing laboratory process water for cooling. Engine intake air was supplied at ambient conditions utilizing the factory engine air box and ducting. Engine exhaust was routed from the test cell through a butterfly valve to control engine exhaust back pressure, and then ducted into the laboratory exhaust blower system for removal. Fuel was supplied to the diesel fuel conditioning module/engine at ambient conditions.

Engine Run-in

Prior to testing, the engine was run-in following the Ford specified engine run-in procedure. This was done despite the previous testing time accrued on the engine to allow for the same duration of engine operation on each fuel system for test consistency. Table 1 below outlines the Ford recommended engine run-in procedure.

Table 1 - Ford Recommended Run-In Procedure

Step	Duration	Speed [rpm]	Load [lb-ft]	Load [Nm]
1	0:05	650	0	
2	0:30	1000	72	97
3	0:30	1200	103	140
4	0:30	1400	141	191
5	0:30	1500	162	219
6	0:30	1600	184	249
7	0:30	1700	208	282
8	0:30	1800	233	316
9	0:30	2000	287	390
10	0:30	2200	348	472
11	0:30	2400	414	561
12	0:30	2500	449	609
13	0:30	2600	486	659
14	0:30	2700	524	710
15	0:30	2800	563	764

Pre and Post Test Engine Performance Checks

Before and after testing, engine powercurves were completed at varying speeds and loads to determine pre-test engine performance. Engine performance was documented at engine speeds of 1400, 1800, 2200, 2400, and 2800 rpm, with load intervals of 25%, 50%, 75%, and 100% of full load. Powercurves were completed at both ambient (95°F) and desert condition (120°F) inlet fuel temperatures. Exhaust gas emissions were sampled at each point on the curve to document engine out emissions. Powercurve plots can be seen in the Engine Performance Curves section.

Test Cycle

The test cycle followed during fuel system evaluations was a modified version of the 210 hr Tactical Wheeled Vehicle Cycle as outlined in CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test. Slight modifications were made to the test cycle to accelerate the testing schedule. The primary modification was the reduction of engine soak time from 10hrs to 3hrs. The engine soak period in the test cycle was originally included for engine lubricant testing, and added no benefit for fuel compatibility testing. Total modified daily runtime was 21hrs per day, 15hrs at rated speed/load and 6hrs at idle, followed by a 3hr engine soak. To keep the modified test cycle rated to idle testing hours consistent with the standard 210hr Tactical Wheeled Vehicle Cycle, the following daily operating arrangement was derived. The engine completed 6 cycles of 2hr 10min at rated speed followed by a 1hr idle step. After the 6 cycles were completed, an additional 2hr rated segment was conducted followed by the 3hr soak. Engine coolant temperatures were maintained at Ford specifications to ensure engine integrity throughout the test. Engine coolant utilized was a 50/50 blend of ethylene glycol antifreeze and deionized water. Engine operating parameters were controlled as specified in Table 2 on the following page.

(Note – Engine idle speed was controlled by PCM at approximately 600 RPM. Temperature controllers remained at rated speed set points for idle conditions, but were not met due to lack of heat generation in the coolant system. Temperatures were allowed to reach their natural steady state value during idle testing steps. Engine oil cooler plumbing was integral to the engine water jacket, thus not directly controlled. Oil temperatures were allowed to meet their own steady state temperature based on water jacket temperature and engine load/speed throughout testing.)

Table 2 - Test Cycle Operation Parameters

Parameter	Rated Speed	Idle
Engine Speed	2800 +/- 25	NC
High Temp Coolant Loop	203 +/- 3	NC
Low Temp Coolant Loop	100 +/- 3	NC
Oil Sump	NC	NC
*NC = not controlled		

Oil Sampling

Four ounces of engine oil was sampled every 21hrs (daily) for used oil analysis. Used oil analysis consisted of the following tests as seen below in Table 3. Engine oil changes were performed on the engine based on used oil condition.

Table 3 - Used Oil Analysis Procedures

Daily Used Oil Analysis		
ASTM	D4739	Total Base Number
ASTM	D664	Total Acid Number
ASTM	D445	Kinematic Viscosity @ 100°C
ASTM	API Gravity	API Gravity
ASTM	D4052	Density
ASTM	TGA SOOT	TGA Soot
ASTM	E168	Oxidation
ASTM	E168	Nitration
ASTM	D5185	Wear Metals by ICP

Used oil analysis results can be seen in the engine oil analysis and engine oil analysis trends section of the report.

Oil Level Checks

Engine oil level was checked daily, and replenished as needed to restore oil level to full mark. This process occurred after the completion of the 3hr soak prior to restarting testing the next day.

Test Fuel Analysis

The test fuel used was JP-8 which was blended at location from commercially available Jet-A. Since the primary focus of testing was fuel lubricity compatibility, only the lubricity enhancer/corrosion inhibitor additive was blended into to the Jet-A. The remaining two additives typically found in JP-8 have little impact on fuel lubricity levels and fuel system durability. The lubricity enhancer used was Innospec Fuel Specialties DCI-4A. Per QPL-25017, the minimum effective treat rate of DCI-4A required an additive concentration of 9ppm in the final fuel blend. In an effort to determine fuel system impact in a "worst case" scenario, the test fuel was treated only at the minimum effective treat rate regardless of the resulting lubricity achieved. After the test fuel was additized and blended, fuel samples were collected to determine critical chemical and physical properties for reporting. Table 4 summarizes these critical properties of the tested JP-8. Table 5 on the following page shows the certificate of analysis (COA) for the Jet-A as received.

Table 4 - Test Fuel Chemical & Physical Analysis

Property	Units	Method	Results
Density @15°C	g/mL	D4052	0.736
Specific Gravity @15°C		D4052	0.737
API Gravity @15°C		D4052	60.6
Flashpoint	°F	D56	111
	°C	D93	43
	°F	D3828	109
Kinematic Viscosity @-20°C	cSt	D445	2.5
Kinematic Viscosity @40°C	cSt	D445	0.9
Hydrocarbon Content			
Carbon	wt%	D5291	83.94
Hydrogen	wt%		16.46
Calculated Cetane Index		D976	57.2
Calculated Cetane Index		D4737	66.8
Cetane Number		D613	64.0
IQT	DCN	D6890-04	58.5
Heat of Combustion (Gross)	BTU/lb	D240	20364.4
Total Acid Number	mg KOH/g	D3242	0.011
Hydrocarbon Type			
Aromatics	%mass	D5186	0.3
Hydrocarbon Type			
Aromatics	%vol	D1319	0.4
Olefins			0.5
Saturates			99.1
Sulfur	ppm	D5453	<10
Nitrogen	wt%	D3228	<0.03
HFRR	mm	D6079	0.840
BOCLE	mm	D5001	0.76
Bulk Modulus @30°C	psi	by Speed of Sound	152749
Distillation			
IBP	°C	D86	152.5
10%			161.5
20%			162.7
50%			168.8
90%			186.0
End Pt			203.0

Table 5 - Valero Jet-A Certificate of Analysis (COA)

01/02/2011 17:11 8303938101 ALCOR PETROLAB LLP

Alcor PetroLab, L.L.P.

20 Laboratory Road, Floresville, Texas 78114 Telephone 830-216-3113 www.alcorpetrolab.com

NuStar
San Antonio Products Terminal
P. O. Box 241017
San Antonio, Texas 78224-1017

January 2, 2011

Sample Type: Jet A
Tank Number.: 103
nt @ 1007 01/02/11 pu @ 1330 01/02/11

Sample Date: 01/02/11
Sample Time: 1330

Volatility	Method	Specification		Result
Initial Boiling Point (°F)	D 86			333.3
Distillation 10% Rec (°F)		400	max	345.4
Distillation 50% Rec (°F)		Report		365.9
Distillation 90% Rec (°F)		Report		412.5
Distillation 95% Rec (°F)		Report		431.4
Distillation Final BP (°F)		572	max	475.5
Distillation Recovery (vol %)				98.2
Distillation Residue (vol %)		1.5	max	0.7
Distillation Loss (vol %)		1.5	max	1.1
Flash Point, Tag Closed (°F)	D 56	100	min	127.0
API Gravity @ 60 (°F)	D 1298	37.0 / 51.0		45.0
Cetane Index	D 4737	40.0	min	39.7
Particulate Matter Mgs/Gal	D 2276	3.0	max	0.8
Sulfur Wt %	D 7220	0.30	max	0.0005
Copper Strip	D130	No. 1	max	1A
Existent Gum Mgs / 100 Mls.	D381	7	max	<1.0
Fluidity				
Freezing Point (°F)	D 2386	-41.0	max	-82.3
Contaminants				
Color (Saybolt)	D 156	+15	min	+30
Appearance	D4176	clear/bright	pass/fail	Pass
Water Reaction: Change	D 1094	2.0	max	0
Water Reaction: Interface Rating	D 1094	2	max	1
Water Reaction: Separation Rating	D 1094	2	max	1
MSEP	D 3948	85	min	98

This Product Conforms to ASTM D1655 for the Above Tests: XX **YES** ___ NO

Reviewed and submitted by,

Chris Taylor CEO

Chris Taylor CEO

Report Number: P010211A

Endurance Test Cycle Results

The following information summarizes the results of the engine fuel system endurance tests. Data includes: engine operating summary, powercurve analysis, engine out emissions, used oil analysis, post test component inspection, post test component photos, and listing of any problem areas or anomalies experienced during testing.

Engine Operating Conditions Summary

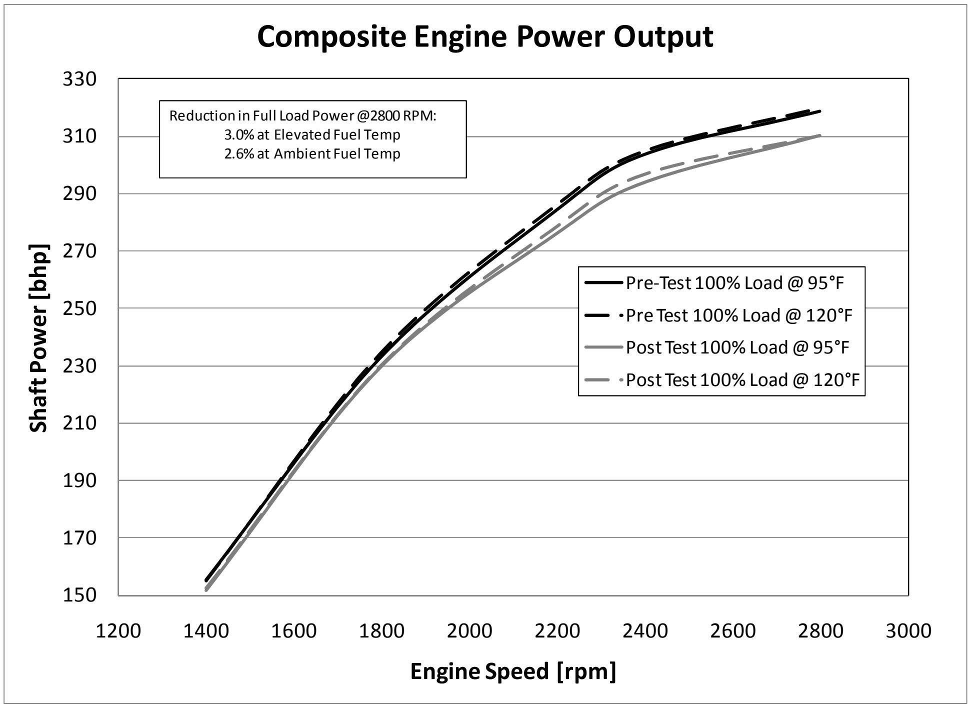
Below is a summary of the engine operating conditions over the 210hr test duration.

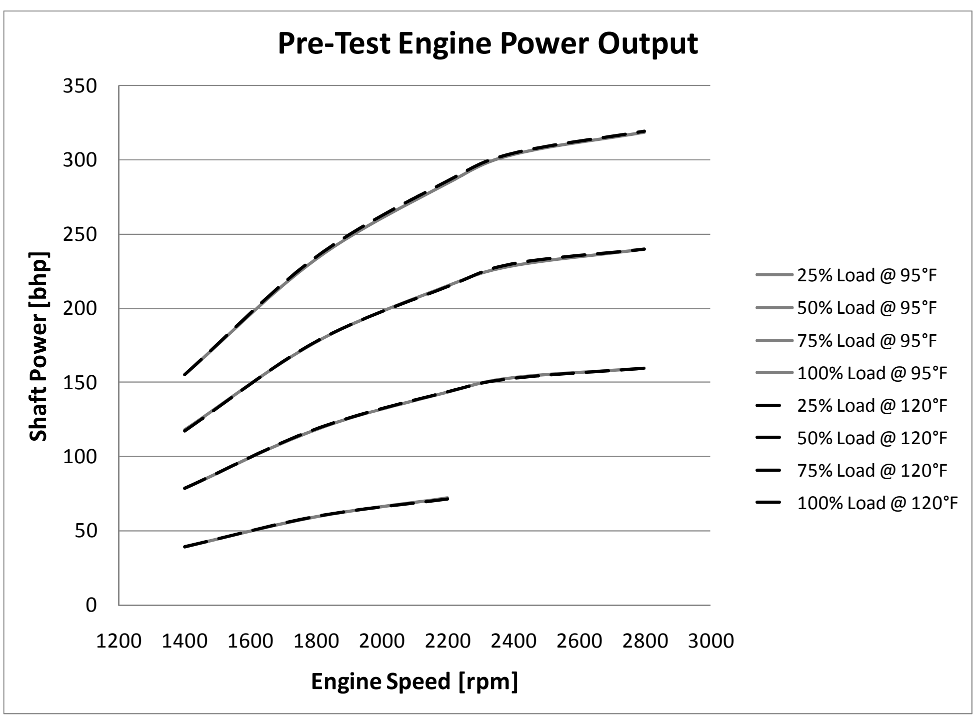
		Rated Conditions (2800 RPM)		Idle Conditions (600 RPM)	
Perameter:	**Units:**	**Average**	**Std. Dev.**	**Average**	**Std. Dev.**
Engine Speed	RPM	2799.98	2.40	601.02	2.15
Torque*	ft*lb	594.10	5.53	40.20	3.25
Fuel Flow	lb/hr	128.67	2.61	2.48	0.61
Power*	bhp	316.73	2.96	4.60	0.37
BSFC*	lb/bhp*hr	0.406	0.008	0.544	0.129
Temperatures:					
High Temperature Loop Coolant In	°F	185.44	0.64	167.98	14.07
High Temperature Loop Coolant Out	°F	203.00	0.45	170.79	14.37
Low Temperature Loop Coolant In	°F	100.06	1.05	82.41	12.97
Low Temperature Loop Coolant Out	°F	123.34	1.28	80.93	10.23
Oil Sump	°F	243.66	1.24	175.31	15.02
Fuel In	°F	84.69	8.12	80.22	10.59
Fuel Pump Drain	°F	101.92	8.09	83.67	10.56
Fuel Return	°F	99.95	3.10	81.53	10.30
Intake Air Before Compressor	°F	75.38	5.52	70.73	7.65
Intake Air After Compressor	°F	334.08	6.68	82.17	8.57
Intake Air After Charge Cooler	°F	106.88	1.03	79.82	10.40
Cylinder 1 Exhaust	°F	1423.18	12.35	268.38	20.03
Cylinder 2 Exhaust	°F	1370.15	13.28	247.25	17.43
Cylinder 3 Exhaust	°F	1401.47	14.35	260.01	17.58
Cylinder 4 Exhaust	°F	1388.66	15.07	252.25	17.40
Cylinder 5 Exhaust	°F	1406.34	14.06	241.99	16.93
Cylinder 6 Exhaust	°F	1436.30	14.35	256.48	16.92
Cylinder 7 Exhaust	°F	1409.89	14.95	251.67	15.51
Cylinder 8 Exhaust	°F	1402.12	16.40	253.14	14.87
Exhaust After Turbo	°F	1179.12	15.46	222.99	20.66
Pressures:					
Oil Galley	psi	54.93	0.40	28.57	2.08
Ambient Pressure	psiA	14.37	0.09	14.37	0.09
Intake Restriction	psi	0.51	0.01	-0.02	0.00
Exhaust Restriction	psi	10.52	0.22	-0.15	0.03
Boost Pressure	psi	18.73	0.52	0.21	0.07
Fuel Rail Pressure	psi	19399.39	28.39	3993.37	25.10

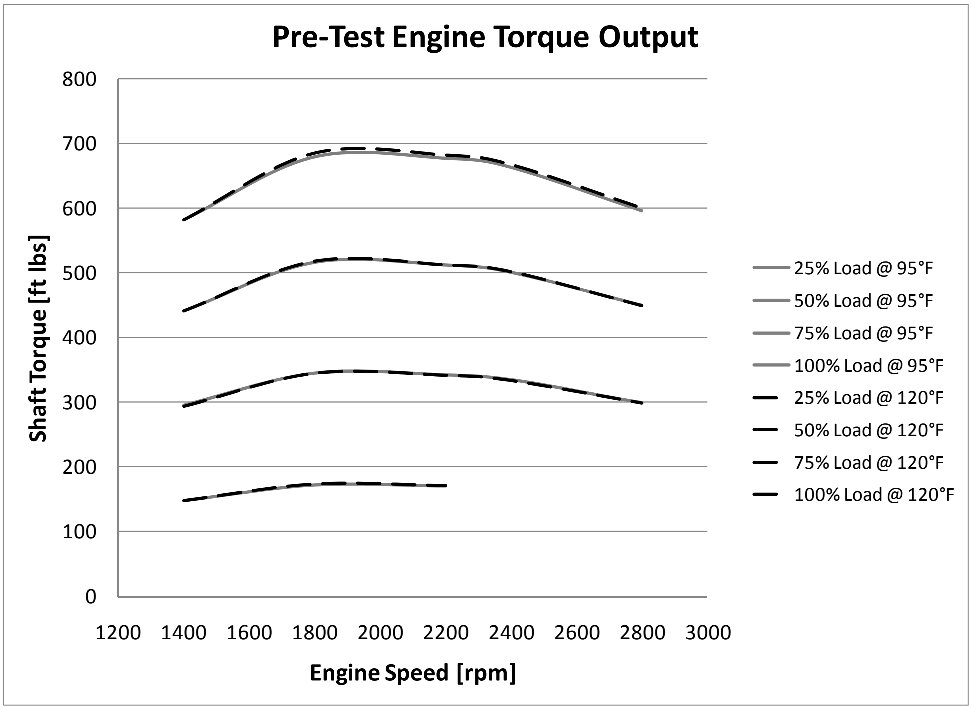
* Non-corrected Values

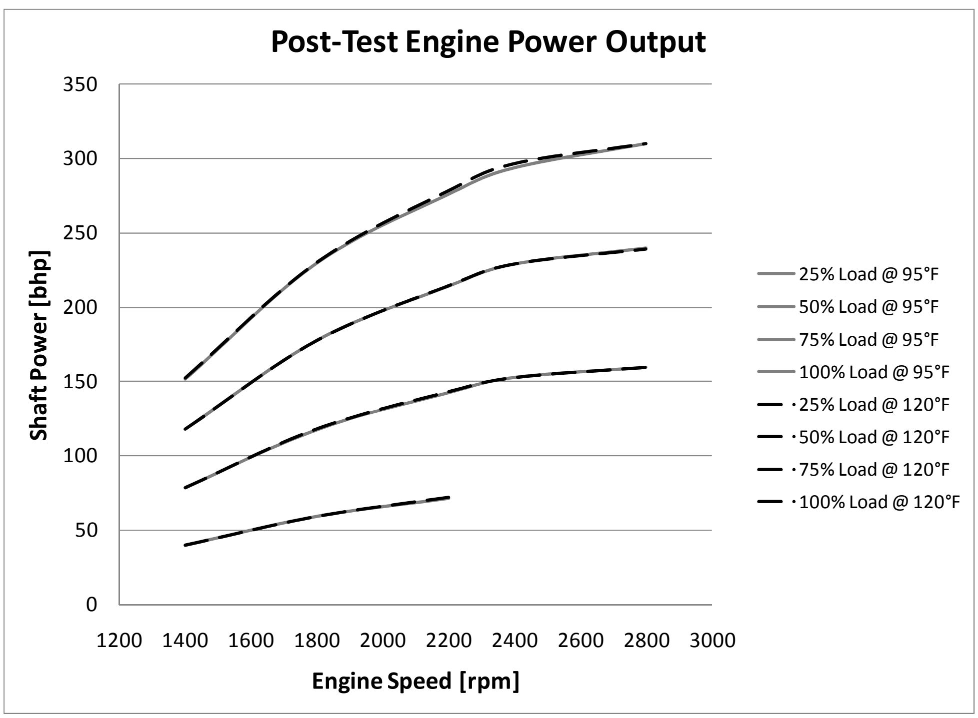
Engine Performance Curves

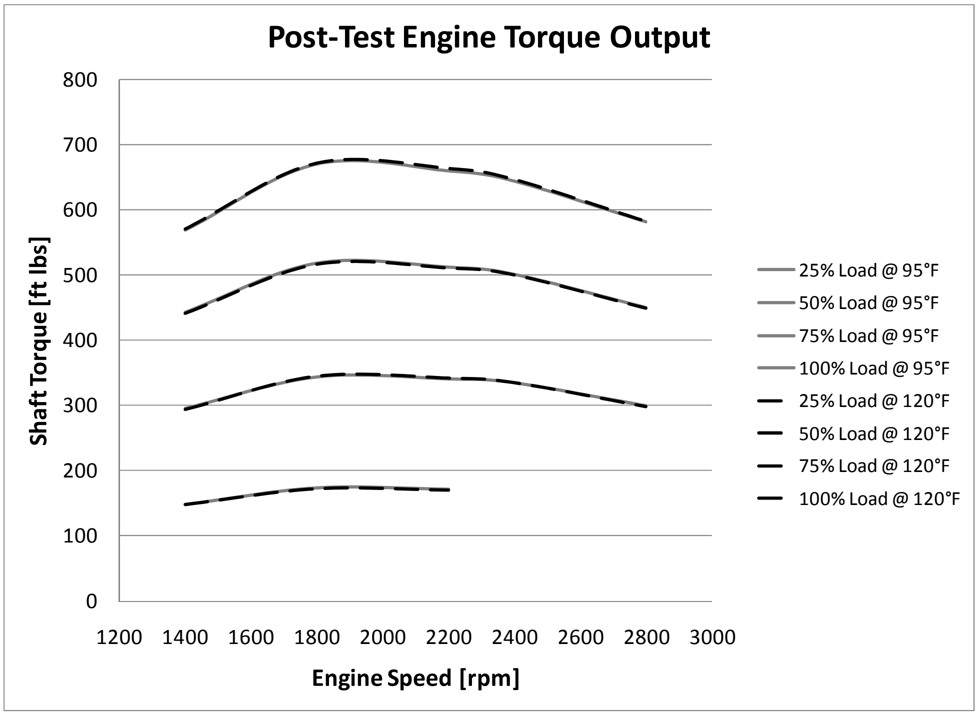
The plots below show the pre and post test engine power curves, as well as a pre and post test composite full load powercurve comparison.






Pre-Test Engine Torque Output
Shaft Torque [ft lbs]
800
700
600
500
400
300
200
100
0
1200 1400 1600 1800 2000 2200 2400 2600 2800 3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F


Post-Test Engine Power Output
Shaft Power [bhp]
350
300
250
200
150
100
50
0
1200 1400 1600 1800 2000 2200 2400 2600 2800 3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F


Post-Test Engine Torque Output
Shaft Torque [ft lbs]
800
700
600
500
400
300
200
100
0
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F

Engine Out Emissions

Direct engine out exhaust measurements were taken at the pre and post test powercurve testing segments to document the engines overall condition. In addition, tailpipe emission changes over the test duration could help identify fuel system degradation and engine performance changes. Mass based calculations were determined following methodology outlined in the Code of Federal Regulations, Title 40, Part 86, Subpart D. Final mass based emissions values were then correlated to engine fuel consumption rates to provide direct comparison of emission produced per unit mass of fuel. These values are denoted as the Emissions Index (EI).

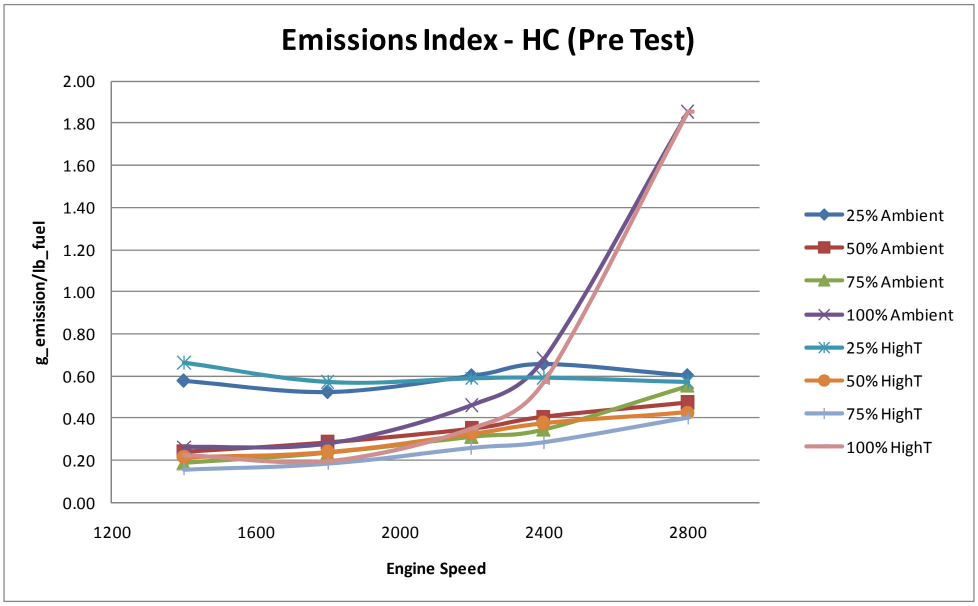


Figure 1 - AF7801 JP-8, Pre Test HC Emissions

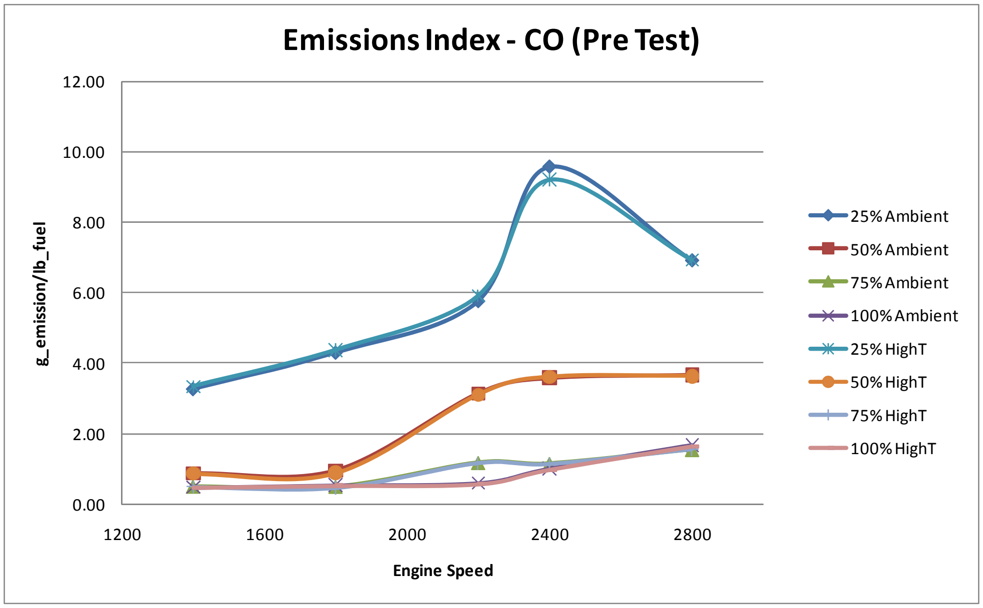


Figure 2 - AF7801 JP-8, Pre Test CO Emissions

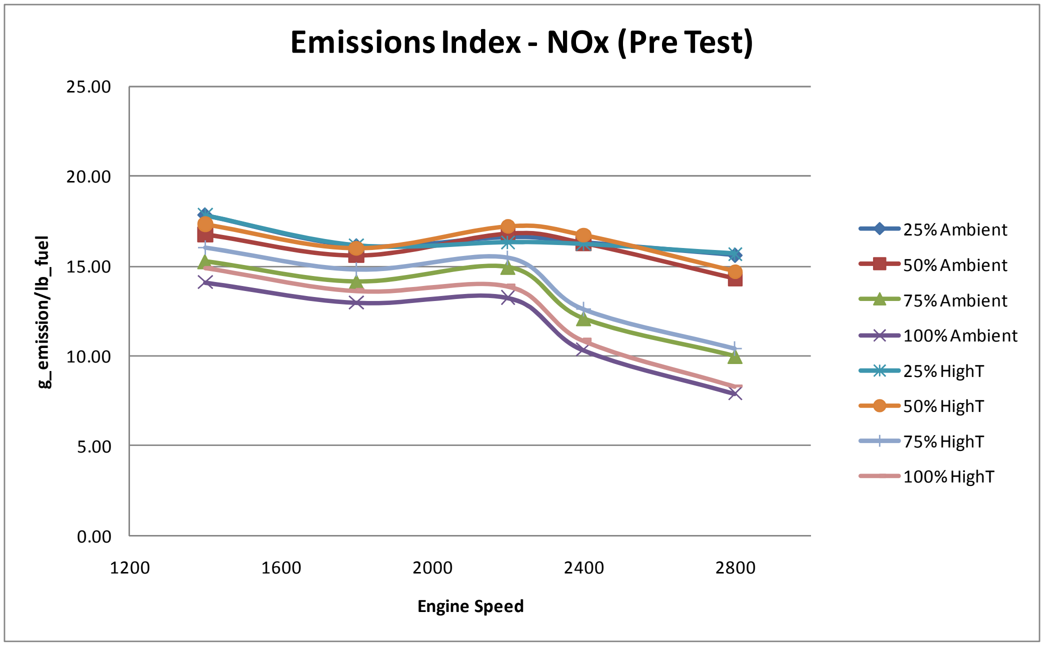


Figure 3 - AF7801 JP-8, Pre Test NOx Emissions

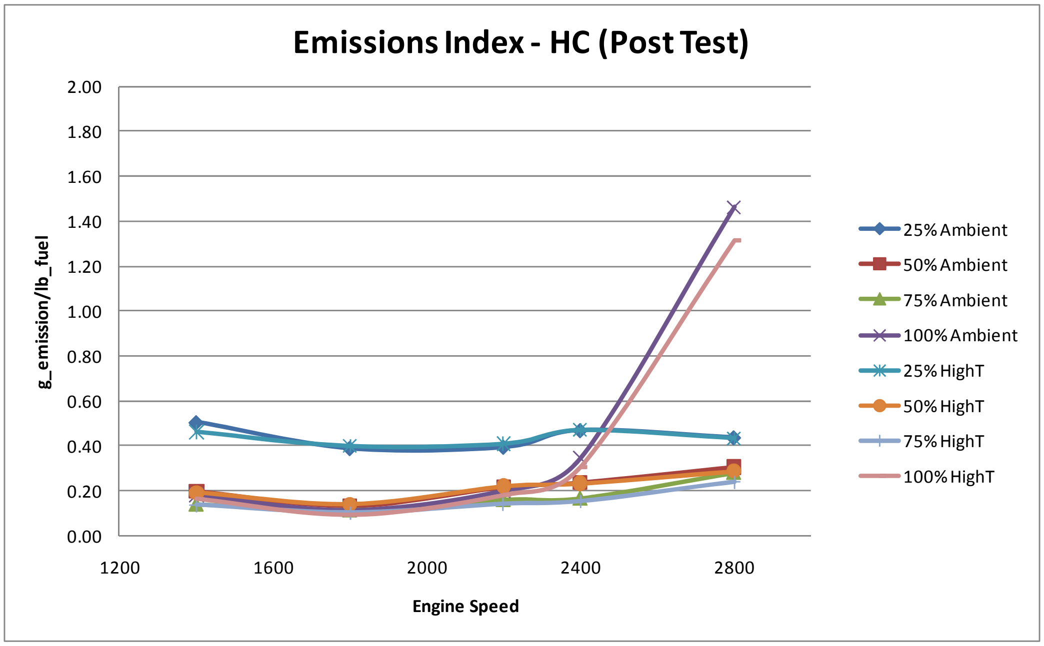


Figure 4 - AF7801 JP-8, Post Test HC Emissions

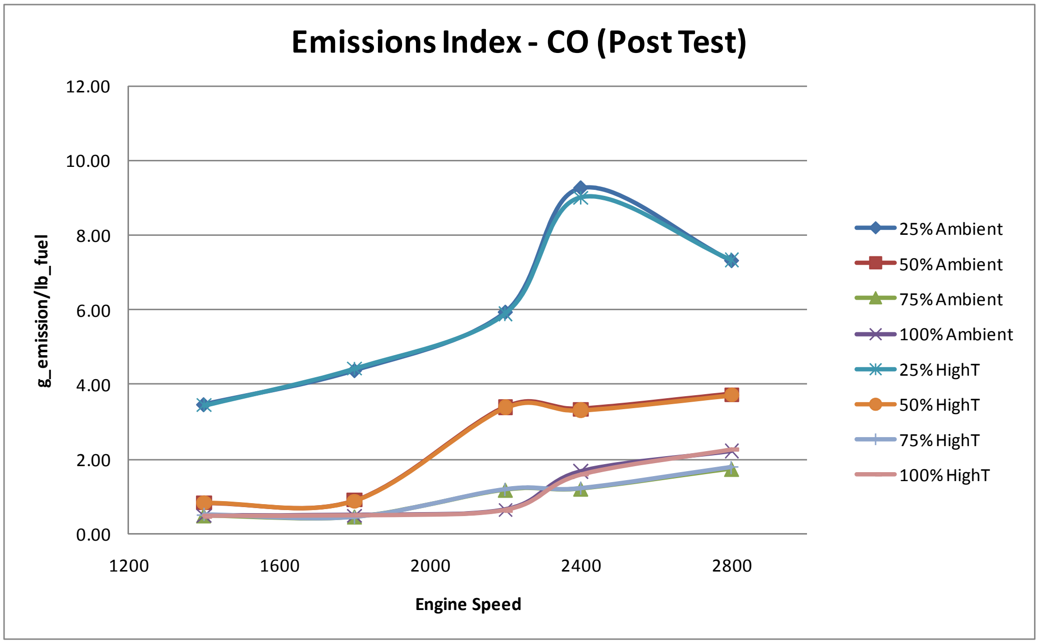


Figure 5 - AF7801 JP-8, Post Test CO Emissions

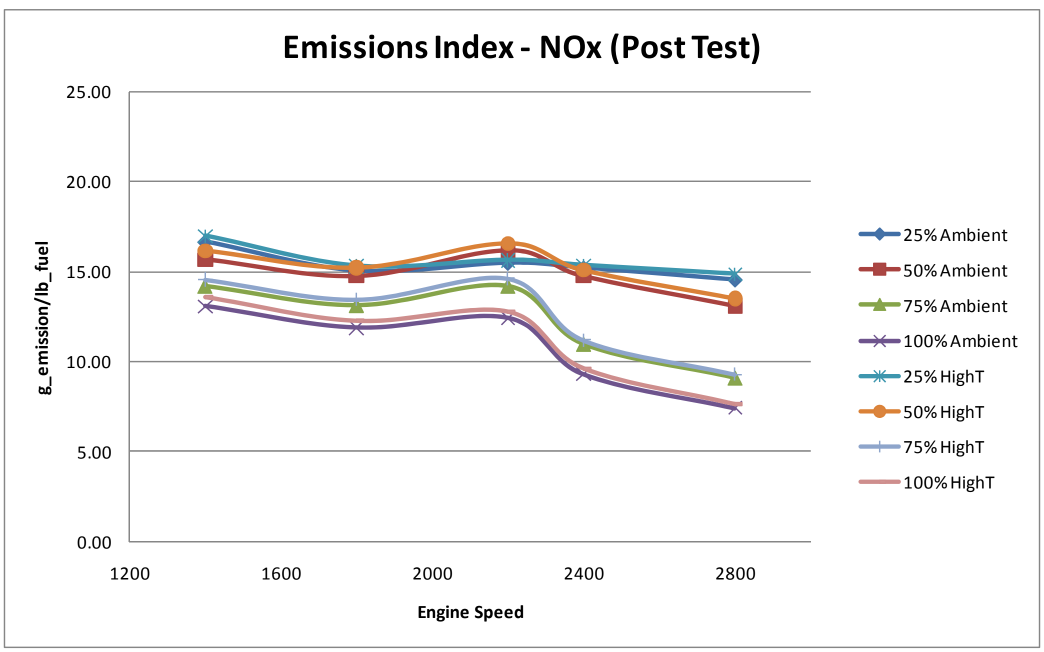


Figure 6 - AF7801 JP-8, Post Test NOx Emissions

Engine Noise Evaluation

Engine noise levels were quantified with the use of a handheld dB meter to use as a comparison with follow on testing. Noise measurements were taken at engine idle conditions with test cell cooling fans turned off in an effort to reduce any chance of data effects due to noise emitted from ancillary test equipment. No engine noise measurements were taken at rated speed conditions due to the extreme noise levels present in the test cell.

Fuel: AF7801
Engine Condition: Idle, Approx 600rpm
Date: 2/7/11

Front - 90.1dB
Top - 86.6dB
Left - 86.4dB
Right - 86.4dB

Fuel: AF7801
Engine Condition: Idle, Approx 600rpm
Date: 2/11/11

Front - 93.0dB
Top - 88.5dB
Left - 89.4dB
Right - 87.4dB

Fuel: AF7801
Engine Condition: Idle, Approx 600rpm
Date: 2/14/11

Front - 91.4dB
Top - 87.2dB
Left - 87.9dB
Right – 88.3dB

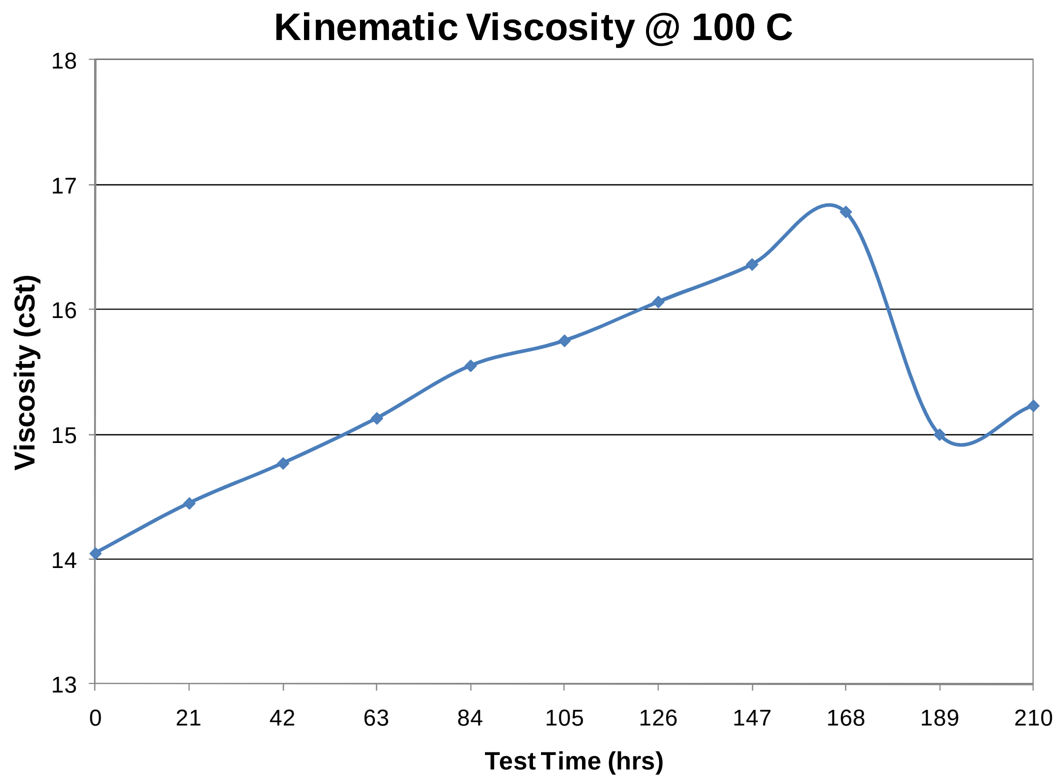
Engine Oil Analysis

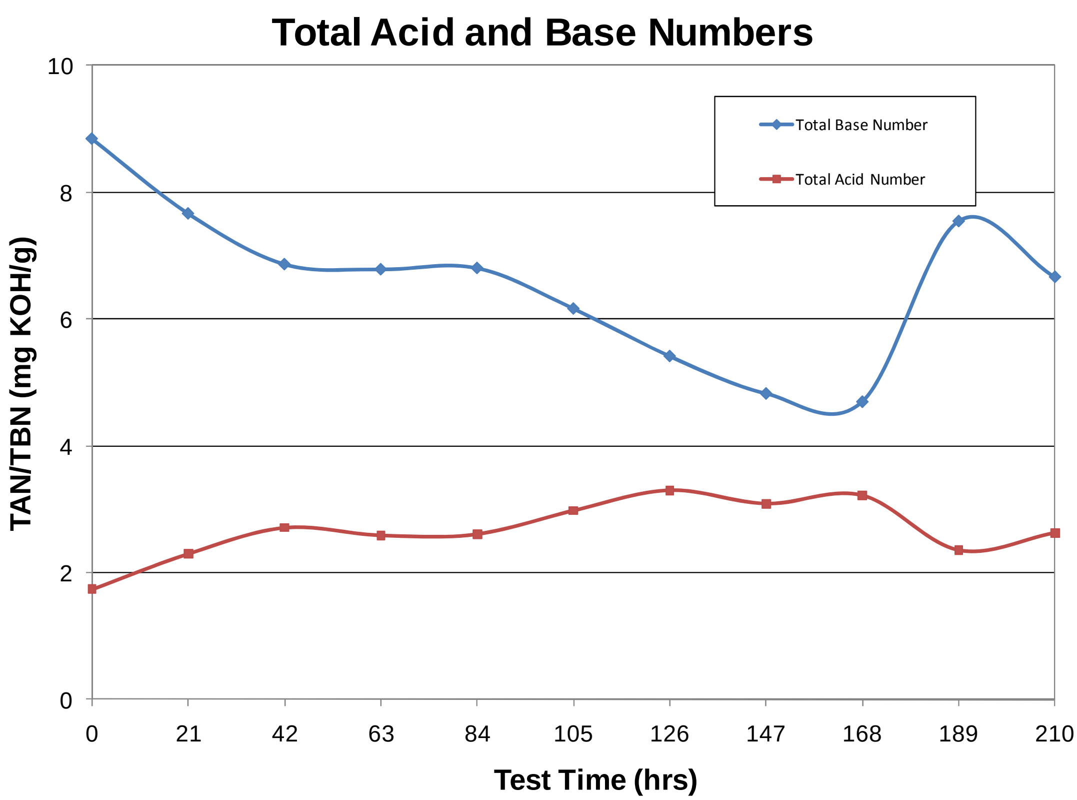
Table 6 below shows the engine used oil analysis over the test duration. An oil change was completed at the completion of 168 testing hours to prevent TAN & TBN cross and acceleration of engine oil degradation. Plots of various used oil property trends are shown below.

Table 6 – Engine Used Oil Analysis Over Test Duration

Property	ASTM Test	Test Hours										
		0	**21**	**42**	**63**	**84**	**105**	**126**	**147**	**168**	**189**	**210**
Density	**D4052**	0.854	0.859	0.861	0.864	0.868	0.870	0.873	0.875	0.878	0.861	0.865
Viscosity @ 100°C (cSt)	**D445**	14.1	14.5	14.8	15.1	15.6	15.8	16.1	16.4	16.8	15.0	15.2
Total Base Number (mg KOH/g)	**D4739**	8.8	7.7	6.9	6.8	6.8	6.2	5.4	4.8	4.7	7.5	6.7
Total Acid Number (mg KOH/g)	**D664**	1.7	2.3	2.7	2.6	2.6	3.0	3.3	3.1	3.2	2.4	2.6
Oxidation (Abs./cm)	**E168 FTNG**	0.0	1.2	2.5	3.9	5.4	6.3	7.1	8.2	9.0	2.4	4.0
Nitration (Abs./cm)	**E168 FTNG**	0.0	0.9	1.4	1.9	2.5	2.5	2.5	2.4	1.9	1.0	1.6
Soot	**Soot**	0.2	0.9	1.5	1.9	2.4	2.8	3.3	3.8	4.2	1.4	2.0
Wear Metals (ppm)	**D5185**											
Al		1	2	3	3	3	3	4	4	4	2	2
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		73	53	48	45	41	42	38	36	35	53	43
Ca		840	871	869	908	931	937	954	987	991	889	932
Cr		<1	1	2	2	2	2	3	3	3	<1	1
Cu		<1	<1	1	2	2	3	3	4	4	1	1
Fe		1	14	27	42	73	82	111	137	169	36	49
Pb		<1	<1	<1	<1	<1	<1	<1	<1	1	<1	<1
Mg		1128	1208	1203	1237	1334	1299	1365	1371	1391	1242	1331
Mn		<1	<1	<1	<1	<1	1	1	1	2	<1	<1
Mo		66	69	69	72	74	74	76	77	79	71	72
Ni		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
P		1104	1065	1042	1033	1056	1054	1089	1110	1102	1088	1084
Si		4	7	6	7	8	8	9	9	9	6	6
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		7	8	8	8	11	8	10	10	10	8	8
Sn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Zn		1254	1284	1278	1287	1337	1354	1360	1383	1417	1316	1333
K		<5	<5	<5	<5	<5	<5	5	6	5	<5	6
Sr		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

Engine Oil Analysis Trends





Oil Consumption Data

Average oil consumption per test hour was 0.046 lbs/hr.
[Calculated by: (Total Additions-Total Samples)/210hrs]

Samples:

Test Time	Date	Sample + Container Weight, lbs	-	Container Weight,lbs	=	Sample Weight, lbs
21 hr	2/1/11	0.29		0.05		0.24
42 hr	2/3/11	0.28		0.05		0.23
63 hr	2/4/11	0.27		0.05		0.22
84 hr	2/5/11	0.29		0.05		0.24
105 hr	2/8/11	0.29		0.05		0.24
126 hr	2/9/11	0.30		0.05		0.25
147 hr	2/10/11	0.29		0.06		0.23
168 hr	2/11/11	0.29		0.06		0.23
189 hr	2/12/11	0.29		0.06		0.23
210 hr	2/15/11	0.29		0.06		0.23
				Total Samples	=	2.34

Additions:

Test Time	Date	Addition + Container Weight, lbs	-	Container Weight,lbs	=	Addition Weight, lbs
21 hr	2/2/11	1.71		0.11		1.60
42 hr	2/3/11	1.41		0.11		1.30
63 hr	N/A	0		0		0
84 hr	2/7/11	3.11		0.11		3.00
105 hr	2/8/11	1.31		0.11		1.20
126 hr	2/9/11	1.49		0.11		1.38
147 hr	2/10/11	1.19		0.11		1.08
168 hr	2/11/11			Engine Oil Change		
189 hr	2/14/11	1.55		0.11		1.44
210 hr	2/15/11	1.11		0.11		1.00
				Total Additions	=	12.00

Post Test Fuel Injection Hardware Inspection

Table 7 shown below outlines the visual inspection results from the post test high pressure common rail fuel injection pump, compared to new unused components.

Table 7 – Outlines of Visual Inspection Results

Part	New	JP-8
Volume Control Valve	New	As new
Pump Body	Very light polish of bores	Very light polish of bores, top & bottom
Pump Bushings	Both new	Both as new
Cam	Visible light grinding marks	Light polish & very light burnish, not measureable, seal contact wear
Roller - Left	New, bright & shiny	Very light burnish & polish
Roller - Right	New, bright & shiny	Very light burnish & polish
Roller Shoe - L	New	New, polish from plunger button
Roller Shoe - R	New	New, polish from plunger button
Follower - L	New	Polish, very light scuff, top & bottom
Follower - R	New	Polish, very light scuff, top & bottom
Plunger - L	New	As new, light polish on plunger button, more than right
Plunger - R	New	As new, light polish on plunger button
Barrel - L	New	As new
Barrel - R	New	As new
Inlet Check - L	New	As new
Inlet Check -R	New	As new

Post Test Fuel Injection Hardware Photos (no magnification)

The following photos document the post test fuel injection hardware condition. Figure 7 and Figure 8 below shows a representative photo of the HPCR pump body. Frame of reference for left and right notations are taken from Figure 8 as it's installed in the engine.

Figure 7 - HPCR Pump Body, Front (Representative Photo)

Figure 8 - HPCR Pump Body, Rear (Representative Photo)

Figure 9 shows the left hand pump body bore, while Figure 10 shows a close up picture of the light polish found on the bore surface from interaction with the cam follower assembly.

Figure 9 - AF7801 JP8, Post Test, Left Pump Bore

Figure 10 - AF7801 JP8, Post Test, Left Pump Bore Close

Figure 11 shows the right hand pump body bore, while Figure 12 shows a close up picture of the light polish found on the bore surface similar to the left hand bore.

Figure 11 - AF7801 JP8, Post Test, Right Pump Bore

Figure 12 - AF7801 JP8, Post Test, Right Pump Bore Close

Figure 13 and Figure 14 shows the pump body rear and front camshaft bushings respectively. The bushings showed no signs of wear.

Figure 13 - AF7801 JP8, Rear Pump Body Camshaft Bushing

Figure 14 - AF7801 JP8, Front Pump Body Camshaft Bushing

Figure 15 shows the HPCR fuel injection pump camshaft.

Figure 15 - AF7801 JP8, HPCR Pump Camshaft

Figure 16 shows a close-up of a cam lobe peak. A slight polish can be seen in the contact areas of the cam surface, but no measureable wear is detected.

Figure 16 - AF7801 JP8, HPCR Pump Camshaft, Lobe Surface Close-up

Figure 17 shows the left bore cam follower and roller assembly. The follower was oriented to show the most severe areas of scuffing present on the follower surface. Figure 18 below shows the left hand roller surface.

Figure 17 - AF7801 JP8, Left Cam Follower

Figure 18 - AF7801 JP8, Left Cam Follower Roller

Figure 19 shows the left cam follower undercrown and the contact area with the high pressure piston head. Figure 20 shows the left hand high pressure piston. Note the similar contact markings where it contacts the follower undercrown. Polishing at this interface was visible, but no physical wear was tactically distinguishable.

Figure 19 - AF7801 JP8, Left Cam Follower Undercrown

Figure 20 - AF7801 JP8, Left High Pressure Piston

Figure 21 shows the right bore cam follower and roller assembly. The follower was oriented to show the most severe areas of scuffing present on the follower surface. Figure 22 below shows the right hand roller surface.

Figure 21 - AF7801 JP8, Right Cam Follower

Figure 22 - AF7801 JP8, Right Cam Follower Roller

Figure 23 shows the right cam follower undercrown and the contact area with the high pressure piston head. Figure 24 shows the right hand high pressure piston. Similar to the left hand assembly, polishing at this interface was visible, but no physical wear was tactically distinguishable.

Figure 23 - AF7801 JP8, Right Cam Follower Undercrown

Figure 24 - AF7801 JP8, Right High Pressure Piston

Post Test Fuel Injection High Magnification Photos

The following photos document the post test fuel injector hardware condition. Figure 25 shows the injector nozzle tip. No substantial deposit formations were seen under low magnification. Figure 26 below shows the injector needle tip. No abnormal wear or markings were found on the tapered tip.

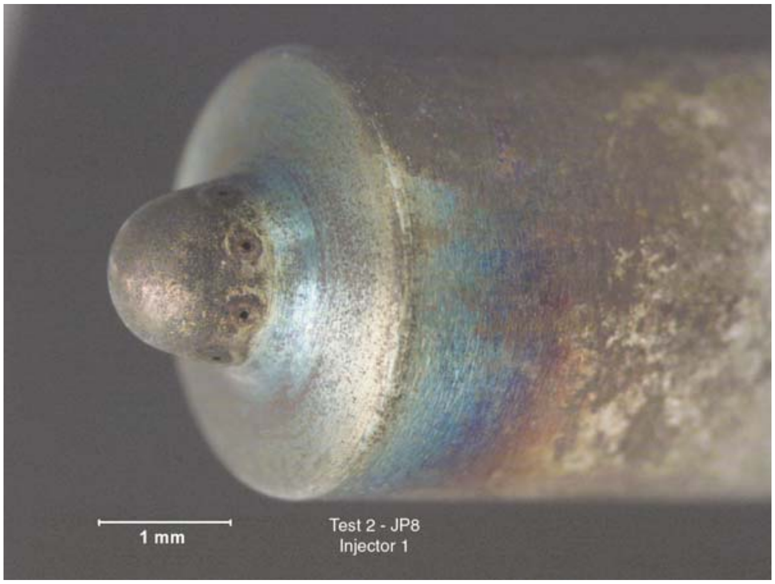


Figure 25 - AF7801 JP8, Injector Nozzle

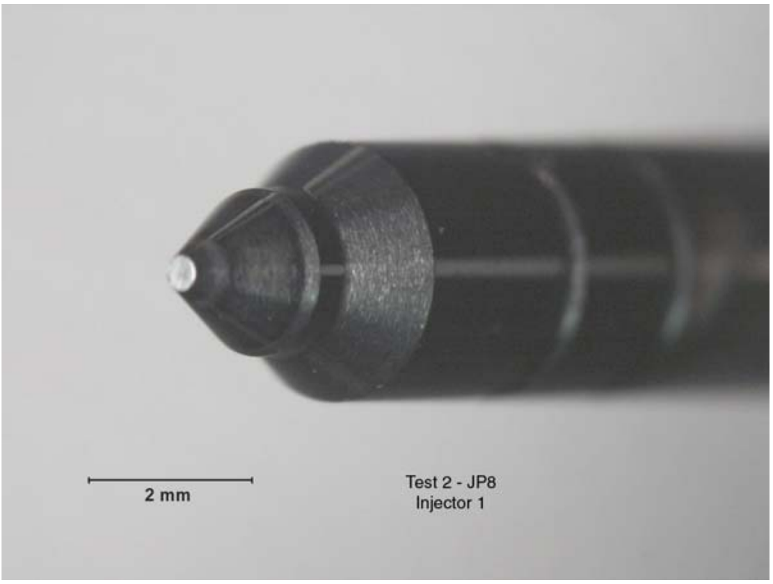


Figure 26 - AF7801 JP8, Injector Needle

Figure 27 and Figure 28 shows the upper and lower hydraulic coupler pistons respectively. No noticeable wear was seen on the piston surface interface, or at the heads of the piston at the piezo stack and control valve interface.

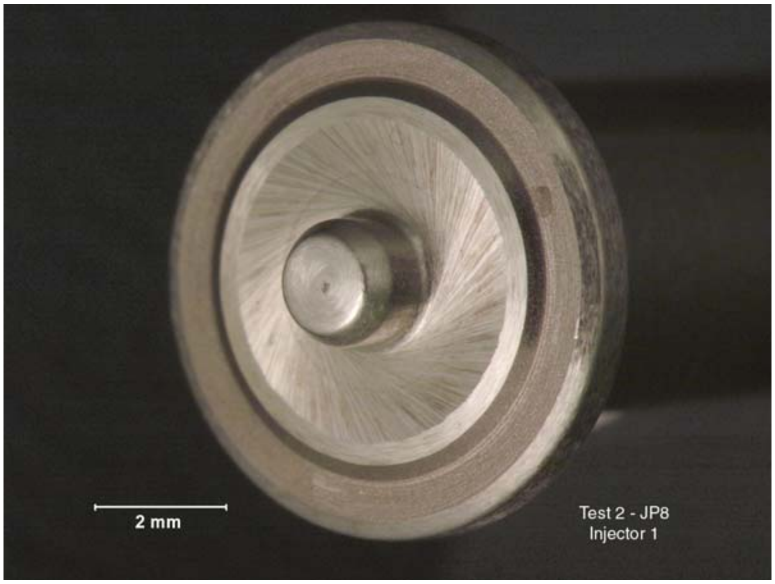


Figure 27 - AF7801 JP8, Upper Hydraulic Coupler Piston

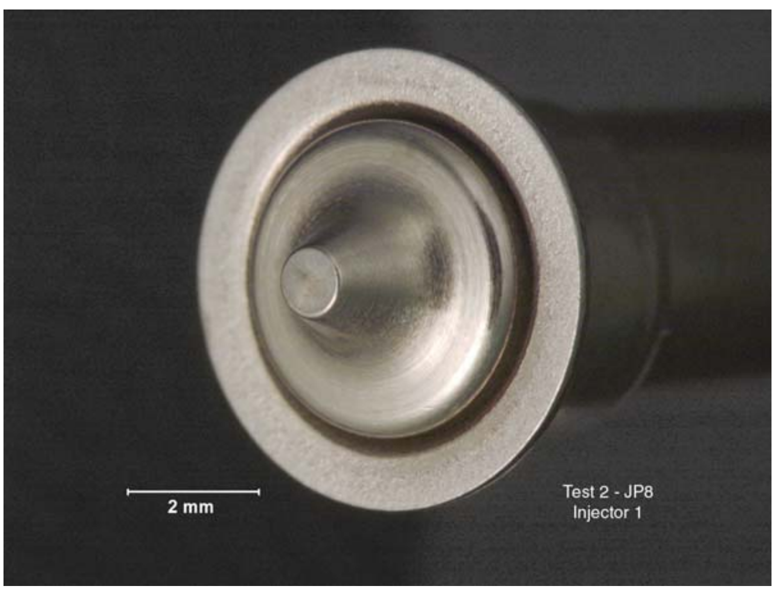


Figure 28 - AF7801 JP8, Lower Hydraulic Coupler Piston

Figure 27 and Figure 28 shows the side profile of the upper hydraulic coupler piston. A wear scar shows on the surface of the piston consistent with wear expected from being slightly cocked in the bore when depressed by the piezo-stack.

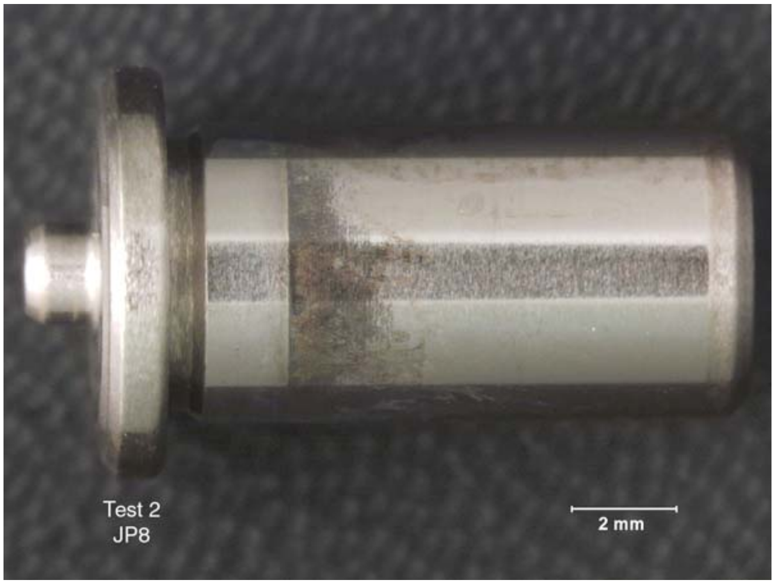


Figure 29 - AF7801 JP8, Upper Hydraulic Coupler Piston, Profile

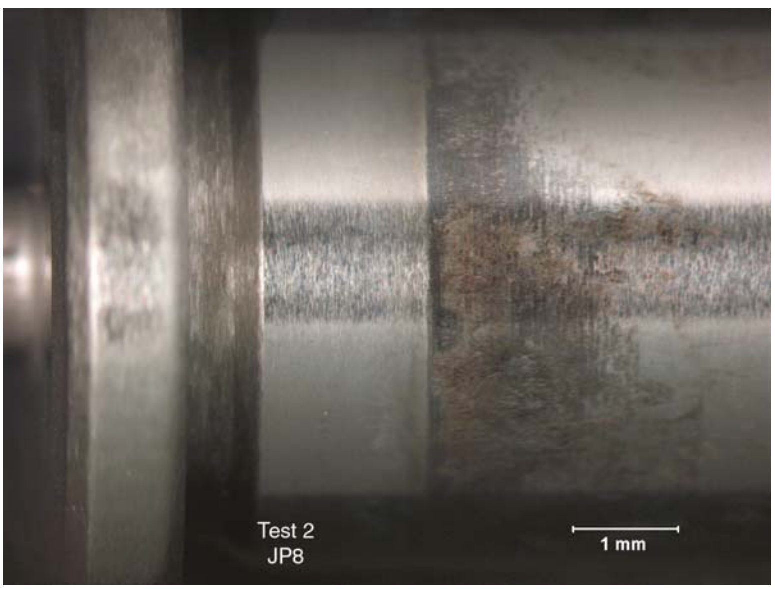


Figure 30 - AF7801 JP8, Lower Hydraulic Coupler Piston, Wear Scar Close Up

Figure 31 and Figure 32 shows the top and bottom surfaces of the intermediate plate. This plate contains the fuel control passages used to manipulate the needle position.

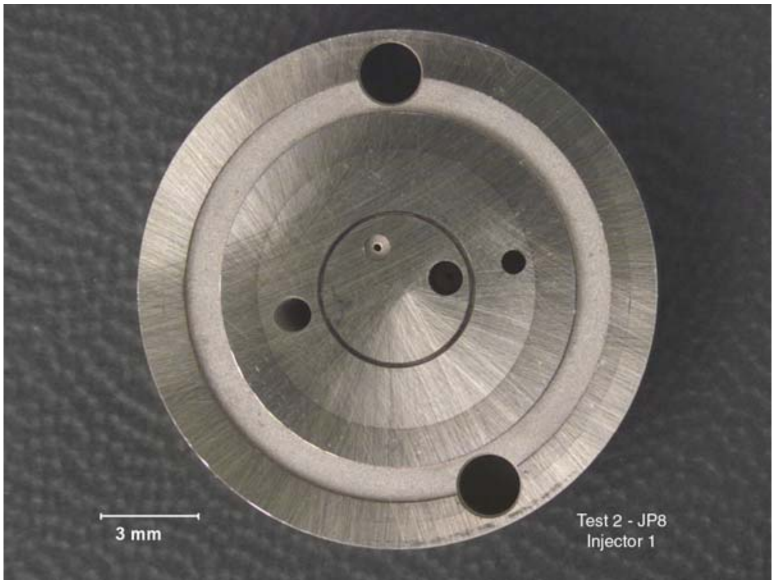


Figure 31 - AF7801 JP8, Intermediate Plate (Top)

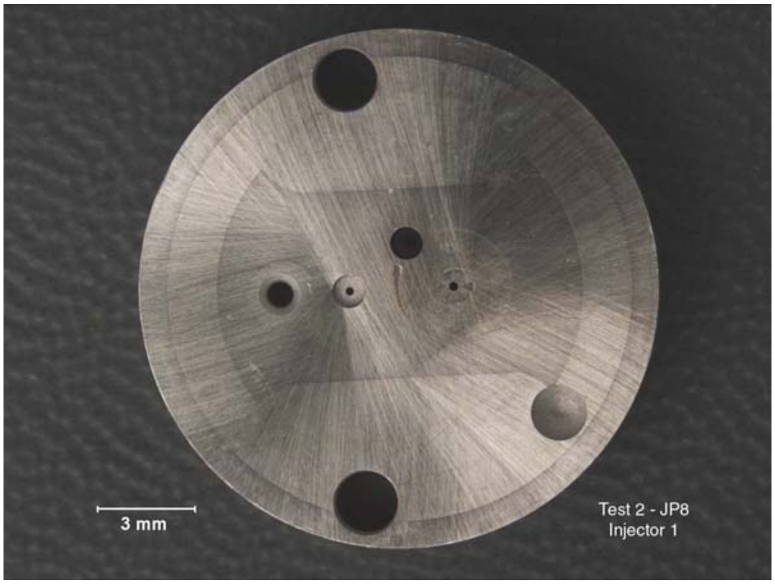


Figure 32 - AF7801 JP8, Intermediate Plate (Bottom)

Figure 33 and Figure 34 shows the top and bottom of the control valve plate. The control valve sits in the bore shown in Figure 34. The lower piston of the hydraulic coupler operates in the bore shown in Figure 33.

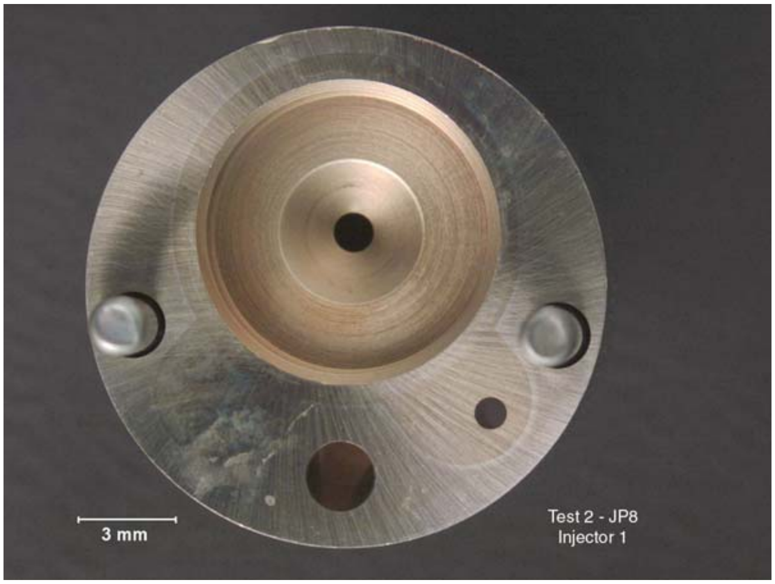


Figure 33 - AF7801 JP8, Control Valve Plate (Top)

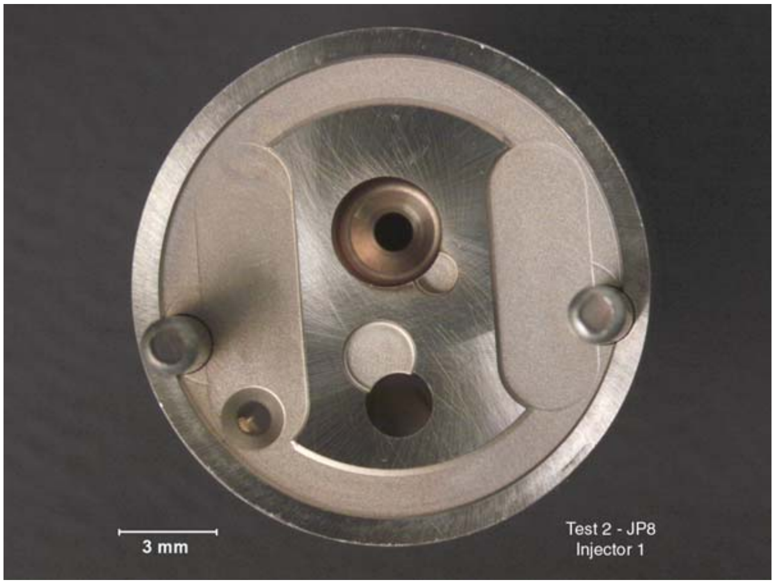


Figure 34 - AF7801 JP8, Control Valve Plate (Bottom)

Figure 35 shows the control valve which regulates the pressure on top of the injector needle, thus controlling lift. No unusual wear was found on the control valve.

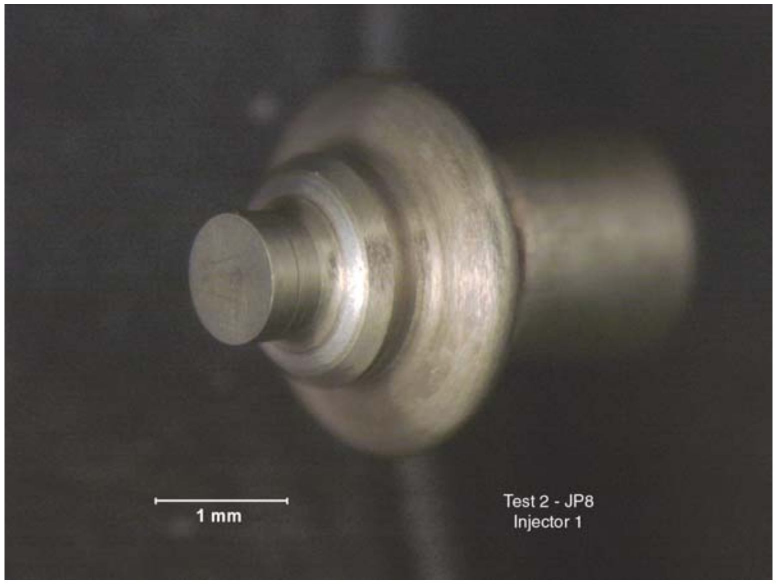


Figure 35 - AF7801 JP8, Fuel Injector Control Valve

Noted Problem Areas

TFLRF staff noted a consistent drop in engine boost pressure over the JP-8 (Test 2) endurance test duration (approximately 5% loss from start to finish). This trend was also noted during the baseline DF2 (Test 1) endurance test. As expected, engine mass air flow and other related parameters showed similar losses over testing. Despite this, the engine fuel flow rate did not follow the same reduction, thus the boost pressure reduction did not impact the overall test goals. As a byproduct, the engine air fuel ratio (AFR) slightly enriched over testing and was noted in elevating exhaust gas port temperature (EGT) increases over the test duration. This trend was also experienced in the 50/50 JP-8/SPK test (Test 3), and resulted in a replacement of the turbocharger assembly prior to the neat SPK test (Test 4).

APPENDIX C

50/50 JP-8/SPK Test Report

(AF7824-67T1-W-210)

Evaluation of 50/50 JP-8/SPK in the Ford 6.7L High Pressure Common Rail Diesel Engine

Project 14734.08

Ford Motor Company 6.7L Diesel

Test Lubricant ID: N/A
Test Lubricant: Full Synthetic, CJ-4, SAE 5W-40
Test Fuel ID: AF7824
Test Fuel: 50/50 JP-8/SPK
JP8, Blended from Valero Jet-A w/9ppm DCI-4A
Shell SPK (as supplied by sponsor) w/9ppm DCI-4A
Test Number: AF7824-67T1-W-210
Start of Test Date: February 23, 2011
End of Test Date: March 9, 2011
Test Duration: 210 Hours
Test Procedure: Tactical Wheeled Vehicle

Conducted for
Mobility & Vehicles Engineering
United States Air Force WR-ALC
Robins AFB, GA

Introduction

This test was used to determine the performance and endurance of a modern high pressure common rail diesel fuel injection system when operated on a 50/50 blend of JP-8 and Synthetic Paraffinic Kerosene (SPK). Testing was completed following a modified version of the 210hr Tactical Wheeled Vehicle Cycle engine endurance test cycle (CRC Report No.406, Development of Military Fuel/Lubricant/Engine Compatibility Test). This work was completed in support of Project 14734.08, Identification of The Effects of Alternative Fuels Utilization on USAF Vehicles and Equipment Powered by Compression Ignition Engines with Common-Rail Fuel Injection.

Test Engine

The Ford 6.7L diesel engine was chosen for testing as a representative engine utilizing modern high pressure common rail fuel injection technology. The Ford 6.7L engine is a direct injected, turbo-charged, intercooled engine, which employs a fuel lubricated high pressure common rail injection pump and piezo-electric fuel injectors. The test engine had approximately 420hrs of previous testing time in support of additional research, but was fitted with a new fuel injection pump and fuel injectors prior to testing to restore the high pressure fuel system to “as new” condition.

Test Stand Configuration

The engine was mounted in a test stand specifically configured for Ford 6.7L engine testing. Engine monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. An appropriately sized absorption dynamometer was used to control engine speed and dissipate load. Engine load was manipulated through the actuation of the engine throttle pedal assembly. Engine coolant temperatures were controlled with the use of liquid-to-liquid heat exchangers utilizing laboratory process water for cooling. Engine intake air was supplied at ambient conditions utilizing the factory engine air box and ducting. Engine exhaust was routed from the test cell through a butterfly valve to control engine exhaust back pressure, and then ducted into the laboratory exhaust blower system for removal. Fuel was supplied to the diesel fuel conditioning module/engine at ambient conditions.

Engine Run-in

Prior to testing, the engine was run-in following the Ford specified engine run-in procedure. This was done despite the previous testing time accrued on the engine to allow for the same duration of engine operation on each fuel system for test consistency. Table 1 below outlines the Ford recommended engine run-in procedure.

Table 1 - Ford Recommended Run-In Procedure

Step	Duration	Speed [rpm]	Load [lb-ft]	Load [Nm]
1	0:05	650	0	
2	0:30	1000	72	97
3	0:30	1200	103	140
4	0:30	1400	141	191
5	0:30	1500	162	219
6	0:30	1600	184	249
7	0:30	1700	208	282
8	0:30	1800	233	316
9	0:30	2000	287	390
10	0:30	2200	348	472
11	0:30	2400	414	561
12	0:30	2500	449	609
13	0:30	2600	486	659
14	0:30	2700	524	710
15	0:30	2800	563	764

Pre and Post Test Engine Performance Checks

Before and after testing, engine powercurves were completed at varying speeds and loads to determine pre-test engine performance. Engine performance was documented at engine speeds of 1400, 1800, 2200, 2400, and 2800 rpm, with load intervals of 25%, 50%, 75%, and 100% of full load. Powercurves were completed at both ambient (95°F) and desert condition (120°F) inlet fuel temperatures. Exhaust gas emissions were sampled at each point on the curve to document engine out emissions. Powercurve plots can be seen in the Engine Performance Curves section.

Test Cycle

The test cycle followed during fuel system evaluations was a modified version of the 210hr Tactical Wheeled Vehicle Cycle as outlined in CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test. Slight modifications were made to the test cycle to accelerate the testing schedule. The primary modification was the reduction of engine soak time from 10hrs to 3hrs. The engine soak period in the test cycle was originally included for engine lubricant testing, and added no benefit for fuel compatibility testing. Total modified daily runtime was 21hrs per day, 15hrs at rated speed/load and 6 hrs at idle, followed by a 3hr engine soak. To keep the modified test cycle rated to idle testing hours consistent with the standard 210hr Tactical Wheeled Vehicle Cycle, the following daily operating arrangement was derived. The engine completed 6 cycles of 2hr 10min at rated speed followed by a 1hr idle step. After the 6 cycles were completed, an additional 2hr rated segment was conducted followed by the 3hr soak. Engine coolant temperatures were maintained at Ford specifications to ensure engine integrity throughout the test. Engine coolant utilized was a 50/50 blend of ethylene glycol antifreeze and deionized water. Engine operating parameters were controlled as specified in Table 2 on the following page.

(Note – Engine idle speed was controlled by PCM at approximately 600 RPM. Temperature controllers remained at rated speed set points for idle conditions, but were not met due to lack of heat generation in the coolant system. Temperatures were allowed to reach their natural steady state value during idle testing steps. Engine oil cooler plumbing was integral to the engine water jacket, thus not directly controlled. Oil temperatures were allowed to meet their own steady state temperature based on water jacket temperature and engine load/speed throughout testing.)

Table 2 - Test Cycle Operation Parameters

Parameter	Rated Speed	Idle
Engine Speed	2800 +/- 25	NC
High Temp Coolant Loop	203 +/- 3	NC
Low Temp Coolant Loop	100 +/- 3	NC
Oil Sump	NC	NC
*NC = not controlled		

Oil Sampling

Four ounces of engine oil was sampled every 21hrs (daily) for used oil analysis. Used oil analysis consisted of the following tests as seen below in Table 3. Engine oil changes were performed on the engine based on used oil condition.

Table 3 - Used Oil Analysis Procedures

Daily Used Oil Analysis		
ASTM	D4739	Total Base Number
ASTM	D664	Total Acid Number
ASTM	D445	Kinematic Viscosity @ 100°C
ASTM	API Gravity	API Gravity
ASTM	D4052	Density
ASTM	TGA SOOT	TGA Soot
ASTM	E168	Oxidation
ASTM	E168	Nitration
ASTM	D5185	Wear Metals by ICP

Used oil analysis results can be seen in the engine oil analysis and engine oil analysis trends section of the report.

Oil Level Checks

Engine oil level was checked daily, and replenished as needed to restore oil level to full mark. This process occurred after the completion of the 3hr soak prior to restarting testing the next day.

Test Fuel Analysis

The test fuel was a 50/50 blend of JP-8 and Synthetic Paraffinic Kerosene (SPK). The JP-8 was blended at location from commercially available Jet-A. The blend consisted of a true 50/50 volumetric blend. The 50/50 blend resulting density was determined to be approximately 0.7% below the minimum density spec required by MIL-PRF-83133, but was determined acceptable by the COR to produce a "worst case scenario" for testing. Since the primary focus of testing was fuel lubricity compatibility, only the lubricity enhancer/corrosion inhibitor additive was blended into to the Jet-A and SPK base fuels. The remaining two additives typically found in JP-8 have little impact on fuel lubricity levels and fuel system durability. The lubricity enhancer used was Innospec Fuel Specialties DCI-4A. Per QPL-25017, the minimum effective treat rate of DCI-4A required an additive concentration of 9ppm in the final fuel blend. In an effort to determine fuel system impact in a "worst case" scenario, the test fuel was treated only at the minimum effective treat rate regardless of the resulting lubricity achieved. After the test fuel was additized and blended, fuel samples were collected to determine critical chemical and physical properties of the fuel for reporting. Table 4 summarizes the critical properties of the tested 50/50 JP-8/SPK. Table 5 shows the certificate of analysis (COA) for the Jet-A as received. Table 6 shows the chemical and physical analysis of the neat SPK as received prior to blending.

Table 4 - Test Fuel Chemical & Physical Analysis

Property	Units	Method	Results
Density @15°C	g/mL	D4052	0.736
Specific Gravity @15°C		D4052	0.737
API Gravity @15°C		D4052	60.6
Flashpoint	°F	D56	111
	°C	D93	43
	°F	D3828	109
Kinematic Viscosity @-20°C	cSt	D445	2.5
Kinematic Viscosity @40°C	cSt	D445	0.9
Hydrocarbon Content			
Carbon	wt%	D5291	83.94
Hydrogen	wt%		16.46
Calculated Cetane Index		D976	57.2
Calculated Cetane Index		D4737	66.8
Cetane Number		D613	64.0
IQT	DCN	D6890-04	58.5
Heat of Combustion (Gross)	BTU/lb	D240	20364.4
Total Acid Number	mg KOH/g	D3242	0.011
Hydrocarbon Type			
Aromatics	%mass	D5186	0.3
Hydrocarbon Type			
Aromatics	%vol	D1319	0.4
Olefins			0.5
Saturates			99.1
Sulfur	ppm	D5453	<10
Nitrogen	wt%	D3228	<0.03
HFRR	mm	D6079	0.840
BOCLE	mm	D5001	0.76
Bulk Modulus @30°C	psi	by Speed of Sound	152749
Distillation			
IBP	°C	D86	152.5
10%			161.5
20%			162.7
50%			168.8
90%			186.0
End Pt			203.0

Table 5 - Valero Jet-A Certificate of Analysis (COA)

01/02/2011 17:11 8303938101 ALCOR PETROLAB LLP

PETROLAB, L.L.P.

20 Laboratory Road, Floresville, Texas 78114 Telephone 830-216-3113 www.alcorpetrolab.com

NuStar
San Antonio Products Terminal
P. O. Box 241017
San Antonio, Texas 78224-1017

January 2, 2011

Sample Type: Jet A
Tank Number.: 103
nt @ 1007 01/02/11 pu @ 1330 01/02/11

Sample Date: 01/02/11
Sample Time: 1330

Volatility	**Method**	**Specification**		**Result**
Initial Boiling Point (°F)	D 86			333.3
Distillation 10% Rec (°F)		400	max	345.4
Distillation 50% Rec (°F)		Report		365.9
Distillation 90% Rec (°F)		Report		412.5
Distillation 95% Rec (°F)		Report		431.4
Distillation Final BP (°F)		572	max	475.5
Distillation Recovery (vol %)				98.2
Distillation Residue (vol %)		1.5	max	0.7
Distillation Loss (vol %)		1.5	max	1.1
Flash Point, Tag Closed (°F)	D 56	100	min	127.0
API Gravity @ 60 (°F)	D 1298	37.0 / 51.0		45.0
Cetane Index	D 4737	40.0	min	39.7
Particulate Matter Mgs/Gal	D 2276	3.0	max	0.8
Sulfur Wt %	D 7220	0.30	max	0.0005
Copper Strip	D130	No. 1	max	1A
Existent Gum Mgs / 100 Mls.	D381	7	max	<1.0
Fluidity				
Freezing Point (°F)	D 2386	-41.0	max	-82.3
Contaminants				
Color (Saybolt)	D 156	+15	min	+30
Appearance	D4176	clear/bright	pass/fail	Pass
Water Reaction: Change	D 1094	2.0	max	0
Water Reaction: Interface Rating	D 1094	2	max	1
Water Reaction: Separation Rating	D 1094	2	max	1
MSEP	D 3948	85	min	98

This Product Conforms to ASTM D1655 for the Above Tests: XX **YES** ___ NO

Reviewed and submitted by,

Chris Taylor CEO

Chris Taylor CEO

Report Number: P010211A

Table 6 - Chemical & Physical Analysis of Shell SPK

Sample AL-27892			
Property	**Units**	**Test No**	**Results**
Density	g/mL	D-4052	0.7377
Specific Gravity		D-4052	0.7381
API Gravity		D-4052	60.2
Flashpoint	°F	D-56	111
Flashpoint	°C	D-93	43.481
Flashpoint	°F	D-3828	109
Freezing Point	°C	D-2386	-54.9
Kinematic Viscosity @-20°C	cSt	D-445	2.4672
Kinematic Viscosity @40°C	cSt	D-445	0.93621
Hydrocarbon Content	Carbon	D-5291	83.94%
	Hydrogen		16.46%
Calculated Cetane Index		D-976	57.2
Calculated Cetane Index		D-4737	66.8
Cetane Number		D-613	64
Heat of Combustion (Gross)	BTU/lb	D-240	20364.4
Copper Corrosion		D-130	1A
Particulate Contamination	mg/L	D-5452	1.1
Total Acid Number	mg KOH/g	D-3242	0.011184
Hydrocarbon Type (%vol)	Aromatics	D-1319	0.4
	Olefins		0.5
	Saturates		99.1
	BTU/lb		18939.4
Nitrogen		D-3228	<0.03
Existent Gums - unwashed	mg/100mL	D-381	10
Existent Gums - washed	mg/100mL		3
Ash Content	%mass	D-482	<0.001
Color		D-156	+21
JFTOT		D-3241	1
HFRR	micro-m	D-6079	523
Scuffing Load BOCLE	g	D-6078	2100
BOCLE	mm	D-5001	0.56
Distillation	°C	D-86	
	IBP		152.5
	10%		161.5
	20%		162.7
	50%		168.8
	90%		186
	End pt		203

Endurance Test Cycle Results

The following information summarizes the results of the engine fuel system endurance tests. Data includes: engine operating summary, powercurve analysis, engine out emissions, used oil analysis, post test component inspection, post test component photos, and listing of any problem areas or anomalies experienced during testing.

Engine Operating Conditions Summary

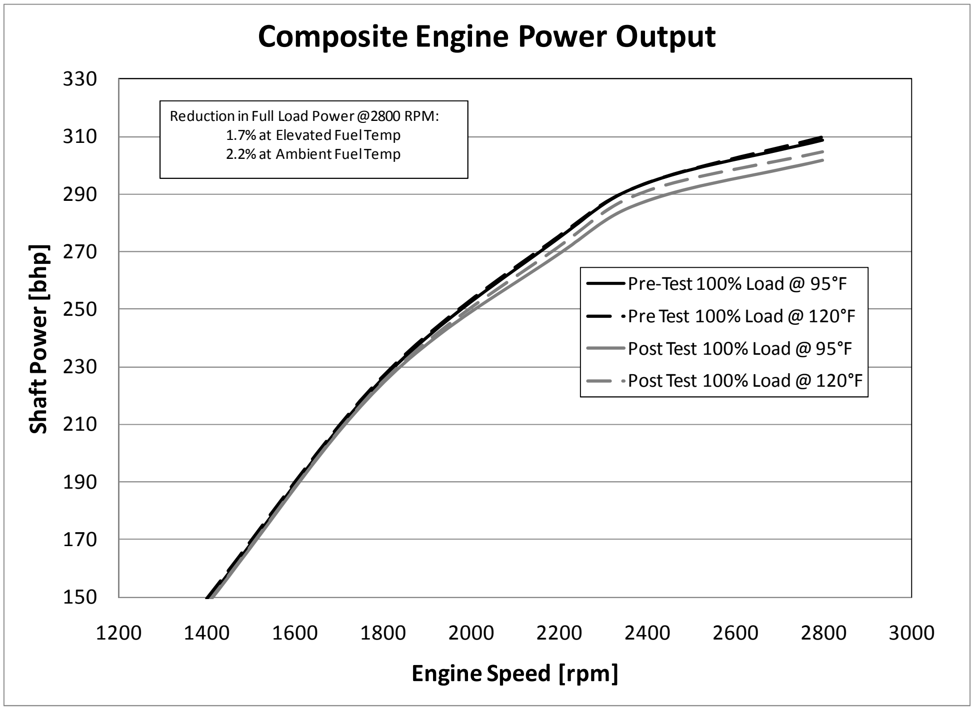
Below is a summary of the engine operating conditions over the test duration.

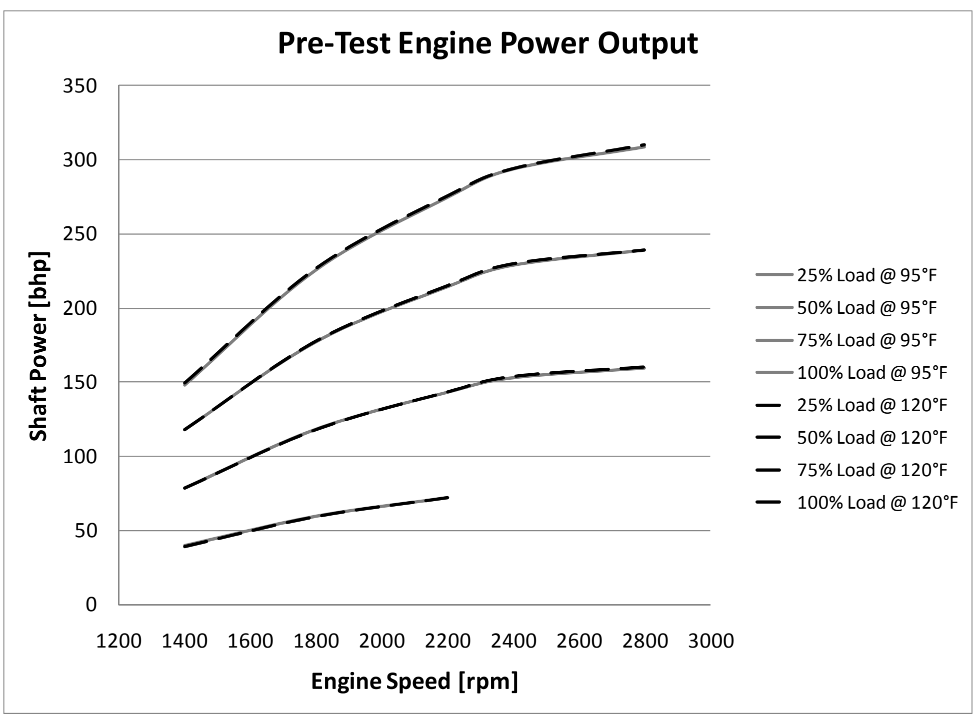
		Rated Conditions (2800 RPM)		**Idle Conditions (600 RPM)**	
Perameter:	**Units:**	**Average**	**Std. Dev.**	**Average**	**Std. Dev.**
Engine Speed	RPM	2800.01	1.93	602.07	2.16
Torque*	ft*lb	575.37	6.10	39.66	2.29
Fuel Flow	lb/hr	124.81	6.57	2.11	0.46
Power*	bhp	306.75	3.26	4.55	0.27
BSFC*	lb/bhp*hr	0.407	0.022	0.465	0.115
Temperatures:					
High Temperature Loop Coolant In	°F	184.91	0.80	174.60	10.81
High Temperature Loop Coolant Out	°F	203.00	0.62	177.42	11.11
Low Temperature Loop Coolant In	°F	100.01	1.08	88.22	5.20
Low Temperature Loop Coolant Out	°F	121.40	1.34	88.14	5.21
Oil Sump	°F	246.24	0.79	181.59	12.01
Fuel In	°F	90.90	3.92	88.05	5.00
Fuel Pump Drain	°F	107.78	6.11	91.54	5.51
Fuel Return	°F	101.39	3.80	89.09	5.37
Intake Air Before Compressor	°F	76.39	1.93	75.51	2.78
Intake Air After Compressor	°F	326.45	4.25	86.25	4.17
Intake Air After Charge Cooler	°F	105.68	1.03	87.40	5.31
Cylinder 1 Exhaust	°F	1470.48	16.95	276.70	14.00
Cylinder 2 Exhaust	°F	1416.01	17.24	268.26	13.16
Cylinder 3 Exhaust	°F	1429.61	18.48	268.54	10.97
Cylinder 4 Exhaust	°F	1424.16	23.45	256.32	11.62
Cylinder 5 Exhaust	°F	1451.84	18.30	257.67	10.17
Cylinder 6 Exhaust	°F	1491.75	20.53	269.02	10.93
Cylinder 7 Exhaust	°F	1464.71	19.47	253.89	10.53
Cylinder 8 Exhaust	°F	1467.54	25.01	262.93	10.72
Exhaust After Turbo	°F	**	**	**	**
Pressures:					
Oil Galley	psi	54.61	0.53	27.59	1.62
Ambient Pressure	psiA	14.26	0.07	14.25	0.07
Intake Restriction	psi	0.41	0.02	-0.02	0.00
Exhaust Restriction	psi	10.29	1.00	-0.15	0.02
Boost Pressure	psi	16.76	0.61	0.02	0.08
Fuel Rail Pressure	psi	19381.76	21.80	3935.05	16.93

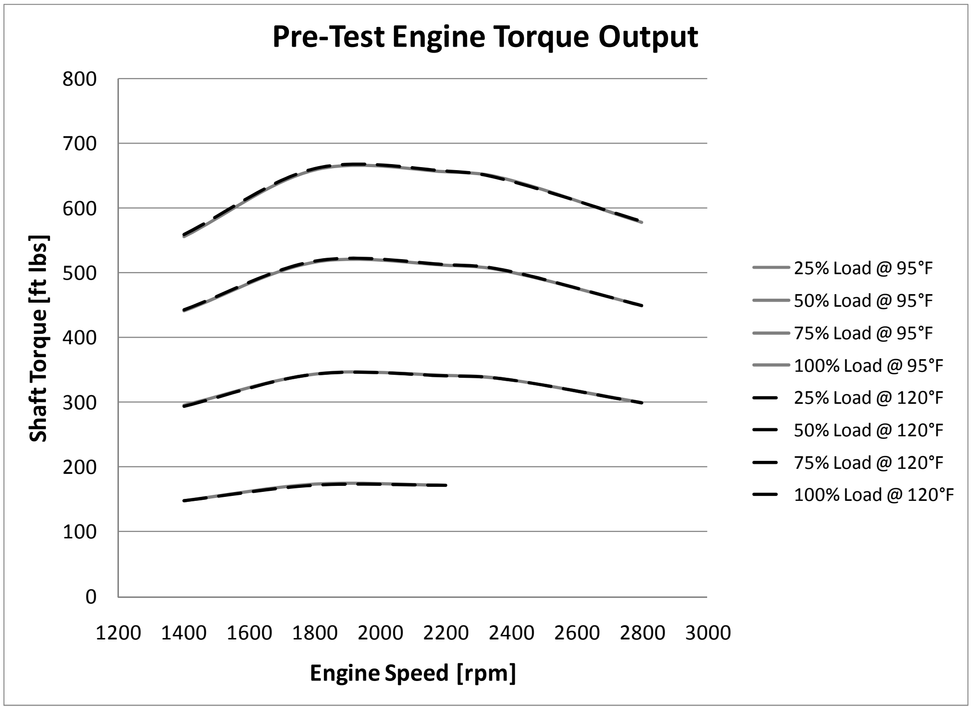
* Non-corrected Values

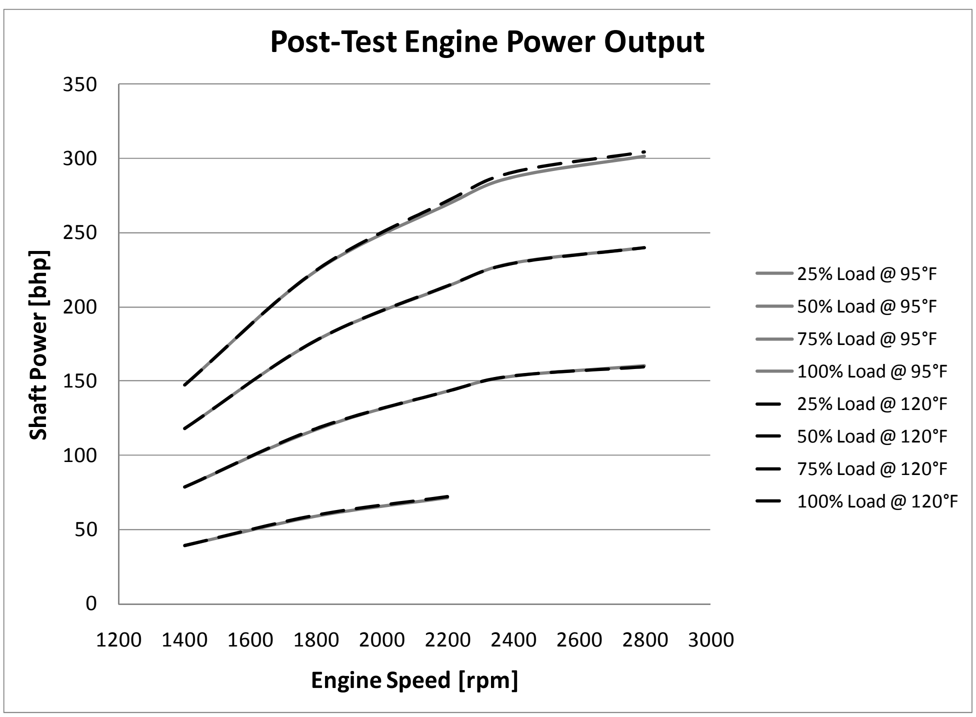
Engine Performance Curves

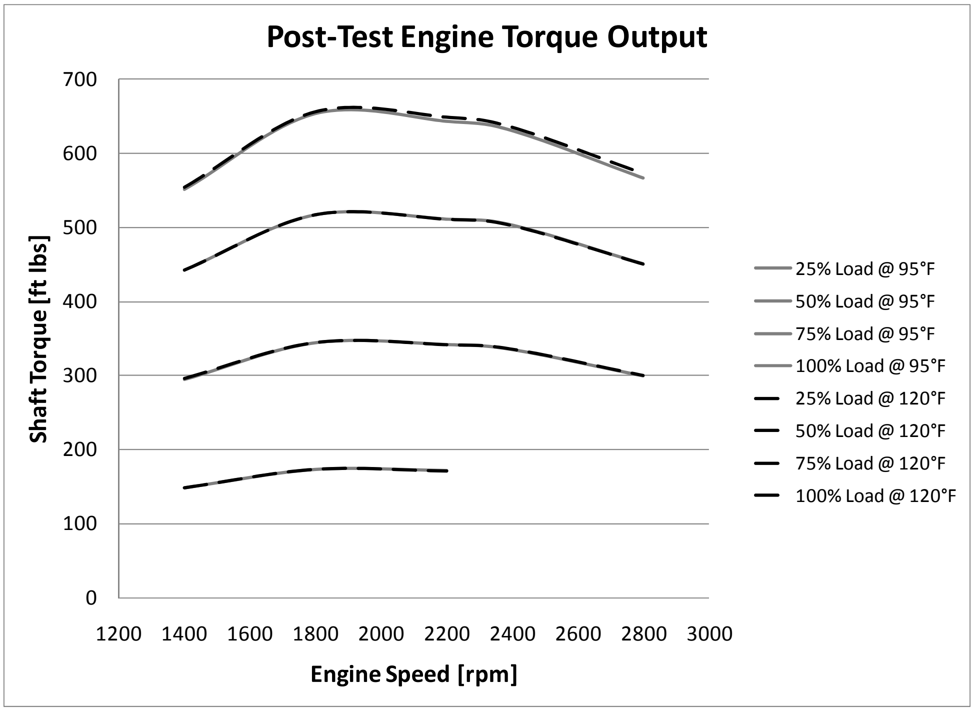
The plots below show the pre and post test engine power curves, as well as a pre and post test composite full load powercurve comparison.






Pre-Test Engine Torque Output
800
700
600
500
400
300
200
100
0
Shaft Torque [ft lbs]
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F


Post-Test Engine Power Output
350
300
250
200
150
100
50
0
Shaft Power [bhp]
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F



Post-Test Engine Torque Output
Shaft Torque [ft lbs]
700
600
500
400
300
200
100
0
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F

Engine Out Emissions

Direct engine out exhaust measurements were taken at the pre and post test powercurve testing segments to document the engines overall condition. In addition, tailpipe emission changes over the test duration could help identify fuel system degradation and engine performance changes. Mass based calculations were determined following methodology outlined in the Code of Federal Regulations, Title 40, Part 86, Subpart D. Final mass based emissions values were then correlated to engine fuel consumption rates to provide direct comparison of emission produced per unit mass of fuel. These values are denoted as the Emissions Index (EI).

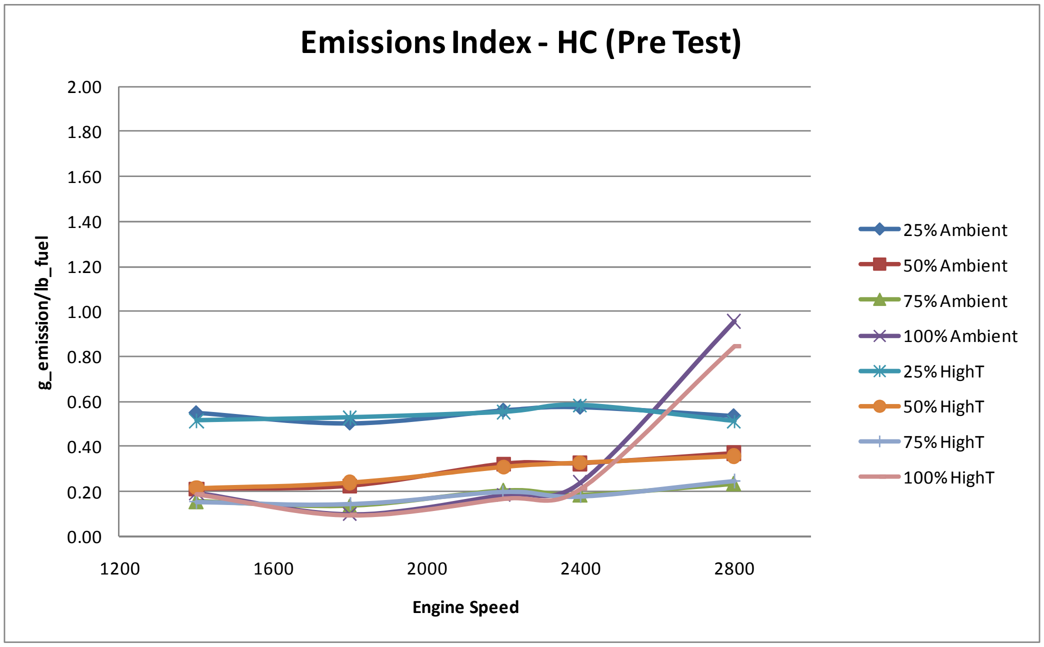


Figure 1 - AF7824 50/50 JP8/SPK, Pre Test HC Emissions

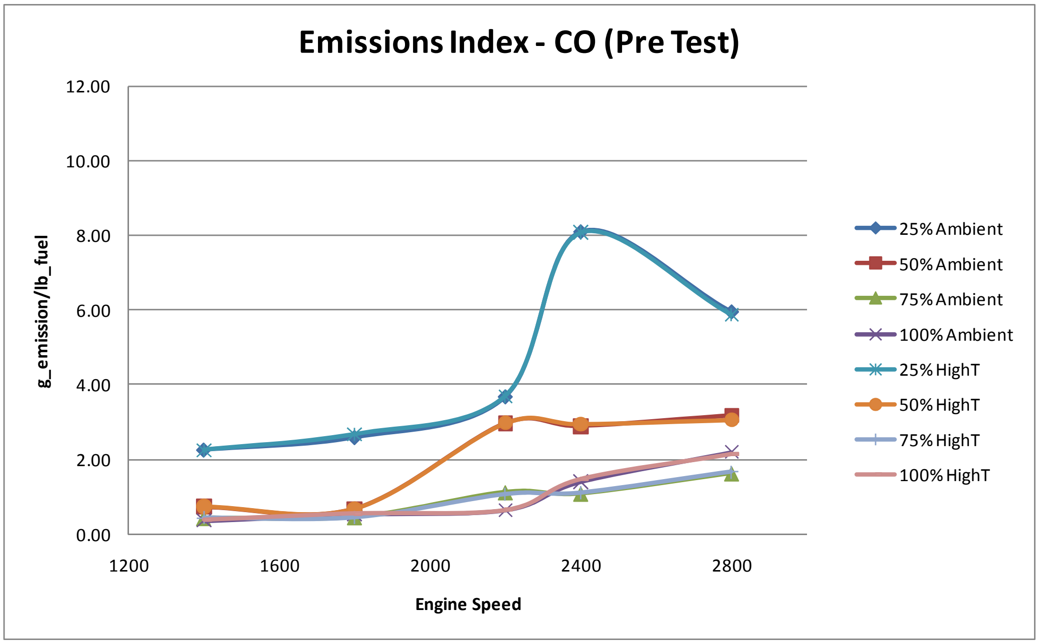


Figure 2 - AF7824 50/50 JP8/SPK, Pre Test CO Emissions

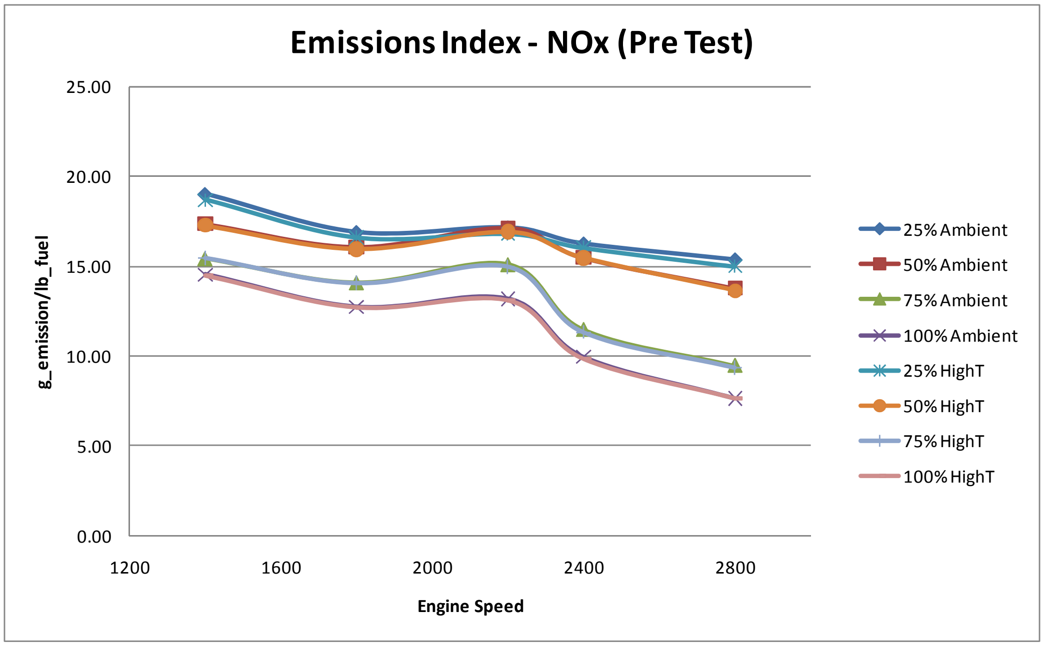


Figure 3 - AF7824 50/50 JP8/SPK, Pre Test NOx Emissions

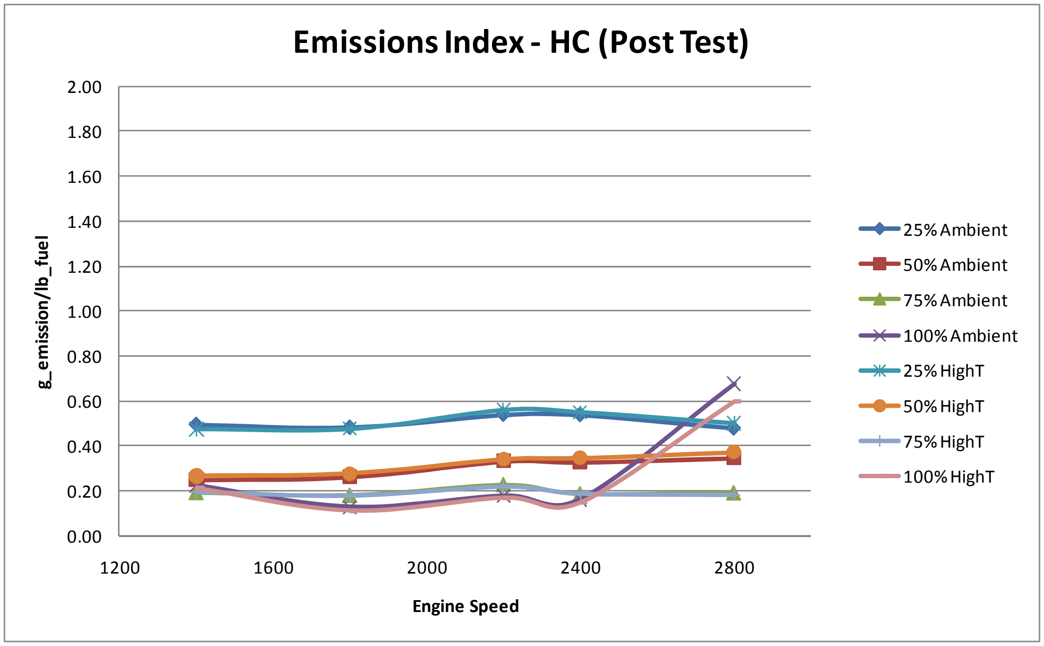


Figure 4 - AF7824 50/50 JP8/SPK, Post Test HC Emissions

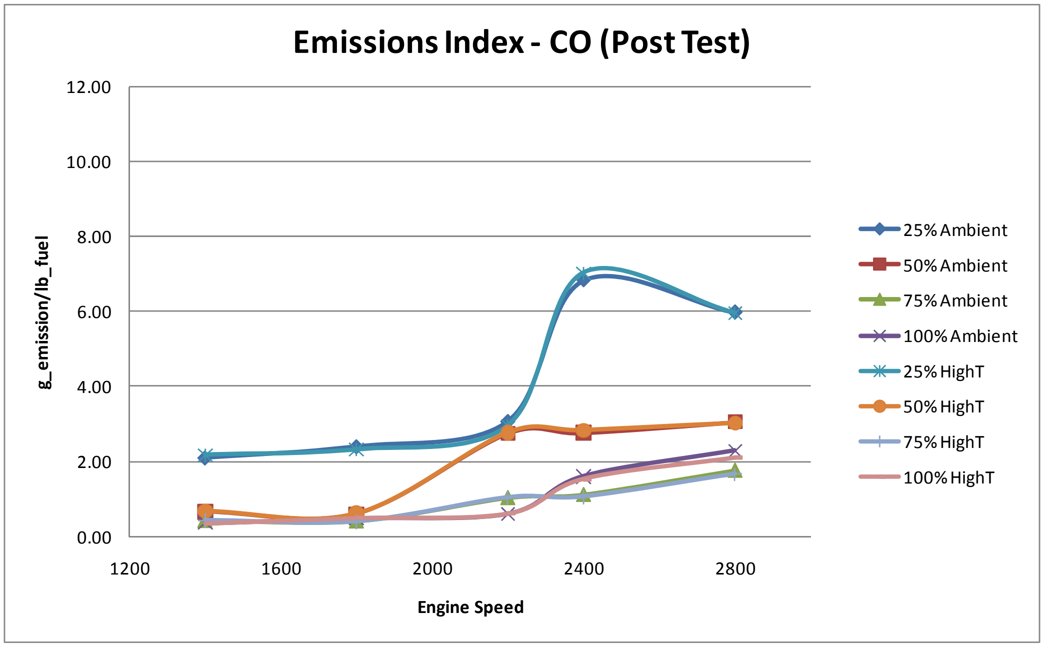


Figure 5 - AF7824 50/50 JP8/SPK, Post Test CO Emissions

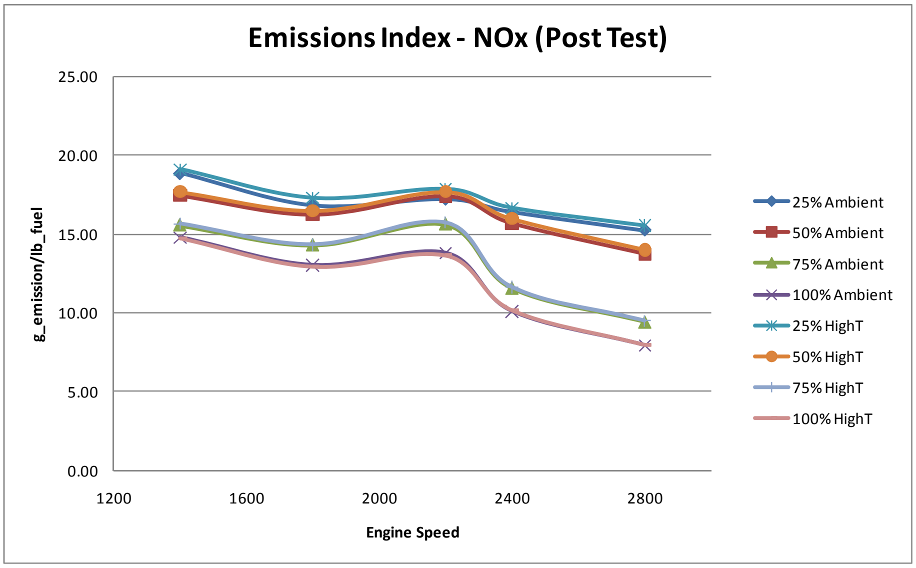


Figure 6 - AF7824 50/50 JP8/SPK, Post Test NOx Emissions

Engine Noise Evaluation

Engine noise levels were quantified with the use of a handheld dB meter to use as a comparison with follow on testing. Noise measurements were taken at engine idle conditions with test cell cooling fans turned off in an effort to reduce any chance of data effects due to noise emitted from ancillary test equipment. No engine noise measurements were taken at rated speed conditions due to the extreme noise levels present in the test cell.

Fuel: AF7824
Engine Condition: Idle, Approx 600rpm
Date: 2/28/11
Front - 92.4dB
Top - 87.3dB
Left - 87.1dB
Right - 87.4dB

Fuel: AF7824
Engine Condition: Idle, Approx 600rpm
Date: 3/3/11
Front - 90.2dB
Top - 85.8dB
Left - 86.7dB
Right - 87.5dB

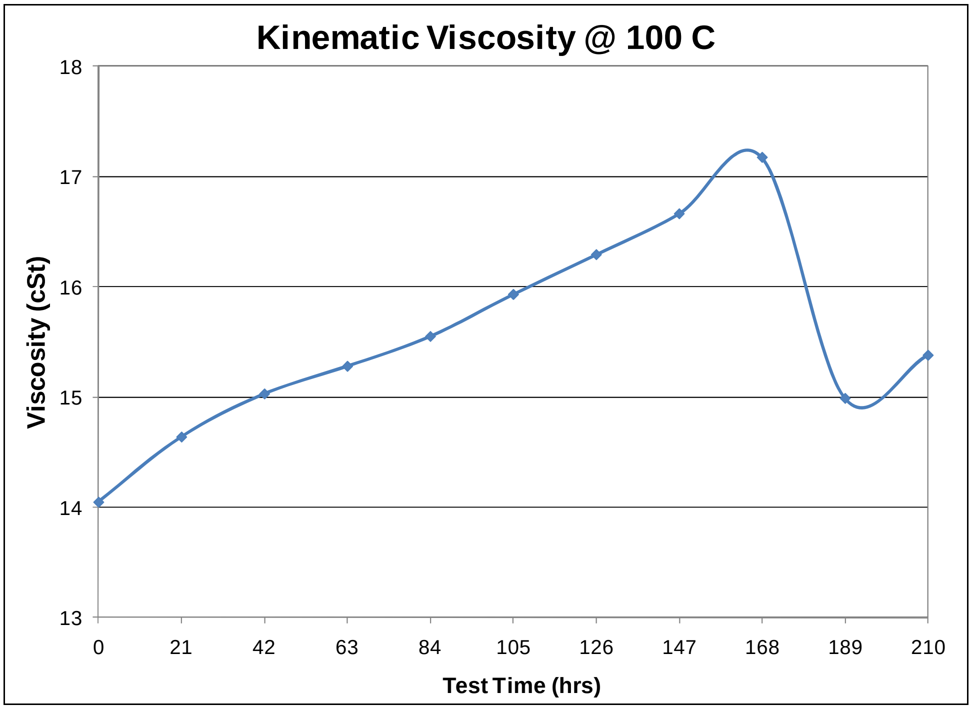
Fuel: AF7824
Engine Condition: Idle, Approx 600rpm
Date: 3/8/11
Front - 90.1dB
Top - 86.7dB
Left - 86.8dB
Right – 87.2dB

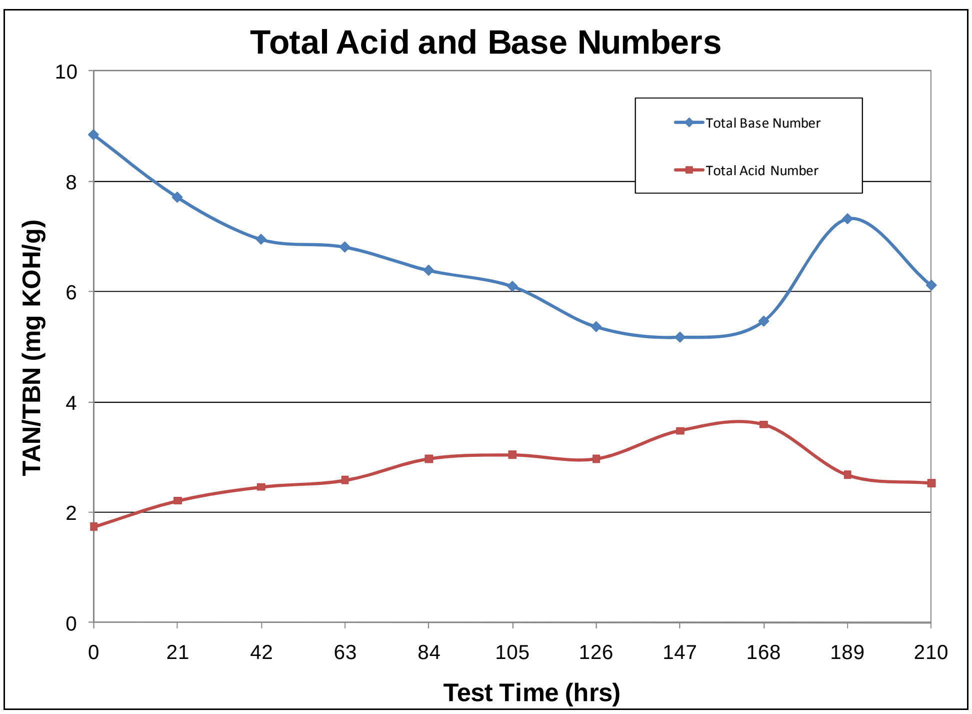
Engine Oil Analysis

The table below shows the engine used oil analysis over the test duration. An oil change was completed at the completion of 168 testing hours to prevent TAN & TBN cross and acceleration of engine oil degradation. Plots of various used oil property trends are shown below.

Property	ASTM Test	Test Hours										
		0	21	42	63	84	105	126	147	168	189	210
Density	D4052	0.854	0.859	0.863	0.865	0.869	0.871	0.875	0.878	0.881	0.862	0.865
Viscosity @ 100°C (cSt)	D445	14.1	14.6	15.0	15.3	15.6	15.9	16.3	16.7	17.2	15.0	15.4
Total Base Number (mg KOH/g)	D4739	8.8	7.7	7.0	6.8	6.4	6.1	5.4	5.2	5.5	7.3	6.1
Total Acid Number (mg KOH/g)	D664	1.7	2.2	2.5	2.6	3.0	3.0	3.0	3.5	3.6	2.7	2.5
Oxidation (Abs./cm)	E168 FTNG	0.0	1.7	3.7	4.8	6.4	7.7	8.3	9.1	10.2	2.6	4.2
Nitration (Abs./cm)	E168 FTNG	0.0	1.0	1.7	2.0	2.5	3.0	3.1	3.1	2.6	1.2	1.9
Soot	Soot	0.3	1.0	1.5	2.0	2.6	3.0	3.5	4.0	4.6	1.4	2.0
Wear Metals (ppm)	D5185											
Al		1	2	2	3	3	3	3	4	4	2	3
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		73	52	44	40	38	38	33	33	31	48	41
Ca		840	909	909	922	948	947	1050	1066	1060	899	920
Cr		<1	<1	1	1	2	2	2	3	3	<1	1
Cu		<1	<1	<1	1	2	2	2	2	3	<1	<1
Fe		1	16	27	40	60	82	106	133	168	34	47
Pb		<1	<1	<1	<1	<1	<1	<1	1	2	<1	<1
Mg		1128	1269	1239	1293	1284	1279	1284	1346	1366	1261	1286
Mn		<1	<1	<1	<1	<1	<1	<1	1	1	<1	<1
Mo		66	70	72	73	75	76	75	76	77	70	74
Ni		<1	<1	<1	<1	<1	<1	<1	<1	1	<1	<1
P		1104	1071	1077	1070	1075	1083	1101	1124	1112	1090	1082
Si		4	6	7	7	8	8	8	9	9	6	6
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		7	7	8	8	9	8	9	11	10	9	8
Sn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Zn		1254	1283	1300	1338	1341	1378	1388	1409	1459	1322	1321
K		<5	<5	5	5	6	<5	<5	<5	<5	6	5
Sr		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

Engine Oil Analysis Trends





Oil Consumption Data

Average oil consumption per test hour was 0.037 lbs/hr.
[Calculated by: (Total Additions-Total Samples)/210hrs]

Samples:

Test Time	Date	Sample + Container Weight, lbs	-	Container Weight,lbs	=	Sample Weight, lbs
21 hr	2/24/11	0.28		0.06		0.22
42 hr	2/25/11	0.29		0.06		0.23
63 hr	2/26/11	0.29		0.06		0.23
84 hr	3/1/11	0.30		0.06		0.24
105 hr	3/2/11	0.30		0.06		0.24
126 hr	3/3/11	0.30		0.06		0.24
147 hr	3/4/11	0.30		0.06		0.24
168 hr	3/5/11	0.30		0.06		0.24
189 hr	3/8/11	0.29		0.06		0.23
210 hr	3/9/11	0.29		0.06		0.23
				Total Samples	=	2.34

Additions:

Test Time	Date	Addition + Container Weight, lbs	-	Container Weight,lbs	=	Addition Weight, lbs
21 hr	2/24/11	0.81		0.11		0.70
42 hr	2/25/11	1.91		0.11		1.80
63 hr	2/28/11	1.27		0.11		1.16
84 hr	3/1/11	1.31		0.11		1.20
105 hr	3/2/11	1.25		0.11		1.14
126 hr	3/3/11	1.56		0.11		1.45
147 hr	3/4/11	1.05		0.11		0.94
168 hr	3/7/11			Engine Oil Change		
189 hr	3/8/11	0.72		0.11		0.61
210 hr	3/9/11	1.12		0.11		1.01
				Total Additions	=	10.01

Post Test Fuel Injection Hardware Inspection

Below outlines the visual inspection results from the post test high pressure common rail fuel injection pump compared to new unused components.

Part	New	JP-8/SPK
Volume Control Valve	New	As new
Pump Body	Very light polish of bores	Light polish & light scuff of bores, top & bottom
Pump Bushings	Both new	Both as new
Cam	Visible light grinding marks	Polish & light burnish, not measureable, seal contact wear, journals V.L. burnish
Roller - Left	New, bright & shiny	Light burnish & polish, Heavy roller end wear against follower
Roller - Right	New, bright & shiny	Light burnish & polish
Roller Shoe - L	New	New, polish from plunger button
Roller Shoe - R	New	New, polish from plunger button
Follower - L	New	Polish, light scuff, top & bottom
Follower - R	New	Polish, light scuff, top & bottom
Plunger - L	New	As new, light polish on plunger button, more than right, more polish than JP-8
Plunger - R	New	As new, light polish on plunger button
Barrel - L	New	As new
Barrel - R	New	As new
Inlet Check - L	New	As new
Inlet Check -R	New	As new

Post Test Fuel Injection Hardware Photos (no magnification)

The following photos document the post test fuel injection hardware condition. Figure 7 and Figure 8 below shows a representative photo of the HPCR pump body. Frame of reference for left and right notations are taken from Figure 8 as it's installed in the engine.

Figure 7 - HPCR Pump Body, Front (Representative Photo)

Figure 8 - HPCR Pump Body, Rear (Representative Photo)

Figure 9 shows the left hand pump body bore. Figure 10 shows a close up picture of the light polish and scuffing found on the bore surface from interaction with the cam follower assembly.

Figure 9 - AF7824 50/50 JP8/SPK, Post Test, Left Pump Bore

Figure 10 - AF7824 50/50 JP8/SPK, Post Test, Left Pump Bore Close

Figure 11 shows the right hand pump body bore. Figure 12 shows a close up picture of the light polish and scuffing found on the bore surface similar to the left hand bore.

Figure 11 - AF7824 50/50 JP8/SPK, Post Test, Right Pump Bore

Figure 12 - AF7824 50/50 JP8/SPK, Post Test, Right Pump Bore Close

Figure 13 and Figure 14 shows the pump body rear and front camshaft bushings respectively. The bushings showed no signs of wear.

Figure 13 - AF7824 50/50 JP8/SPK, Rear Pump Body Camshaft Bushing

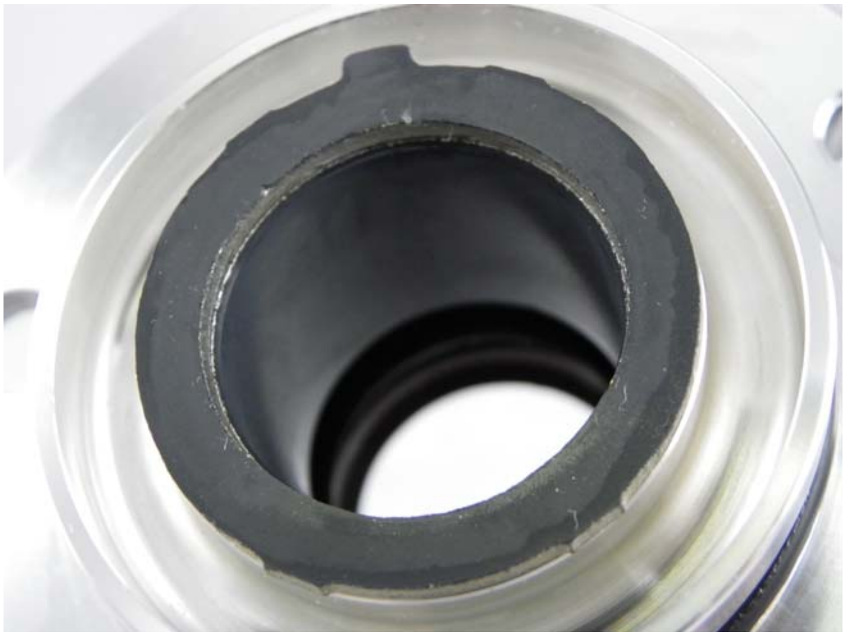


Figure 14 - AF7824 50/50 JP8/SPK, Front Pump Body Camshaft Bushing

Figure 15 shows the HPCR fuel injection pump camshaft.

Figure 15 - AF7824 50/50 JP8/SPK, HPCR Pump Camshaft

Figure 16 shows a close-up of a cam lobe peak. A polish and light burnish can be seen in the contact areas of the cam surface, but no measureable wear is detected. A light burnish was also noted on the journal bearing surface of the cam.

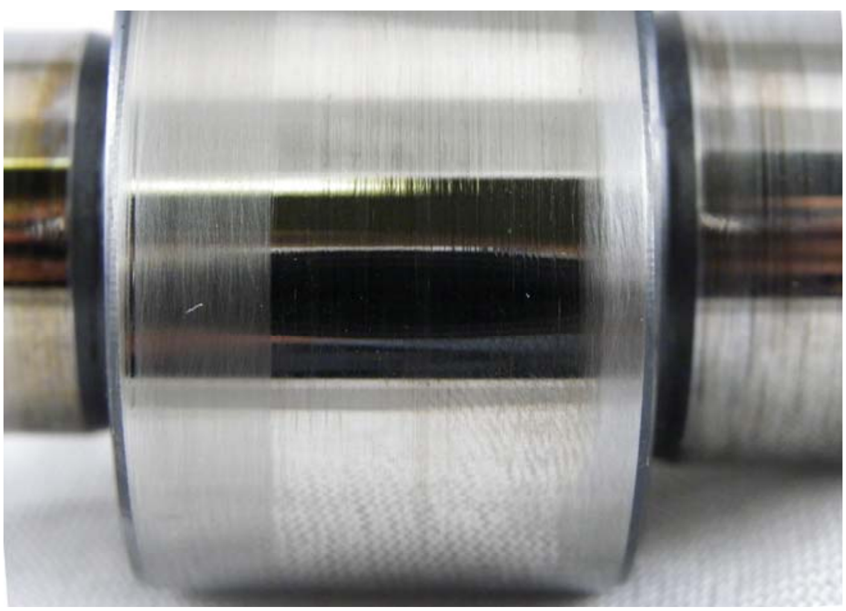


**Figure 16 - AF7824 50/50 JP8/SPK, HPCR Pump Camshaft,
Lobe Surface Close-up**

Figure 17 shows the left bore cam follower and roller assembly. The follower was oriented to show the most severe areas of scuffing present on the follower surface. Figure 18 below shows the left hand roller surface.

Figure 17 - AF7824 50/50 JP8/SPK, Left Cam Follower

Figure 18 - AF7824 50/50 JP8/SPK, Left Cam Follower Roller

Specific to the left hand follower assembly for the 50/50 fuel only, one side of the roller had experienced severe wear into the shoe/follower assembly. Figure 19, Figure 20, and Figure 21 document this wear. As seen in the photos, the outside edge of the roller contains major scoring from contact with the shoe/follower. In addition, the shoe/follower edge has the roller profile ground into its surface.

Figure 19 - AF7824 50/50 JP8/SPK, Left Hand Follower Roller Wear - 1

Figure 20 - AF7824 50/50 JP8/SPK, Left Hand Follower Roller Wear - 2

Figure 21 - AF7824 50/50 JP8/SPK, Left Hand Follower Roller Wear - 3

At this time it is unknown whether this wear is due to a fuel related issue, or a manufacturing problem inherent to this particular pump. If this were a fuel related issue, one would expect the right hand roller/follower assembly to show a similar wear pattern, which it does not. If during manufacturing, the roller was made with a slight taper or the bore machining in the pump body was slightly out of tolerance, this could potentially preload the roller to one side of the shoe forcing it to experience more side loading instead of naturally floating in the middle. Further testing with similar fuels will be needed to determine the cause. It is thought that the increased friction at this interface increased the temperature of the fuel in the immediate area within the pump further lowering the fuels viscosity. This could be a contributing factor to the increase in scuffing present on the follower surface.

Figure 22 shows the left cam follower undercrown and the contact area with the high pressure piston head. Figure 23 shows the left hand high pressure piston. Note the similar contact markings where it contacts the follower undercrown. Polishing at this interface was visible, but no physical wear was tactically distinguishable.

Figure 22 - AF7824 50/50 JP8/SPK, Left Cam Follower Undercrown

Figure 23 - AF7824 50/50 JP8/SPK, Left High Pressure Piston

Figure 24 shows the left bore cam follower and roller assembly. The follower was oriented to show the most severe areas of scuffing present on the follower surface. Figure 25 below shows the right hand roller surface.

Figure 24 - AF7824 50/50 JP8/SPK, Right Cam Follower

Figure 25 - AF7824 50/50 JP8/SPK, Right Cam Follower Roller

Figure 26 shows the left cam follower undercrown and the contact area with the high pressure piston head. Figure 27 shows the left hand high pressure piston. Similar to the left hand assembly, polishing at this interface was visible, but no physical wear was tactically distinguishable.

Figure 26 - AF7824 50/50 JP8/SPK, Right Cam Follower Undercrown

Figure 27 - AF7824 50/50 JP8/SPK, Right High Pressure Piston

Post Test Fuel Injection High Magnification Photos

The following photos document the post test fuel injector hardware condition. Figure 28 shows the injector nozzle tip. No substantial deposit formations were seen under low magnification. Figure 29 below shows the injector needle tip. No abnormal wear or markings were found on the tapered tip.

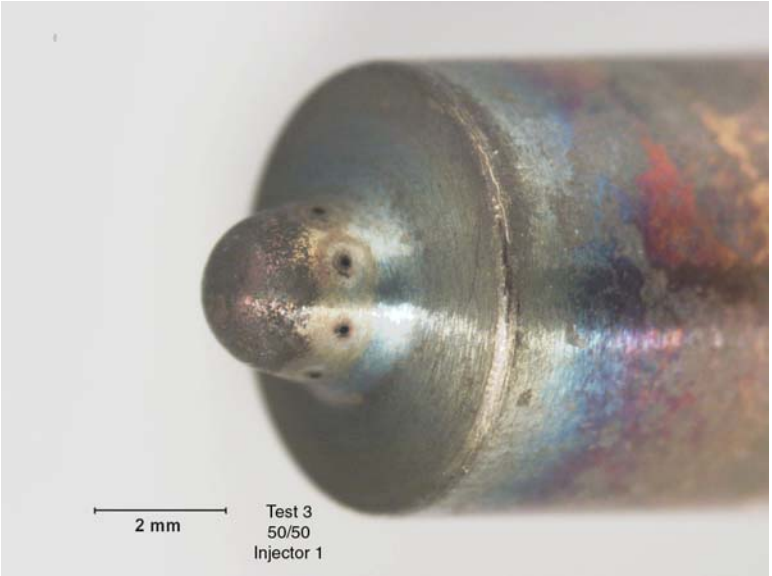


Figure 28 - AF7824 50/50 JP8/SPK, Injector Nozzle

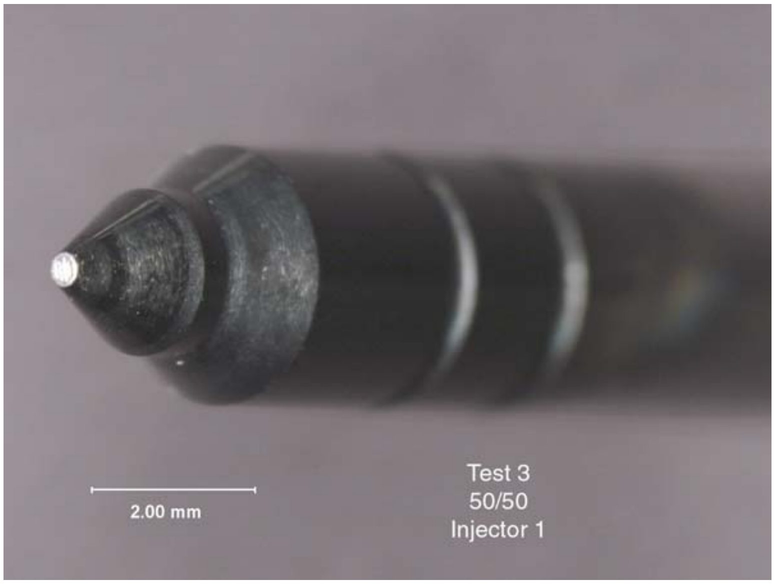


Figure 29 - AF7824 50/50 JP8/SPK, Injector Needle

Figure 30 and Figure 31 shows the upper and lower hydraulic coupler pistons respectively. No noticeable wear was seen on the piston surface interface, or at the heads of the piston at the piezo stack and control valve interface.

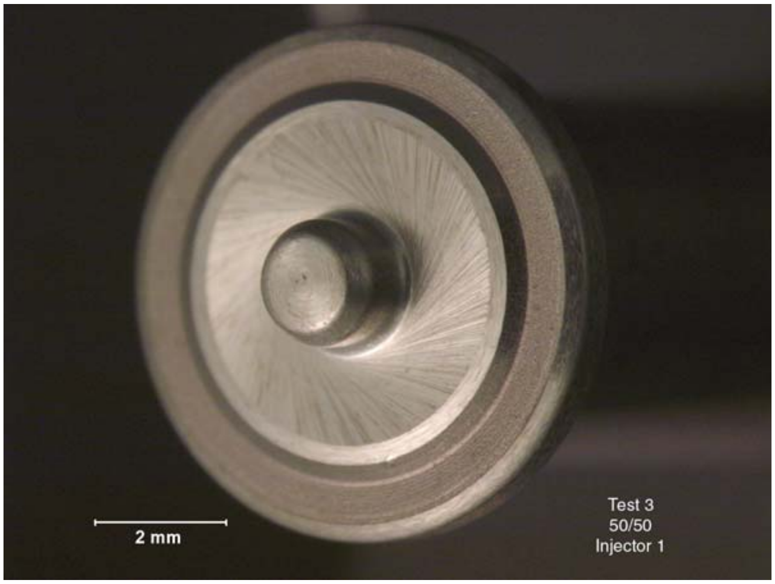


Figure 30 - AF7824 50/50 JP8/SPK, Upper Hydraulic Coupler Piston

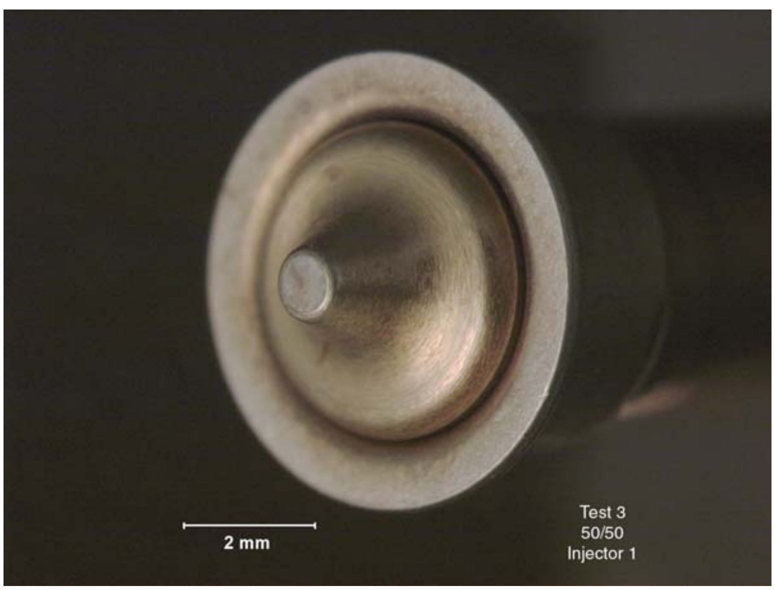


Figure 31 - AF7824 50/50 JP8/SPK, Lower Hydraulic Coupler Piston

Figure 30 and Figure 31 shows the side profile of the upper hydraulic coupler piston. A wear scar shows on the surface of the piston consistent with wear expected from being slightly cocked in the bore when depressed by the piezo-stack.

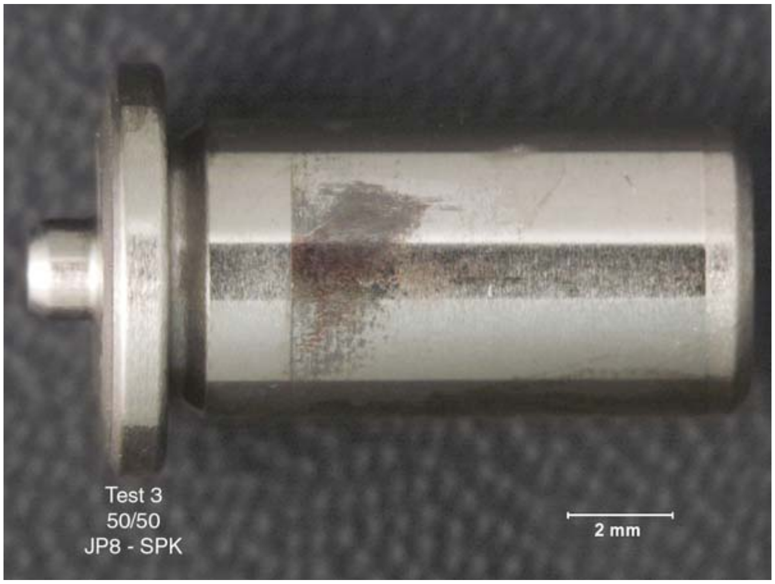


Figure 32 - AF7824 50/50 JP8/SPK, Upper Hydraulic Coupler Piston, Profile

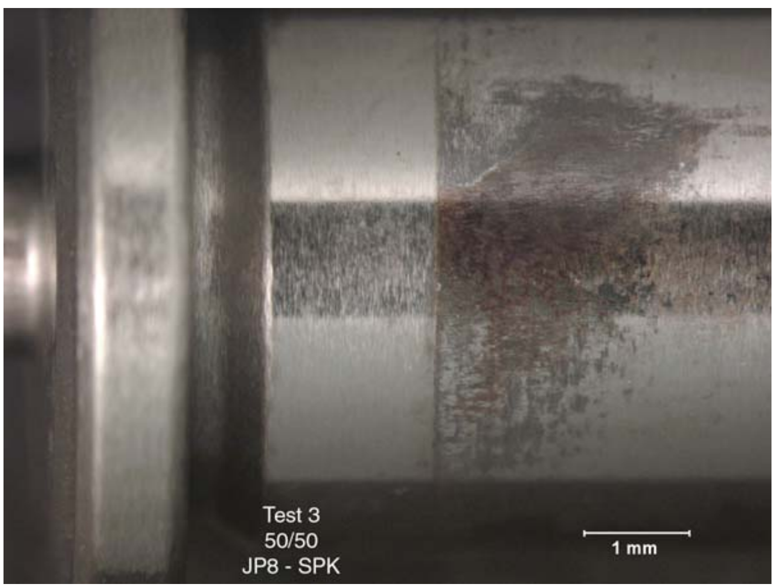


Figure 33 - AF7824 50/50 JP8/SPK, Lower Hydraulic Coupler Piston, Wear Scar Close Up

Figure 34 and Figure 35 shows the top and bottom surfaces of the intermediate plate. This plate contains the fuel control passages used to manipulate the needle position.

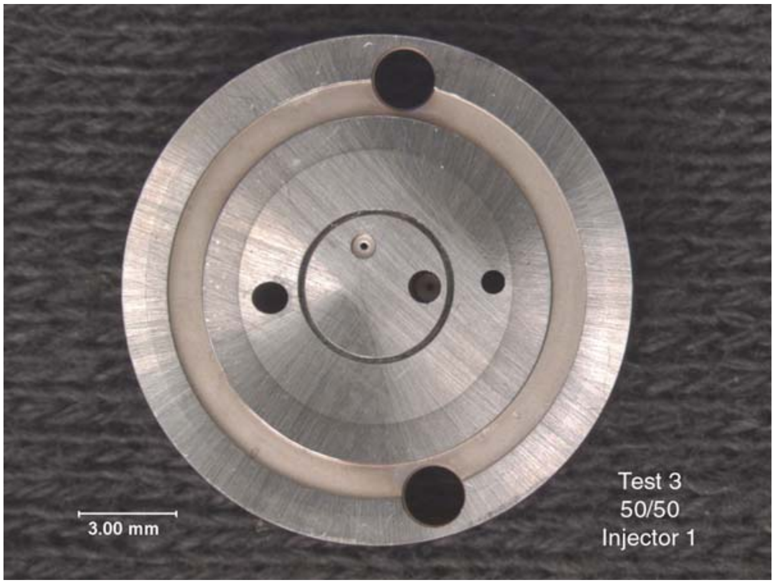


Figure 34 - AF7824 50/50 JP8/SPK, Intermediate Plate (Top)

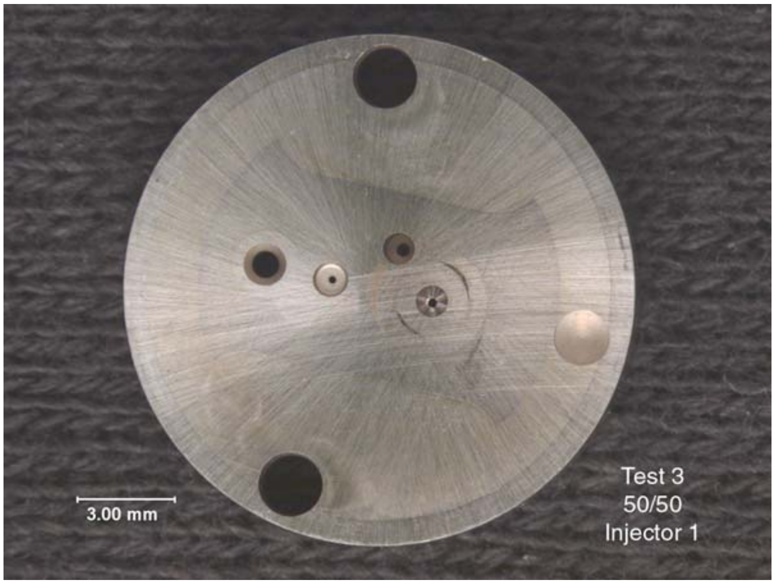


Figure 35 - AF7824 50/50 JP8/SPK, Intermediate Plate (Bottom)

Figure 36 and Figure 37 shows the top and bottom of the control valve plate. The control valve sits in the bore shown in Figure 37. The lower piston of the hydraulic coupler operates in the bore shown in Figure 36.

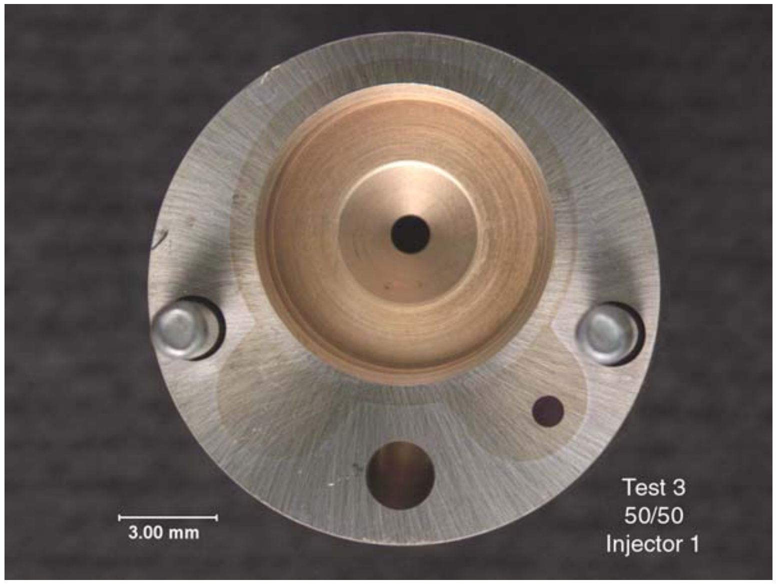


Figure 36 - AF7824 50/50 JP8/SPK, Control Valve Plate (Top)

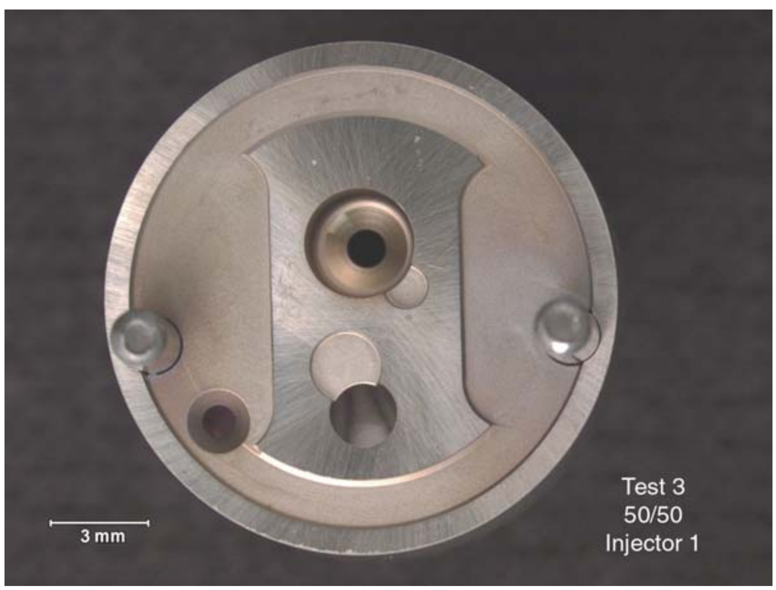


Figure 37 - AF7824 50/50 JP8/SPK, Control Valve Plate (Bottom)

Figure 38 shows the control valve which regulates the pressure on top of the injector needle, thus controlling lift. No unusual wear was found on the control valve.

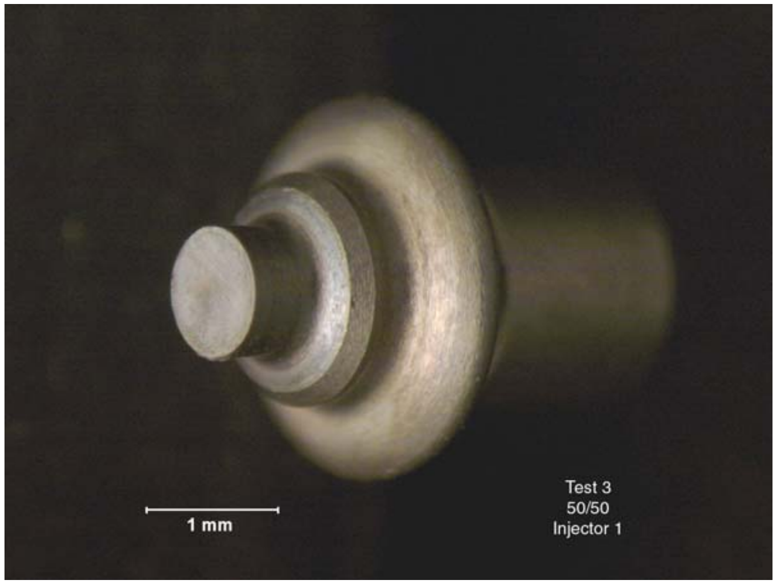


Figure 38 - AF7824 50/50 JP8/SPK, Fuel Injector Control Valve

Noted Problem Areas

TFLRF staff noted a drop in engine boost pressure over the 50/50 JP-8/SPK (Test 3) endurance test duration (approximately 8% loss from start to finish). This trend was also noted during the baseline DF2 (Test 1) and JP-8 (Test 2) endurance tests. Consistent with the previous tests, engine mass air flow and other related parameters showed similar losses over testing. Despite this, the engine fuel flow rate did not follow the same reduction, thus the boost pressure reduction did not impact the overall test goals. As a byproduct, the engine air fuel ratio (AFR) slightly enriched over testing and was noted in elevating exhaust gas port temperature (EGT) increases over the test duration. Due to the total amount of degradation experienced over the first three tests, TFLRF staff felt the need to replace the turbocharger assembly prior to the neat SPK test (Test 4). This was required since boost levels produced at the end of the 50/50 JP-8/SPK test were only slightly higher than the PCM limit before starting engine de-rates.

APPENDIX D

UPK Test Report

(AF7868-67T1-W-210)

Evaluation of Synthetic Paraffinic Kerosene (SPK) in the Ford 6.7L High Pressure Common Rail Diesel Engine

Project 14734.04

Ford Motor Company 6.7L Diesel

Test Lubricant ID: N/A
Test Lubricant: Full Synthetic, CJ-4, SAE 5W-40
Test Fuel ID: AF7868
Test Fuel: SPK (as supplied by sponsor) w/9ppm DCI-4A
Test Number: AF7868-67T1-W-210
Start of Test Date: March 30, 2011
End of Test Date: April 16, 2011
Test Duration: 210 Hours
Test Procedure: Tactical Wheeled Vehicle

Conducted for
U.S. Army TARDEC
Force Projection Technologies
Warren, MI

Introduction

This test was used to determine the performance and endurance of a modern high pressure common rail diesel fuel injection system when operated on 100% Synthetic Paraffinic Kerosene (SPK). Testing was completed following a modified version of the 210hr Tactical Wheeled Vehicle Cycle engine endurance test cycle (CRC Report No.406, Development of Military Fuel/Lubricant/Engine Compatibility Test). This work was completed in support of Project 14734.04, Assessment of Fuels for Military Use, 2010 and Beyond.

Test Engine

The Ford 6.7L diesel engine was chosen for testing as a representative engine utilizing modern high pressure common rail fuel injection technology. The Ford 6.7L engine is a direct injected, turbo-charged, intercooled engine, which employs a fuel lubricated high pressure common rail injection pump and piezo-electric fuel injectors. The test engine had approximately 630hrs of previous testing time in support of additional research, but was fitted with a new fuel injection pump and fuel injectors prior to testing to restore the high pressure fuel system to “as new” condition.

Test Stand Configuration

The engine was mounted in a test stand specifically configured for Ford 6.7L engine testing. Engine monitoring, control, and data acquisition was supplied by Southwest Research Institute (SwRI) developed PRISM software. An appropriately sized absorption dynamometer was used to control engine speed and dissipate load. Engine load was manipulated through the actuation of the engine throttle pedal assembly. Engine coolant temperatures were controlled with the use of liquid-to-liquid heat exchangers utilizing laboratory process water for cooling. Engine intake air was supplied at ambient conditions utilizing the factory engine air box and ducting. Engine exhaust was routed from the test cell through a butterfly valve to control engine exhaust back pressure, and then ducted into the laboratory exhaust blower system for removal. Fuel was supplied to the diesel fuel conditioning module/engine at ambient conditions.

Engine Run-in

Prior to testing, the engine was run-in following the Ford specified engine run-in procedure. This was done despite the previous testing time accrued on the engine to allow for the same duration of engine operation on each fuel system for test consistency. Table 1 below outlines the Ford recommended engine run-in procedure.

Table 1 - Ford Recommended Run-In Procedure

Step	Duration	Speed	Load	
		[rpm]	[lb-ft]	[Nm]
1	0:05	650	0	
2	0:30	1000	72	97
3	0:30	1200	103	140
4	0:30	1400	141	191
5	0:30	1500	162	219
6	0:30	1600	184	249
7	0:30	1700	208	282
8	0:30	1800	233	316
9	0:30	2000	287	390
10	0:30	2200	348	472
11	0:30	2400	414	561
12	0:30	2500	449	609
13	0:30	2600	486	659
14	0:30	2700	524	710
15	0:30	2800	563	764

Pre and Post Test Engine Performance Checks

Before and after testing, engine powercurves were completed at varying speeds and loads to determine pre-test engine performance. Engine performance was documented at engine speeds of 1400, 1800, 2200, 2400, and 2800 rpm, with load intervals of 25%, 50%, 75%, and 100% of full load. Powercurves were completed at both ambient (95°F) and desert condition (120°F) inlet fuel temperatures. Exhaust gas emissions were sampled at each point on the curve to document engine out emissions. Powercurve plots can be seen in the Engine Performance Curves section.

Test Cycle

The test cycle followed during fuel system evaluations was a modified version of the 210hr Tactical Wheeled Vehicle Cycle as outlined in CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test. Slight modifications were made to the test cycle to accelerate the testing schedule. The primary modification was the reduction of engine soak time from 10hrs to 3hrs. The engine soak period in the test cycle was originally included for engine lubricant testing, and added no benefit for fuel compatibility testing. Total modified daily runtime was 21hrs per day, 15hrs at rated speed/load and 6hrs at idle, followed by a 3hr engine soak. To keep the modified test cycle rated to idle testing hours consistent with the standard 210hr Tactical Wheeled Vehicle Cycle, the following daily operating arrangement was derived. The engine completed 6 cycles of 2hr 10min at rated speed followed by a 1hr idle step. After the 6 cycles were completed, an additional 2hr rated segment was conducted followed by the 3hr soak. Engine coolant temperatures were maintained at Ford specifications to ensure engine integrity throughout the test. Engine coolant utilized was a 50/50 blend of ethylene glycol antifreeze and deionized water. Engine operating parameters were controlled as specified in Table 2 below.

(Note – Engine idle speed was controlled by PCM at approximately 600 RPM. Temperature controllers remained at rated speed set points for idle conditions, but were not met due to lack of heat generation in the coolant system. Temperatures were allowed to reach their natural steady state value during idle testing steps. Engine oil cooler plumbing was integral to the engine water jacket, thus not directly controlled. Oil temperatures were allowed to meet their own steady state temperature based on water jacket temperature and engine load/speed throughout testing.)

Table 2 - Test Cycle Operation Parameters

Parameter	Rated Speed	Idle
Engine Speed	2800 +/- 25	NC
High Temp Coolant Loop	203 +/- 3	NC
Low Temp Coolant Loop	100 +/- 3	NC
Oil Sump	NC	NC
*NC = not controlled		

Oil Sampling

Four ounces of engine oil was sampled every 21 hrs (daily) for used oil analysis. Used oil analysis consisted of the following tests as seen below in Table 3. Engine oil changes were performed on the engine based on used oil condition.

Table 3 - Used Oil Analysis Procedures

Daily Used Oil Analysis		
ASTM	D4739	Total Base Number
ASTM	D664	Total Acid Number
ASTM	D445	Kinematic Viscosity @ 100°C
ASTM	API Gravity	API Gravity
ASTM	D4052	Density
ASTM	TGA SOOT	TGA Soot
ASTM	E168	Oxidation
ASTM	E168	Nitration
ASTM	D5185	Wear Metals by ICP

Used oil analysis results can be seen in the engine oil analysis and engine oil analysis trends section of the report.

Oil Level Checks

Engine oil level was checked daily, and replenished as needed to restore oil level to full mark. This process occurred after the completion of the 3hr soak prior to restarting testing the next day.

Test Fuel Analysis

The test fuel was 100% synthetic paraffinic kerosene (SPK) manufactured by Shell and provided for testing by the test sponsor. Since the primary focus of testing was fuel lubricity compatibility, only the lubricity enhancer/corrosion inhibitor additive was blended into to the SPK. The remaining two additives typically found in JP-8 type fuels have little impact on fuel lubricity levels and fuel system durability. The lubricity enhancer used was Innospec Fuel Specialties DCI-4A. Per QPL-25017, the minimum effective treat rate of DCI-4A required an additive concentration of 9ppm in the final fuel blend. In an effort to determine fuel system impact in a "worst case" scenario, the test fuel was treated only at the minimum effective treat rate regardless of the resulting lubricity achieved. After the test fuel was additized and blended, fuel samples were collected to determine critical chemical and physical properties of the fuel for reporting. Table 4 summarizes the critical chemical and physical properties of the tested SPK.

Table 4 - Test Fuel Chemical & Physical Analysis

Property	Units	Method	Results
Density @15°C	g/mL	D4052	0.736
Specific Gravity @15°C		D4052	0.737
API Gravity @15°C		D4052	60.6
Flashpoint	°F	D56	111
	°C	D93	43
	°F	D3828	109
Kinematic Viscosity @-20°C	cSt	D445	2.5
Kinematic Viscosity @40°C	cSt	D445	0.9
Hydrocarbon Content			
Carbon	wt%	D5291	83.94
Hydrogen	wt%		16.46
Calculated Cetane Index		D976	57.2
Calculated Cetane Index		D4737	66.8
Cetane Number		D613	64.0
IQT	DCN	D6890-04	58.5
Heat of Combustion (Gross)	BTU/lb	D240	20364.4
Total Acid Number	mg KOH/g	D3242	0.011
Hydrocarbon Type			
Aromatics	%mass	D5186	0.3
Hydrocarbon Type			
Aromatics	%vol	D1319	0.4
Olefins			0.5
Saturates			99.1
Sulfur	ppm	D5453	<10
Nitrogen	wt%	D3228	<0.03
HFRR	mm	D6079	0.840
BOCLE	mm	D5001	0.76
Bulk Modulus @30°C	psi	by Speed of Sound	152749
Distillation			
IBP	°C	D86	152.5
10%			161.5
20%			162.7
50%			168.8
90%			186.0
End Pt			203.0

Endurance Test Cycle Results

The following information summarizes the results of the engine fuel system endurance tests. Data includes: engine operating summary, powercurve analysis, engine out emissions, used oil analysis, post test component inspection, post test component photos, and listing of any problem areas or anomalies experienced during testing.

Engine Operating Conditions Summary

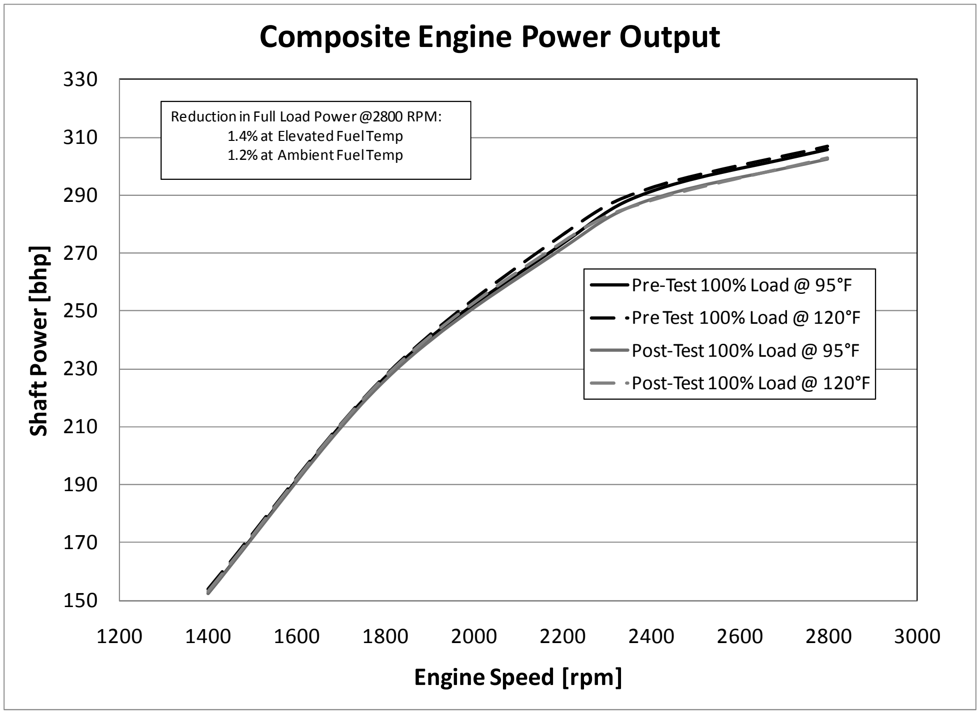
Below is a summary of the engine operating conditions over the test duration.

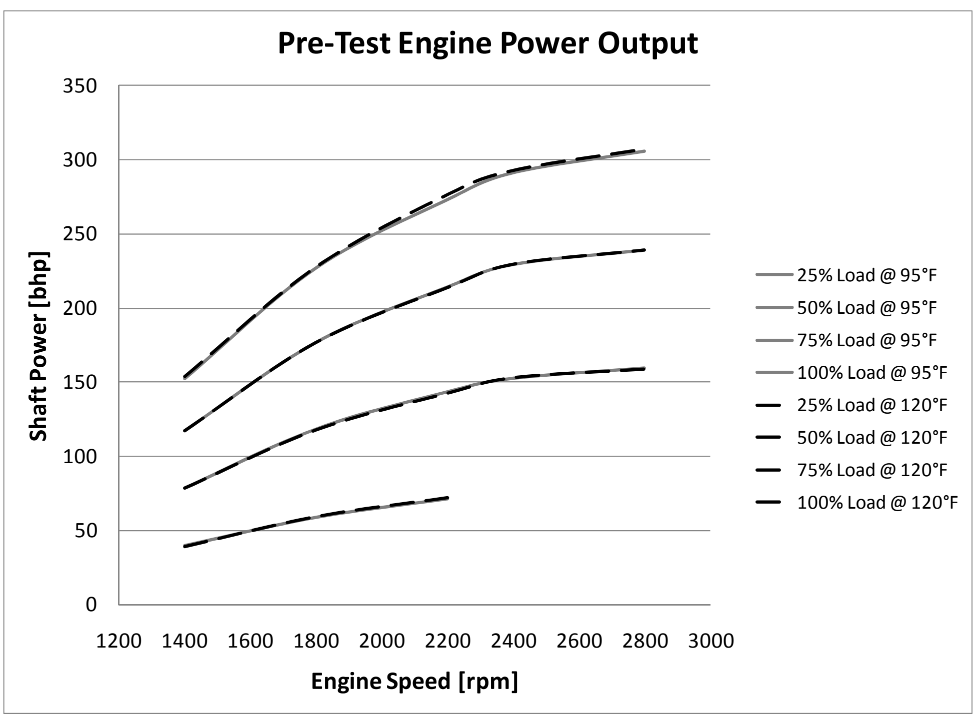
		Rated Conditions (2800 RPM)		Idle Conditions (600 RPM)	
Perameter:	**Units:**	**Average**	**Std. Dev.**	**Average**	**Std. Dev.**
Engine Speed	RPM	2799.99	2.11	602.39	2.22
Torque*	ft*lb	580.89	5.15	39.94	2.32
Fuel Flow	lb/hr	122.65	2.11	2.32	0.46
Power*	bhp	309.69	2.76	4.58	0.27
BSFC*	lb/bhp*hr	0.396	0.008	0.518	0.336
Temperatures:					
High Temperature Loop Coolant In	°F	185.34	0.85	171.54	11.91
High Temperature Loop Coolant Out	°F	203.00	0.59	174.37	12.23
Low Temperature Loop Coolant In	°F	100.10	1.30	91.22	5.75
Low Temperature Loop Coolant Out	°F	124.28	1.35	91.21	5.77
Oil Sump	°F	247.30	1.68	178.79	13.01
Fuel In	°F	92.89	4.67	90.57	5.79
Fuel Pump Drain	°F	109.22	5.01	93.94	6.06
Fuel Return	°F	102.37	1.79	91.85	5.86
Intake Air Before Compressor	°F	77.56	2.13	77.08	2.78
Intake Air After Compressor	°F	333.16	5.03	90.60	3.96
Intake Air After Charge Cooler	°F	107.01	1.21	90.28	5.97
Cylinder 1 Exhaust	°F	1390.12	15.30	263.98	14.27
Cylinder 2 Exhaust	°F	1323.56	5.06	249.95	12.44
Cylinder 3 Exhaust	°F	1353.50	11.63	264.94	12.42
Cylinder 4 Exhaust	°F	1356.49	16.60	258.59	13.07
Cylinder 5 Exhaust	°F	1352.27	17.74	261.16	15.28
Cylinder 6 Exhaust	°F	1388.84	10.60	269.26	12.37
Cylinder 7 Exhaust	°F	1346.72	11.98	260.11	12.59
Cylinder 8 Exhaust	°F	1354.35	16.33	263.87	10.34
Exhaust, Left Manifold Exit	°F	1326.09	18.51	233.26	14.15
Exhaust, Right Manifold Exit	°F	1345.11	14.58	225.12	15.67
Exhaust After Turbo	°F	1117.57	13.94	217.67	14.18
Pressures:					
Oil Galley	psi	52.91	0.34	26.75	1.76
Ambient Pressure	psiA	14.23	0.06	14.22	0.06
Intake Restriction	psi	0.48	0.01	14.24	0.06
Exhaust Restriction	psi	10.71	0.28	-0.13	0.03
Boost Pressure	psi	19.41	0.45	0.35	0.03
Fuel Rail Pressure	psi	19406.54	21.36	4019.02	23.14

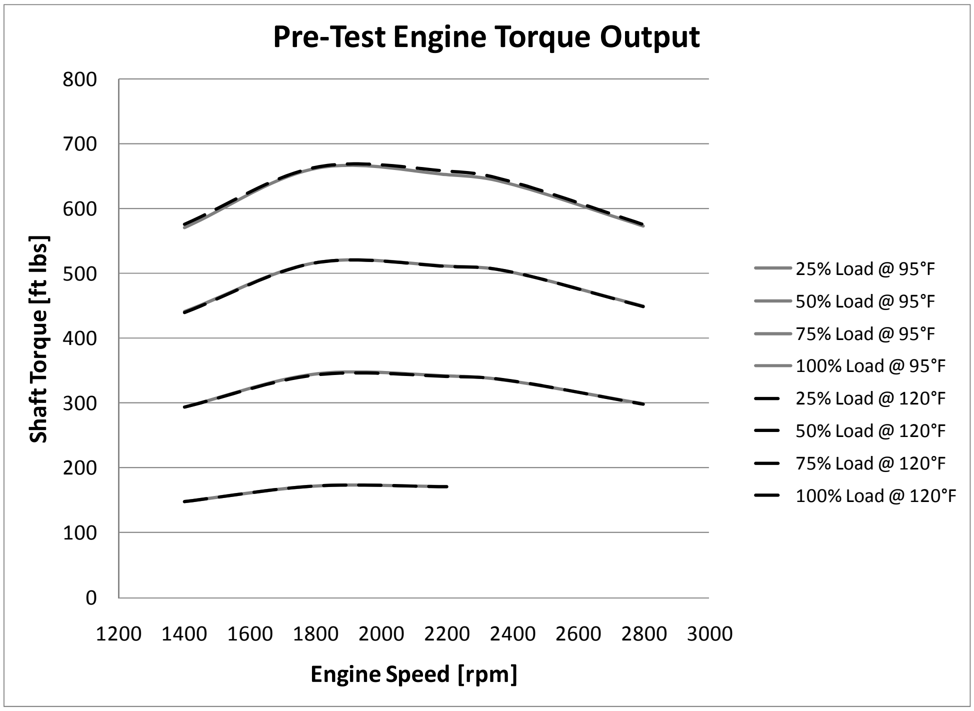
* Non-corrected Values

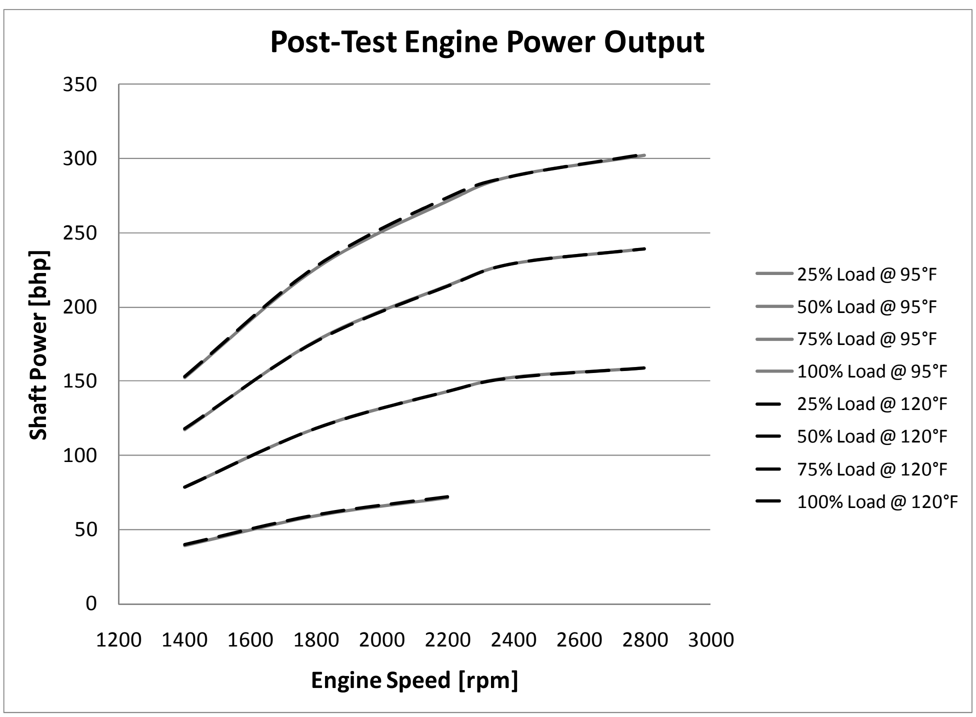
Engine Performance Curves

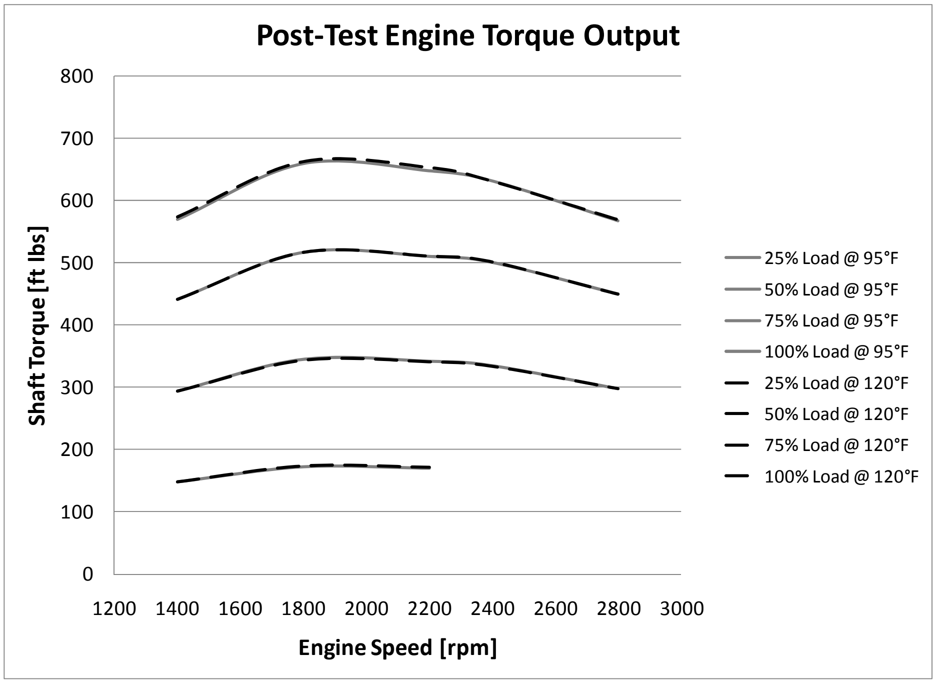
The plots below show the pre and post test engine power curves, as well as a pre and post test composite full load powercurve comparison.






Pre-Test Engine Torque Output
Shaft Torque [ft lbs]
800
700
600
500
400
300
200
100
0
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F


Post-Test Engine Power Output
Shaft Power [bhp]
350
300
250
200
150
100
50
0
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F


Post-Test Engine Torque Output
Shaft Torque [ft lbs]
800
700
600
500
400
300
200
100
0
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Engine Speed [rpm]
25% Load @ 95°F
50% Load @ 95°F
75% Load @ 95°F
100% Load @ 95°F
25% Load @ 120°F
50% Load @ 120°F
75% Load @ 120°F
100% Load @ 120°F

Engine Out Emissions

Direct engine out exhaust measurements were taken at the pre and post test powercurve testing segments to document the engines overall condition. In addition, tailpipe emission changes over the test duration could help identify fuel system degradation and engine performance changes. Mass based calculations were determined following methodology outlined in the Code of Federal Regulations, Title 40, Part 86, Subpart D. Final mass based emissions values were then correlated to engine fuel consumption rates to provide direct comparison of emission produced per unit mass of fuel. These values are denoted as the Emissions Index (EI).

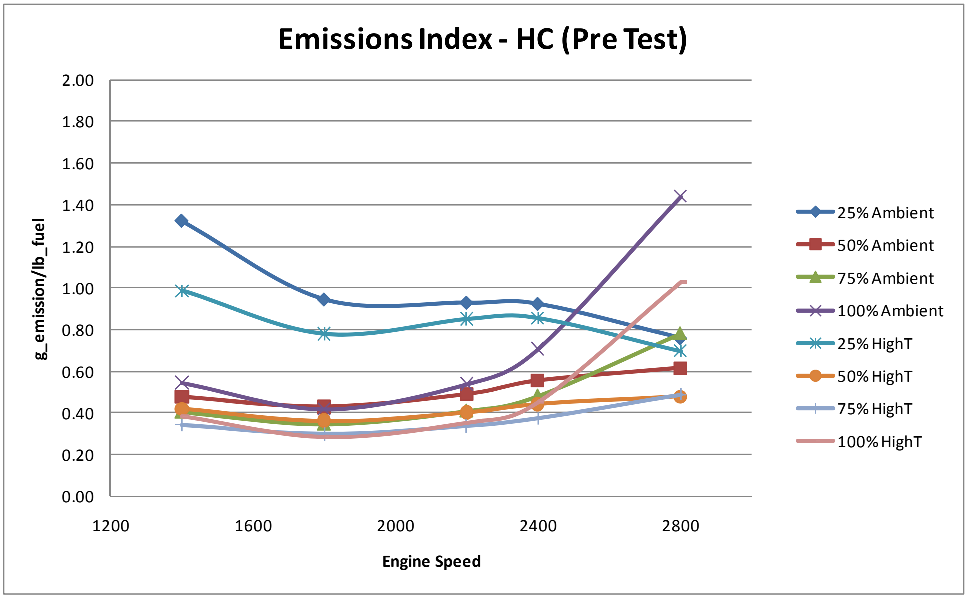


Figure 1 - AF7868 SPK, Pre Test HC Emissions

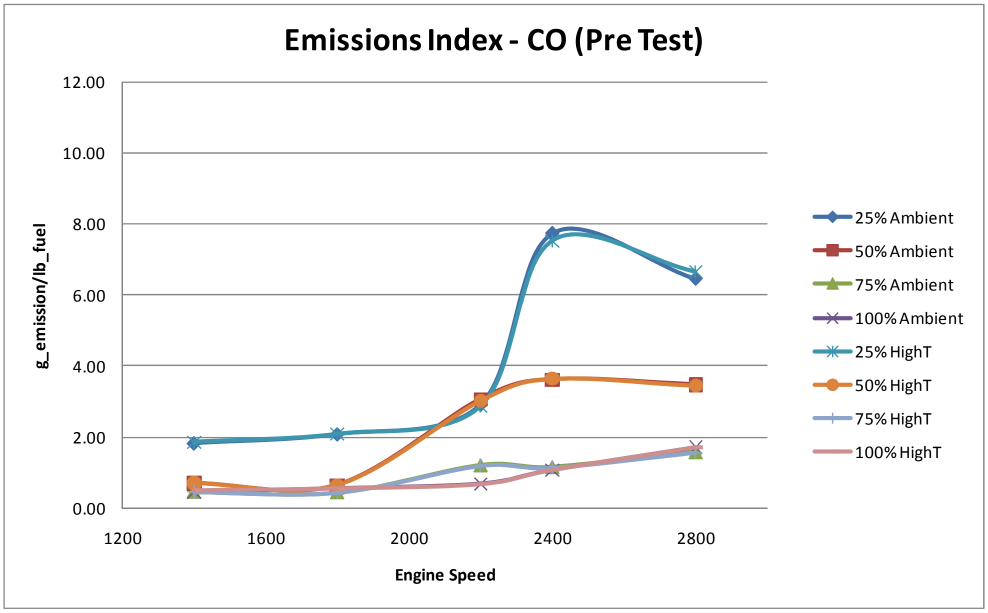


Figure 2 - AF7868 SPK, Pre Test CO Emissions

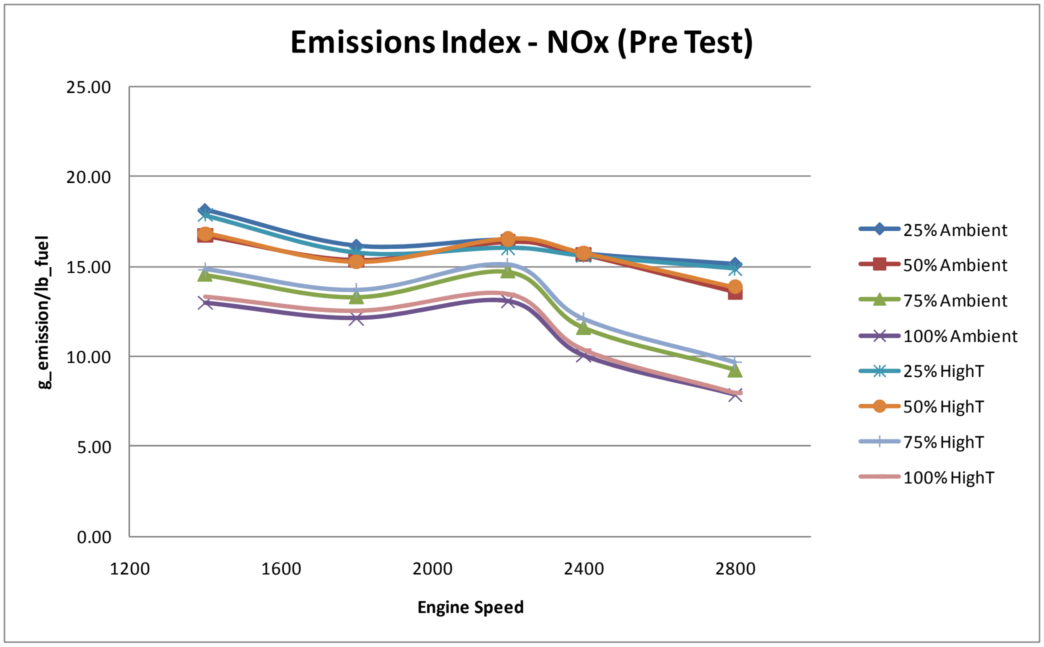


Figure 3 - AF7868 SPK, Pre Test NOx Emissions

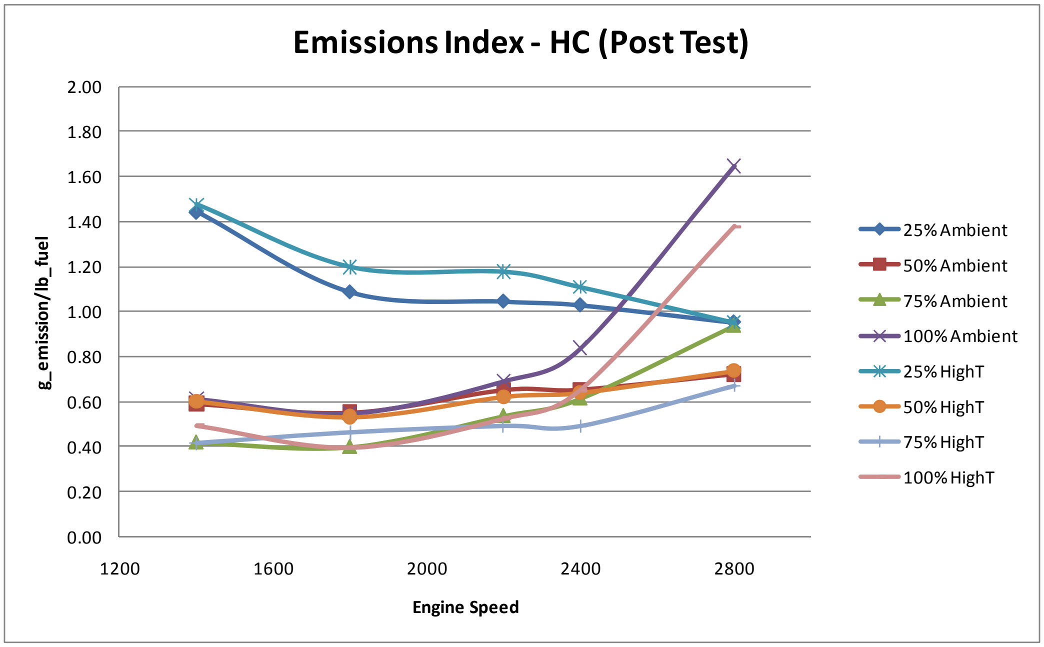


Figure 4 - AF7868 SPK, Post Test HC Emissions

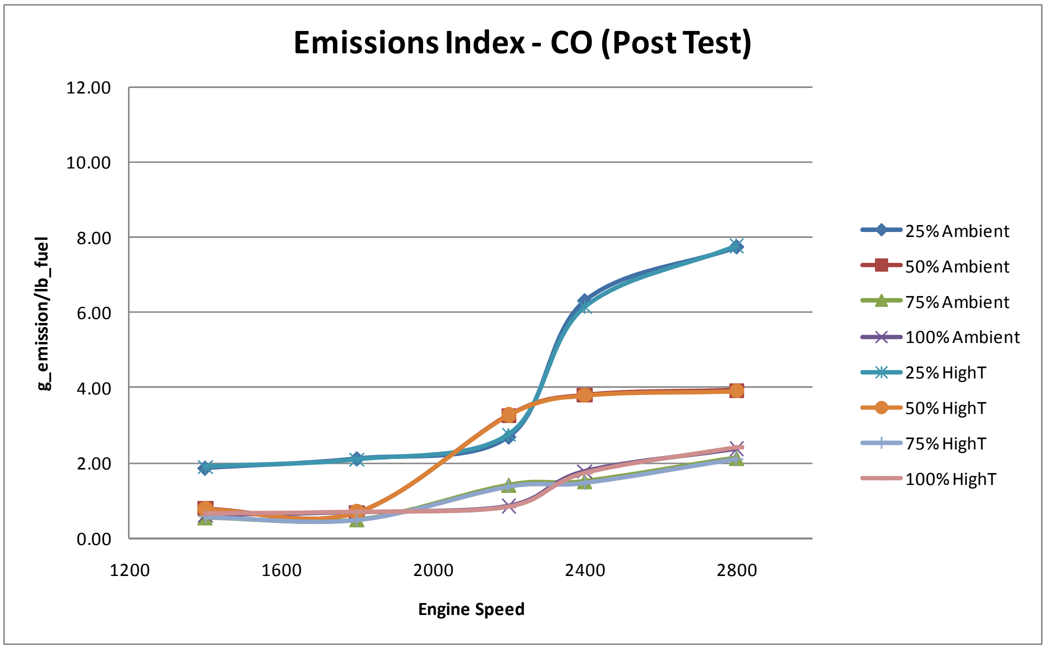


Figure 5 - AF7868 SPK, Post Test CO Emissions

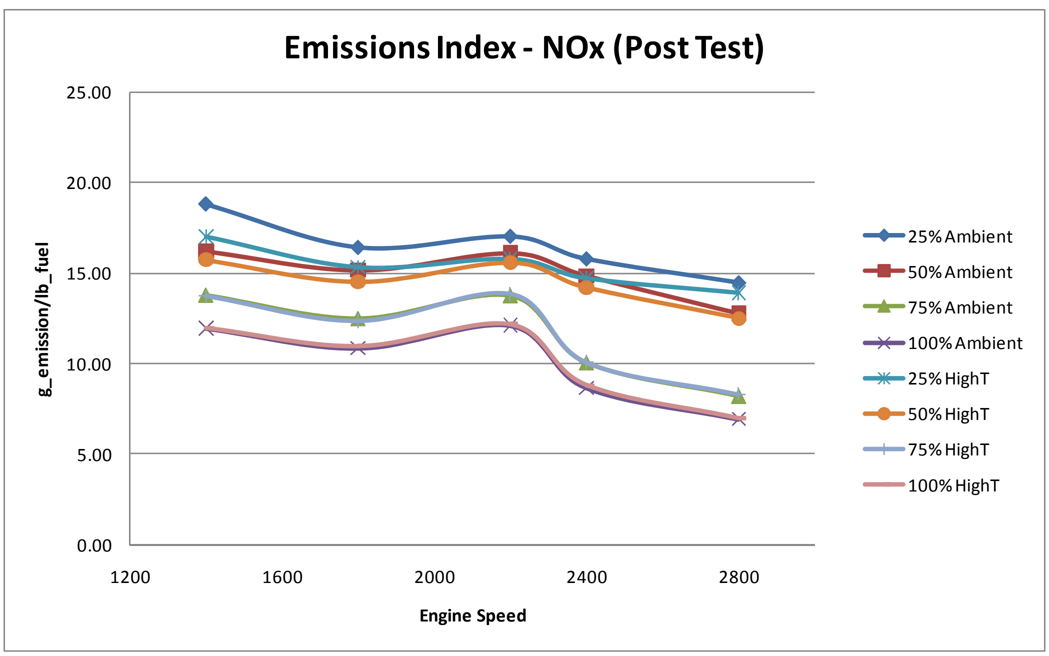


Figure 6 - AF7868 SPK, Post Test NOx Emissions

Engine Noise Evaluation

Engine noise levels were quantified with the use of a handheld dB meter to use as a comparison with follow on testing. Noise measurements were taken at engine idle conditions with test cell cooling fans turned off in an effort to reduce any chance of data effects due to noise emitted from ancillary test equipment. No engine noise measurements were taken at rated speed conditions due to the extreme noise levels present in the test cell.

Fuel: AF7868
Engine Condition: Idle, Approx 600rpm
Date: 3/30/11

Front - 90.4dB
Top - 86.8dB
Left - 86.5dB
Right - 87.0dB

Fuel: AF7868
Engine Condition: Idle, Approx 600rpm
Date: 4/5/11

Front - 92.0dB
Top - 87.2dB
Left - 87.0dB
Right - 87.9dB

Fuel: AF7868
Engine Condition: Idle, Approx 600rpm
Date: 4/13/11

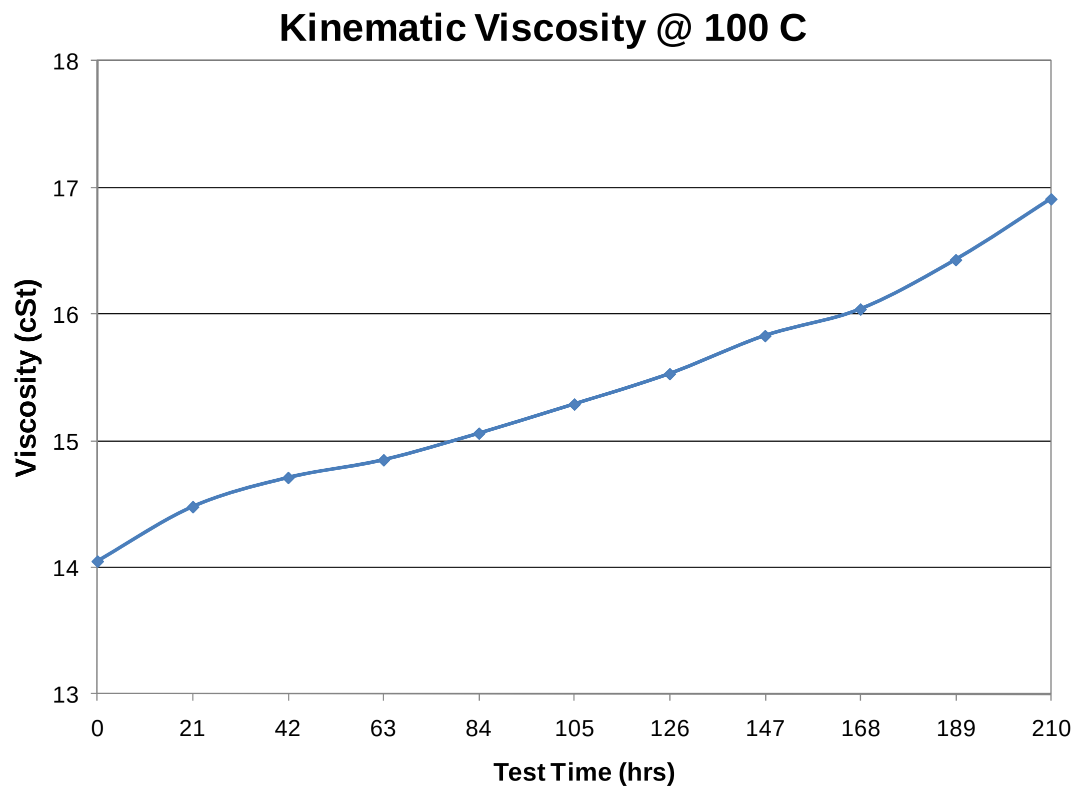
Front - 90.3dB
Top - 87.8dB
Left - 87.0dB
Right - 8.4dB

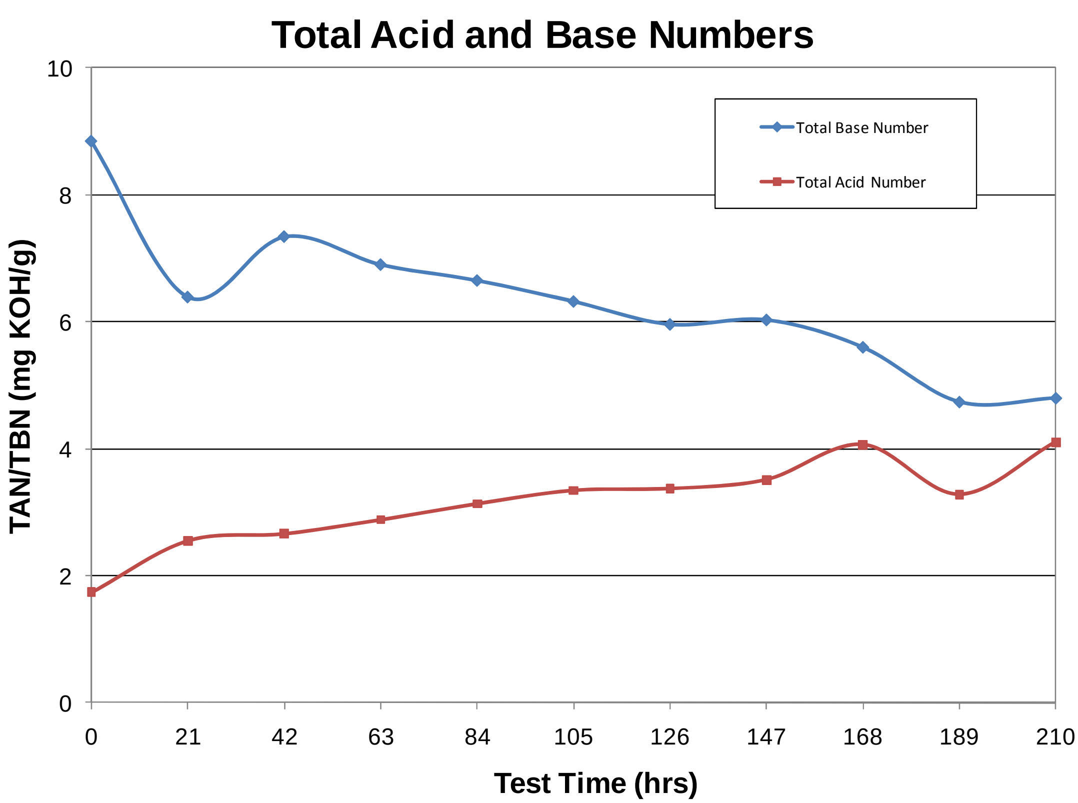
Engine Oil Analysis

The table below shows the engine used oil analysis over the test duration. No oil changes were required during testing. Plots of various used oil property trends are shown below.

Property	ASTM Test	Test Hours										
		0	21	42	63	84	105	126	147	168	189	210
Density	D4052	0.854	0.858	0.860	0.862	0.865	0.867	0.869	0.871	0.873	0.878	0.886
Viscosity @ 100°C (cSt)	D445	14.1	14.5	14.7	14.9	15.1	15.3	15.5	15.8	16.0	16.4	16.9
Total Base Number (mg KOH/g)	D4739	8.8	6.4	7.3	6.9	6.7	6.3	6.0	6.0	5.6	4.7	4.8
Total Acid Number (mg KOH/g)	D664	1.7	2.6	2.7	2.9	3.1	3.3	3.4	3.5	4.1	3.3	4.1
Oxidation (Abs./cm)	E168 FTNG	0.0	2.5	4.4	5.9	7.9	9.8	11.5	12.5	14.0	15.0	16.0
Nitration (Abs./cm)	E168 FTNG	0.0	1.0	1.6	2.1	2.8	3.2	3.6	3.6	3.7	3.6	3.5
Soot	Soot	0.3	0.8	1.0	1.3	1.7	2.0	2.4	2.6	3.0	3.3	3.7
Wear Metals (ppm)	D5185											
Al		1	1	2	2	3	3	3	3	4	4	4
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		73	51	40	34	32	31	31	30	29	29	32
Ca		840	894	890	919	954	969	981	1009	1063	1062	1071
Cr		<1	<1	<1	1	2	2	2	2	2	3	3
Cu		<1	<1	<1	<1	1	1	2	2	2	3	3
Fe		1	16	22	30	41	54	77	92	121	138	163
Pb		<1	<1	<1	<1	<1	<1	1	2	2	2	3
Mg		1128	1235	1221	1308	1313	1331	1359	1392	1457	1446	1471
Mn		<1	<1	<1	<1	<1	<1	<1	<1	1	1	1
Mo		66	70	72	73	74	76	79	79	83	84	88
Ni		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
P		1104	1056	1076	1061	1088	1107	1119	1112	1169	1189	1200
Si		4	6	11	6	6	7	7	7	8	8	9
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	1	1
Na		7	7	8	8	10	8	9	9	10	11	12
Sn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Zn		1254	1293	1286	1331	1384	1389	1423	1451	1487	1532	1557
K		<5	<5	6	<5	<5	<5	<5	5	<5	6	<5
Sr		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

Engine Oil Analysis Trends





Oil Consumption Data

Average oil consumption per test hour was 0.066 lbs/hr.
[Calculated by: (Total Additions-Total Samples)/210hrs]

Samples:

Test Time	Date	Sample + Container Weight, lbs	-	Container Weight,lbs	=	Sample Weight, lbs
21 hr	3/31/11	0.30		0.06		0.24
42 hr	4/1/11	0.28		0.06		0.22
63 hr	4/2/11	0.29		0.05		0.24
84 hr	4/5/11	0.30		0.06		0.24
105 hr	4/6/11	0.29		0.06		0.23
126 hr	4/12/11	0.30		0.05		0.25
147 hr	4/13/11	0.30		0.06		0.24
168 hr	4/14/11	0.30		0.05		0.25
189 hr	4/15/11	0.29		0.06		0.23
210 hr	4/16/11	0.30		0.06		0.24
				Total Samples	=	2.38

Additions:

Test Time	Date	Addition + Container Weight, lbs	-	Container Weight,lbs	=	Addition Weight, lbs
21 hr	3/31/11	1.19		0.11		1.08
42 hr	4/1/11	1.89		0.11		1.78
63 hr	4/4/11	1.22		0.11		1.11
84 hr	4/5/11	1.51		0.11		1.40
105 hr	4/6/11	1.77		0.11		1.66
126 hr	4/12/11	1.97		0.11		1.86
147 hr	4/13/11	1.99		0.11		1.88
168 hr	4/14/11	1.92		0.11		1.81
189 hr	4/15/11	1.89		0.11		1.78
210 hr	4/18/11	1.97		0.11		1.86
				Total Additions	=	16.22

Post Test Fuel Injection Hardware Inspection

Below outlines the visual inspection results from the post test high pressure common rail fuel injection pump compared to new unused components.

Part	New	SPK
Volume Control Valve	New	As new
Pump Body	Very light polish of bores	Light polish & very light scuff of bores, top & bottom
Pump Bushings	Both new	Both as new
Cam	Visible light grinding marks	Light polish & very light burnish, not measureable, seal contact wear
Roller - Left	New, bright & shiny	Very light burnish & polish
Roller - Right	New, bright & shiny	Very light burnish & polish
Roller Shoe - L	New	New, polish from plunger button
Roller Shoe - R	New	New, polish from plunger button
Follower - L	New	Polish, very light scuff, top & bottom
Follower - R	New	Polish, very light scuff, top & bottom
Plunger - L	New	As new, light polish on plunger button, more than right
Plunger - R	New	As new, light polish on plunger button
Barrel - L	New	As new
Barrel - R	New	As new
Inlet Check - L	New	As new
Inlet Check -R	New	As new

Post Test Fuel Injection Hardware Photos (no magnification)

The following photos document the post test fuel injection hardware condition. Figure 7 and Figure 8 below shows a representative photo of the HPCR pump body. Frame of reference for left and right notations are taken from Figure 8 as it's installed in the engine.

Figure 7 - HPCR Pump Body, Front (Representative Photo)

Figure 8 - HPCR Pump Body, Rear (Representative Photo)

Figure 9 shows the left hand pump body bore. Figure 10 shows a close up picture of the light polish found on the bore surface from interaction with the cam follower assembly.

Figure 9 - AF7868 SPK, Post Test, Left Pump Bore

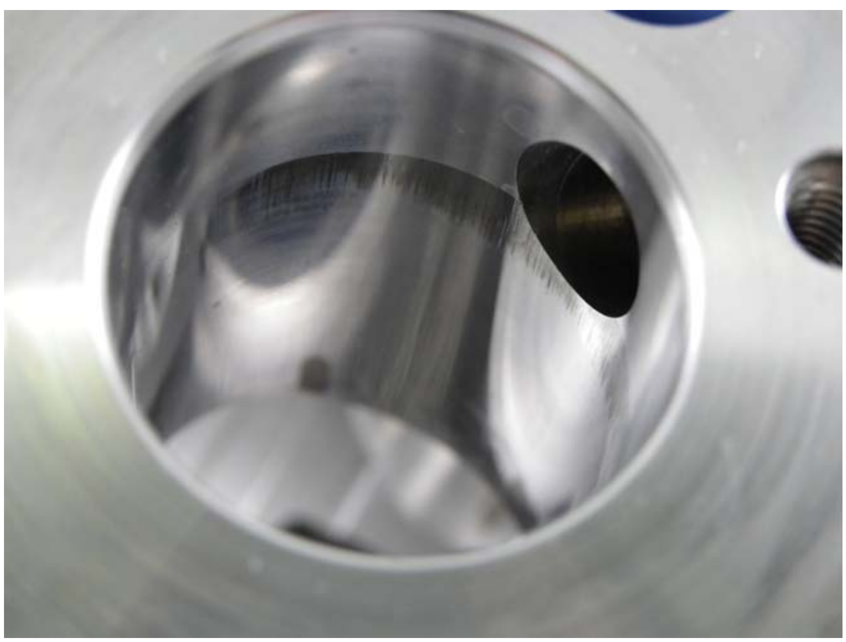


Figure 10 - AF7868 SPK, Post Test, Left Pump Bore Close

Figure 11 shows the right hand pump body bore. Figure 12 below shows a close up picture of the light polish found on the bore surface similar to the left hand bore.

Figure 11 - AF7868 SPK, Post Test, Right Pump Bore

Figure 12 - AF7868 SPK, Post Test, Right Pump Bore Close

Figure 13 and Figure 14 below shows the pump body rear and front camshaft bushings respectively. The bushings showed no signs of wear.

Figure 13 - AF7868 SPK, Rear Pump Body Camshaft Bushing

Figure 14 - AF7868 SPK, Front Pump Body Camshaft Bushing

Figure 15 shows the HPCR fuel injection pump camshaft.

Figure 15 - AF7868 SPK, HPCR Pump Camshaft

Figure 16 shows a close-up of a cam lobe peak. A slight polish can be seen in the contact areas of the cam surface, but no measureable wear is detected.

Figure 16 - AF7868 SPK, HPCR Pump Camshaft, Lobe Surface Close-up

Figure 17 shows the left bore cam follower and roller assembly. The follower was oriented to show the most severe areas of scuffing present on the follower surface. Figure 18 below shows the left hand roller surface.

Figure 17 - AF7868 SPK, Left Cam Follower

Figure 18 - AF7868 SPK, Left Cam Follower Roller

Figure 19 shows the left cam follower undercrown and the contact area with the high pressure piston head. Figure 20 shows the left hand high pressure piston. Note the similar contact markings where it contacts the follower undercrown. Polishing at this interface was visible, but no physical wear was tactically distinguishable.

Figure 19 - AF7868 SPK, Left Cam Follower Undercrown

Figure 20 - AF7868 SPK, Left High Pressure Piston

Figure 21 shows the left bore cam follower and roller assembly. The follower was oriented to show the most severe areas of scuffing present on the follower surface. Figure 22 below shows the right hand roller surface.

Figure 21 - AF7868 SPK, Right Cam Follower

Figure 22 - AF7868 SPK, Right Cam Follower Roller

Figure 23 shows the left cam follower undercrown and the contact area with the high pressure piston head. Figure 24 shows the left hand high pressure piston. Similar to the left hand assembly, polishing at this interface was visible, but no physical wear was tactically distinguishable.

Figure 23 - AF7868 SPK, Right Cam Follower Undercrown

Figure 24 - AF7868 SPK, Right High Pressure Piston

Post Test Fuel Injection High Magnification Photos

The following photos document the post test fuel injector hardware condition. Figure 25 shows the injector nozzle tip. No substantial deposit formations were seen under low magnification. Figure 26 below shows the injector needle tip. No abnormal wear or markings were found on the tapered tip.

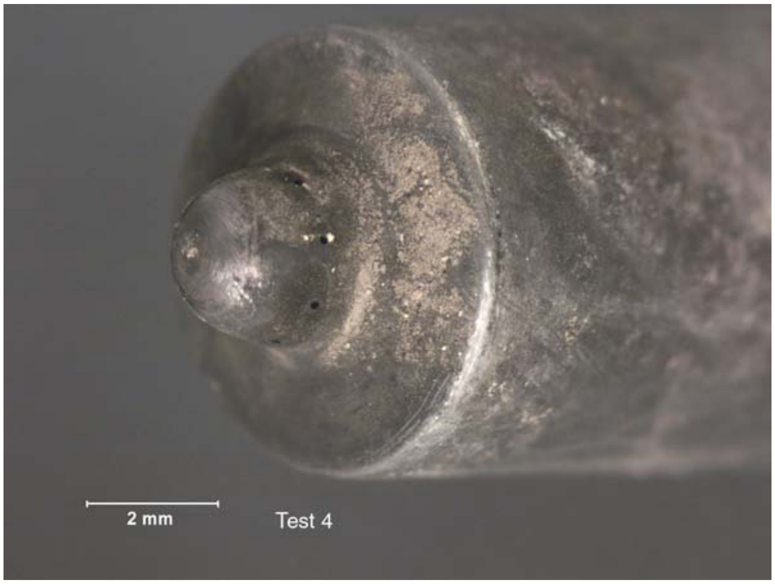


Figure 25 - AF7868 SPK, Injector Nozzle

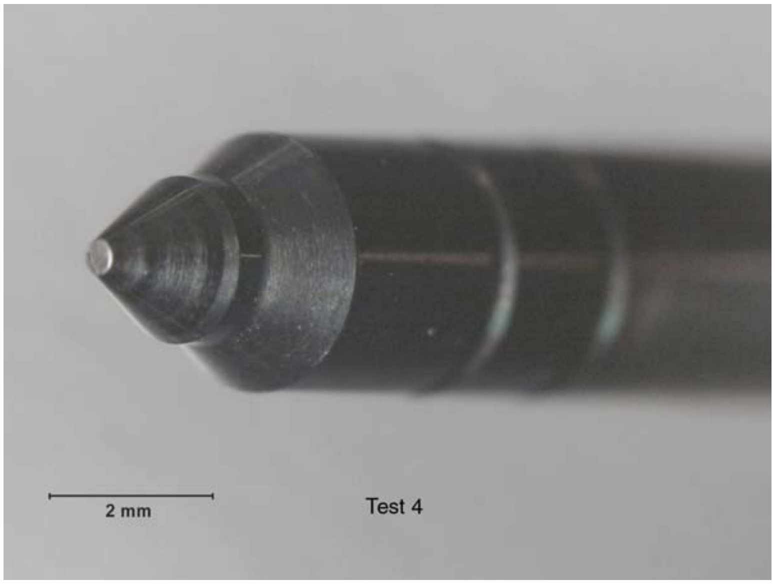


Figure 26 - AF7868 SPK, Injector Needle

Figure 27 and Figure 28 shows the upper and lower hydraulic coupler pistons respectively. No noticeable wear was seen on the piston surface interface, or at the heads of the piston at the piezo stack and control valve interface.

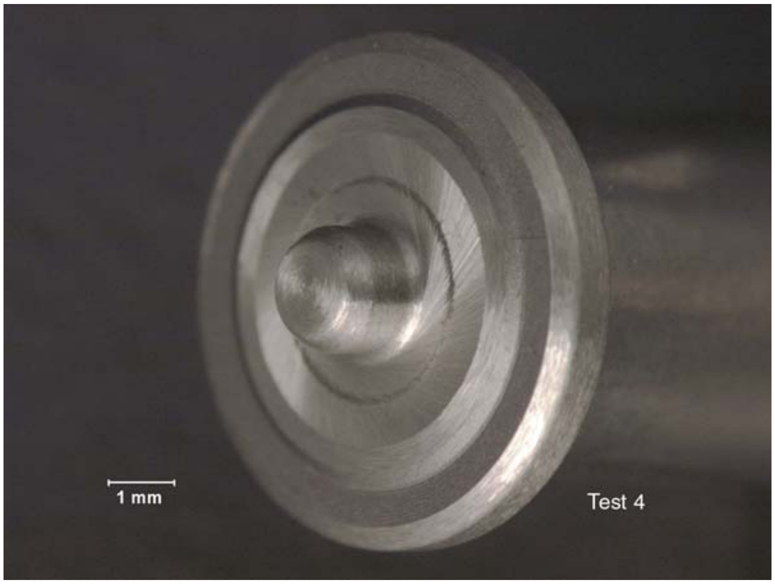


Figure 27 - AF7868 SPK, Upper Hydraulic Coupler Piston

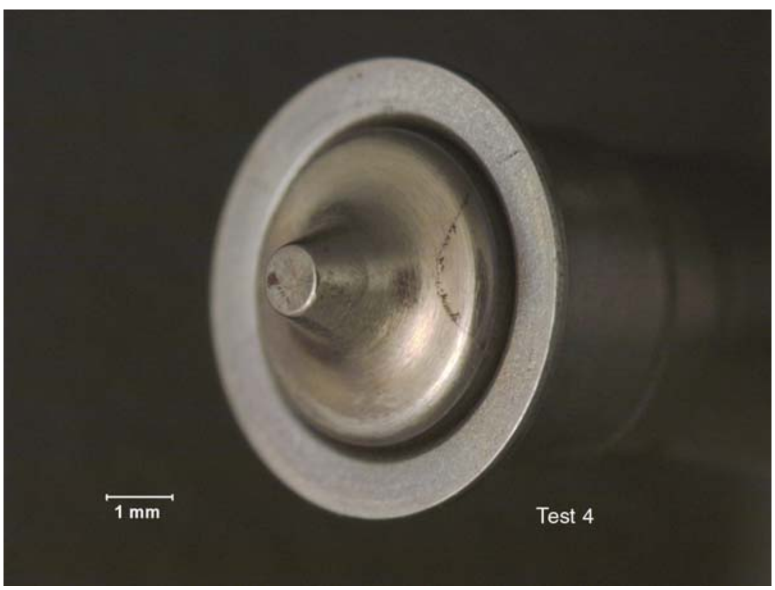


Figure 28 - AF7868 SPK, Lower Hydraulic Coupler Piston

Figure 27 and Figure 28 shows the side profile of the upper hydraulic coupler piston. A wear scar shows on the surface of the piston consistent with wear expected from being slightly cocked in the bore when depressed by the piezo stack.

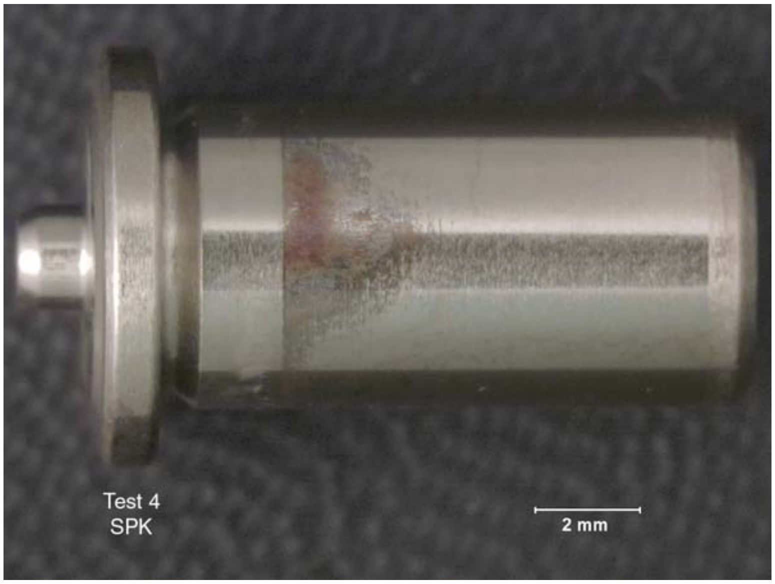


Figure 29 - AF7868 SPK, Upper Hydraulic Coupler Piston, Profile

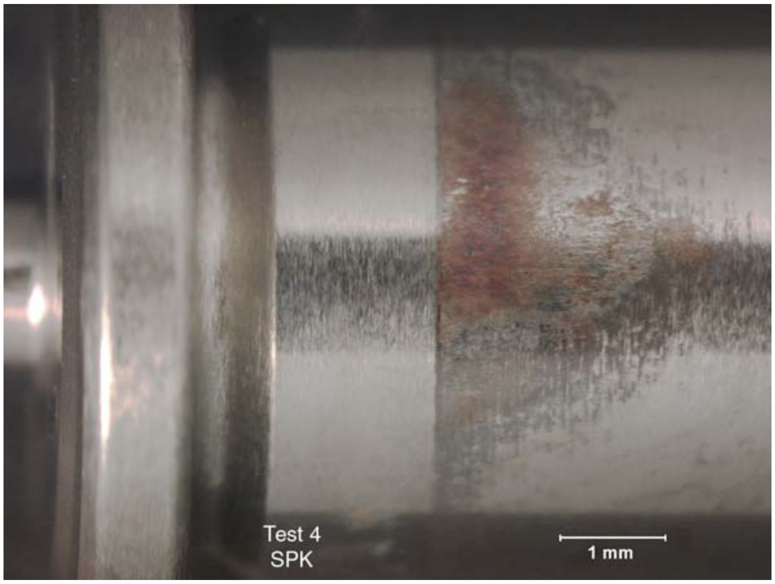


Figure 30 - AF7868 SPK, Lower Hydraulic Coupler Piston, Wear Scar Close Up

Figure 31 and Figure 32 shows the top and bottom surfaces of the intermediate plate. This plate contains the fuel control passages used to manipulate the needle position.

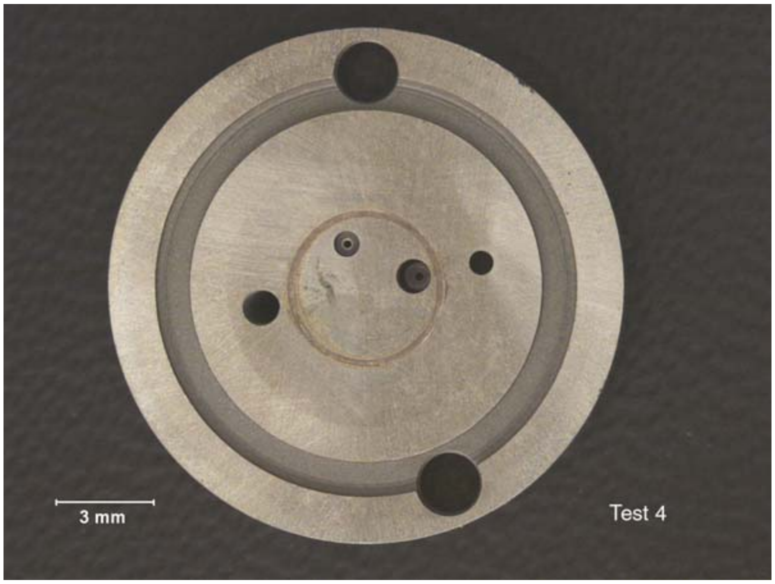


Figure 31 - AF7868 SPK, Intermediate Plate (Top)

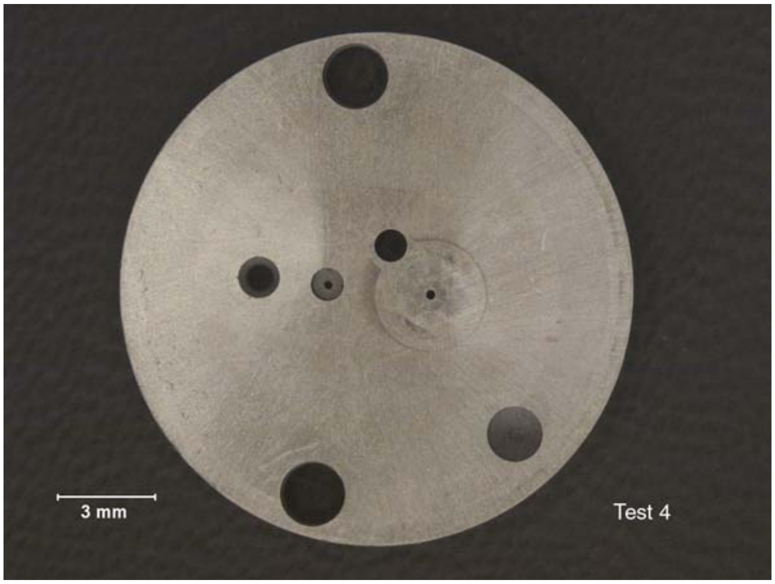


Figure 32 - AF7868 SPK, Intermediate Plate (Bottom)

Figure 33 and Figure 34 shows the top and bottom of the control valve plate. The control valve sits in the bore shown in Figure 34. The lower piston of the hydraulic coupler operates in the bore shown in Figure 33.

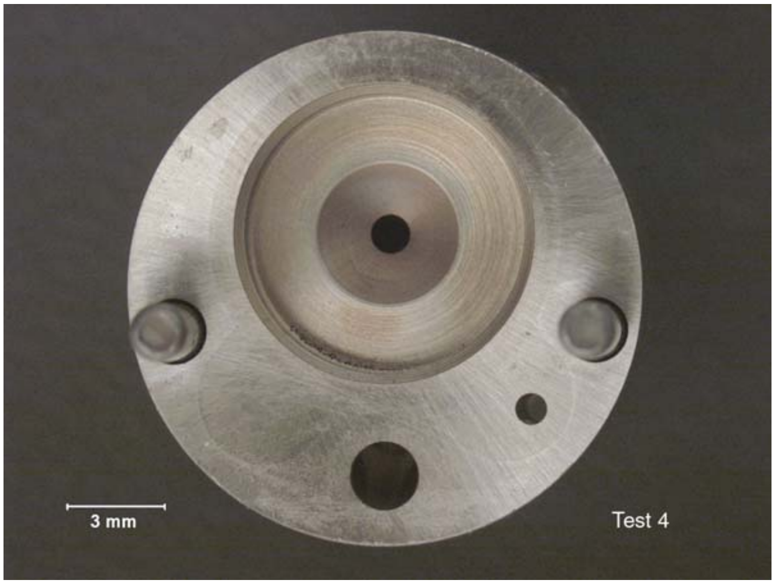


Figure 33 - AF7868 SPK, Control Valve Plate (Top)

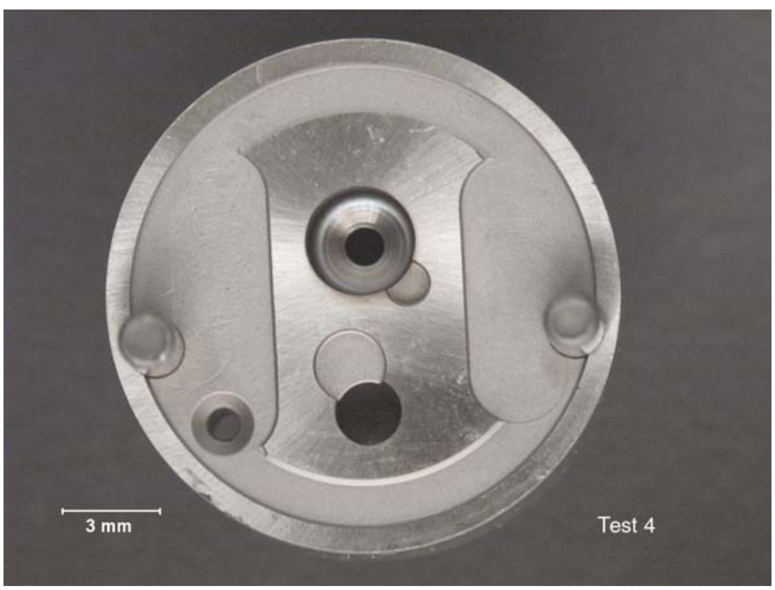


Figure 34 - AF7868 SPK, Control Valve Plate (Bottom)

Figure 35 shows the control valve which regulates the pressure on top of the injector needle, thus controlling lift. No unusual wear was found on the control valve.

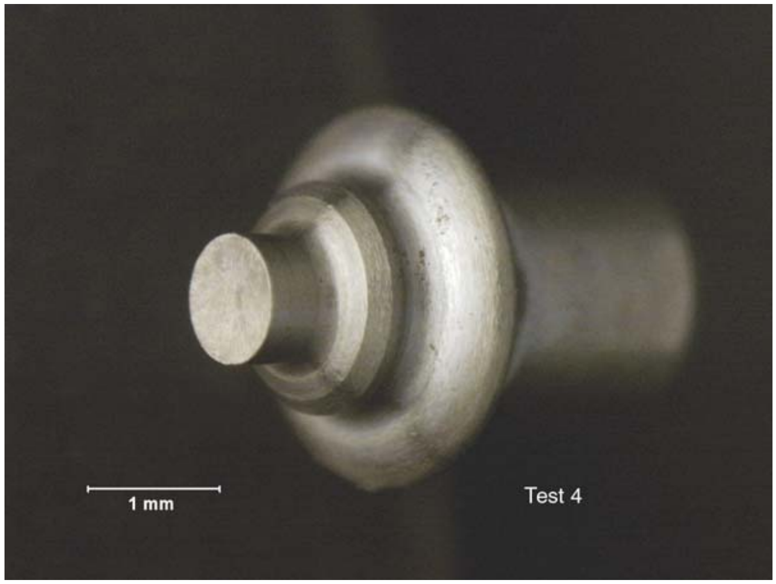


Figure 35 - AF7868 SPK, Fuel Injector Control Valve

Noted Problem Areas

Due to previously noted engine boost pressure degradation during Test 1, 2, and 3, the turbocharger assembly was replaced prior to testing. A full load DF2 powercurve was completed to map full load engine output, and the engine power output returned back within 1.2% of the original new engine output.

At approximately 46hrs, the thermocouple in exhaust port cylinder number 4 failed and was replaced. At approximately 109hrs, the thermocouple in exhaust port cylinder 8 failed. Due to the time that the thermocouples had been in use (through tests 1, 2, and 3), and evidence from failures of cylinder 4 and 8, it appeared that the exhaust port thermocouples were likely at the end of their useful life and failing due to the continued exposure to the high pressure and temperature environment created in the exhaust system of the engine. In an effort to ensure continued satisfactory monitoring of fuel injector health, testing was temporarily halted and all 8 exhaust port thermocouples were replaced. To complete this task, all upper intake and turbo assembly components must be removed from the engine. During this time, it was noted that the new replacement turbocharger appeared to be leaking oil into the compressor housing from the dynamic shaft seal of the center bearing housing. Significant deposits from the excess oil formed in the outlet of the compressor, charge pipe, and inlet of the intercooler. Due to availability issues with Ford, it was decided to continue to use the turbo as found. All thermocouples were replaced, and the engine was reassembled and testing continued. No other issues were noted relating to the turbocharger oil leak except for slightly higher oil consumption during testing.