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MILITARY FUEL AND ALTERNATIVE FUEL EFFECTS ON A MODERN DIESEL ENGINE EMPLOYING A FUEL-LUBRICATED HIGH PRESSURE COMMON RAIL FUEL INJECTION SYSTEM

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ABSTRACT

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. Testing was conducted using the Ford 6.7L diesel engine to determine the impact on engine and HPCR fuel system performance with the following test fuels: diesel (ULSD), JP-8, 50%:50% volumetric blend of JP-8/Synthetic Paraffinic Kerosene (SPK), and 100% SPK. The U.S. Army 210-hr Tactical Wheeled Vehicle Cycle (TWVC) engine endurance test was used to determine engine and HPCR system performance. Engine performance over the test duration, pre- and post-test powercurves and post-test fuel injection component inspections were used to determine each fuels performance.

INTRODUCTION

A large number of commercial off-the-shelf (COTS) compression ignition engines available to the U.S. military employ High Pressure Common Rail (HPCR) fuel injection systems. With the development of these engines primarily focused on compatibility with ultra-low sulfur diesel (ULSD), there is a potential for significant performance and endurance impacts to be experienced with the use of military-specific fuels. Many critical chemical and physical properties can have an impact on fuel system function, but primary concerns lie with the varying fuel lubricity and viscosity of military fuels. Many of these modern HPCR systems utilize fuel-lubricated high pressure pumps, and can generate upwards of 2000-bar fuel rail pressures placing large demands on the fuel to adequately lubricate and protect internal components. In addition, a reduction in fuel viscosity can have dramatic impacts on internal leakage and filling rates, and can have adverse effects on engine out performance. With the large in-flux of these types of fuel systems in the diesel engine market, questions have arisen on whether modern HPCR fuel systems will be able to maintain an adequate level of durability and performance using current and future (synthetic based) military fuels.

OBJECTIVE & APPROACH

The purpose of this testing was to evaluate the performance and durability of a modern fuel-lubricated HPCR fuel system when using diesel and various military fuels in a fired engine endurance test. The Ford Motor Company 6.7L “Scorpion” Powerstroke diesel engine was chosen as a representative modern diesel utilizing a fuel-lubricated HPCR fuel system. It was chosen for testing due to its recent introduction into the market at the time of testing, as well as its expected entrance into several U.S. Air Force flight line vehicles. Testing was completed by operating the engine following a modified version of the U.S. Army 210-hr Tactical Wheeled Vehicle (TWV) engine endurance cycle [1]. In an effort to fully ascertain the impact of varying fuels on the HPCR fuel system, a matrix of four fuels was selected for evaluation. These included: a baseline (ultra-low sulfur) diesel (ULSD), JP-8, 50/50 blend of JP-8 and Synthetic Paraffinic Kerosene (SPK), and 100% SPK. Each test was completed using all new fuel system components installed on a single test engine to maintain consistency throughout. Over the test duration, engine performance and function was closely monitored to track any changes present in fuel system function. In addition, pre- and post-test powercurves were utilized to document engine performance degradation across the test duration, as well as baseline to compare engine output between fuels. At the completion of testing, all fuel system components removed from the engine were completely disassembled for an internal inspection. Fuel system components were compared between each test, as well as to a new un-used set of hardware to fully document overall condition.

Test Cycle Description

As previously stated, testing was completed following a modified version of the U.S. Army 210-hr Tactical Wheeled Vehicle Cycle (TWVC). Modifications were made to accelerate the test cycle by shortening the engine soak period. The standard cycle requires engine operation for 14hrs daily, followed by shutdown and a daily soak of 10hrs. This extended engine soak period was included primarily for engine lubricant evaluations, and added no real benefit to fuels testing. In an effort to accelerate the testing schedule, the cycle was modified to decrease engine soak time from 10hrs to 3hrs. This yielded an operational cycle of 21hrs daily, 15hrs at rated speed/load, and 6 hrs at idle. Each day engine operation consisted of 6 cycles made up of 2hr 10min duration at rated speed followed by a 1hr idle period. After completion, an additional 2hr rated step was run, followed by the engine shutdown and 3hr soak. This operation arrangement was done to keep the proportion of total rated to idle hours on the accelerated test cycle consistent with the standard 210-hr cycle procedure. Throughout testing, critical engine parameters were controlled to test specifications to ensure engine integrity. These parameters can be seen in Table 1. Engine inlet air was drawn in at ambient test cell conditions throughout testing. In addition, fuel was supplied to the engine at ambient conditions in an effort to not interfere with the thermal recirculation valve located within the engines diesel fuel conditioning module. To ensure engine integrity for all tests, a commercially available synthetic CJ-4 engine oil was used for oil changes. Oil viscosity was selected following the engine manufacturers recommendations. Daily oil samples were collected from the engine to monitor used oil condition. Oil change intervals were determined by engine oil degradation during testing, and a fresh engine oil charge was completed at the start of every test.

**Note – Engine idle speed was controlled by the engines powertrain control module (PCM) at approximately 600rpm at 0% throttle actuation. Engine coolant setpoints were maintained to the rated speed setpoints, but were not met due to lack of heat generation in the engine. Jacket temperatures in the idle steps were allowed to meet their own steady state temperatures. In addition, engine oil sump temperature was dictated by an internal jacket water to oil heat exchanger and was not directly controlled, and thus was allowed to reach steady state temperature based on engine load and speed.*

Parameter	Units	Rated	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			

Table 1: Test Cycle Operation Parameters

Engine & Fuel System Description

The Ford 6.7L engine is a V8, direct injected, turbo-charged, air-water intercooled engine which employs a fuel-lubricated high pressure common rail pump, and piezo-electric fuel injectors. The engine used for testing was produced and used in its “export” configuration, which entails the absence of the engine exhaust gas recirculation system, and exhaust aftertreatment system. The engine produced approximately 320hp (238kW) at 2800rpm, and 700 lbf·ft (950 N·m) of torque at 1800rpm when using diesel fuel. Figure 1 below shows the engine test cell installation.

Figure 1 – Ford 6.7L Engine Installation

The fuel injection system utilizes a two piston fuel-lubricated high pressure fuel pump to supply fuel to two fuel rails located outboard of the cylinder heads. The fuel injection pump is mounted at the front of the engine valley and gear driven at 1:1 engine speed. Internally, the pump contains a two lobe camshaft which yields 4 pressure pulses per engine revolution. Two roller follower assemblies are used, one in each pump bore, and are actuated by the camshafts rotation. These follower assemblies are then used to actuate the fuel plunger within the barrel to generate high pressure fuel. Fuel entering the barrel of the pump is metered through the use of a volume control valve (VCV) while fuel rail pressure is controlled through a rail mounted pressure control valve (PCV). These controls allow the PCM to only pressurize fuel needed for engine operation and adjust rapidly to changing engine conditions. This was intended to increase the overall efficiency of the engine and fuel system. Figure 2 shows the 6.7L fuel injection hardware.

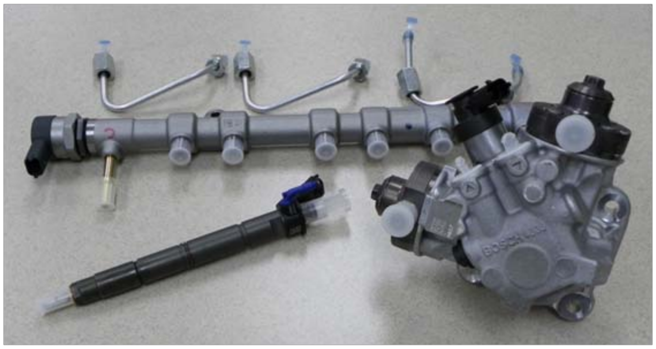

Figure 2 – Ford 6.7L Fuel Injection Pump, Rail & Injector

The fuel injector is actuated by the use of a piezo-electric stack operating on one half (upper) of a hydraulic coupler. This hydraulic coupler is used to translate the small linear movement of the piezo-stack to a larger linear movement due to the ratio of diameters of the hydraulic coupler. The lower half of the hydraulic coupler is used to actuate the injector control valve which regulates fuel pressure on the top side of the needle, thus controlling needle lift. Although simple in theory, the fuel injector contains many small precision components that can be affected by the fuels properties.

TEST FUEL

As previously stated, a test matrix of four fuels was used to evaluate the HPCR fuel system performance. The ULSD used for testing was commercially available certification test fuel, while the three remaining fuels were blended on location for testing. For JP-8 variant testing, a commercially available Jet-A was used as a base fuel to produce the tested JP-8. Since testing focused primarily on fuel lubricity concerns, only the corrosion inhibitor/lubricity enhancer additive was included during the blending process, as the remaining additives typically used to produce JP-8 (anti-static, anti-icing) have no significant impact on fuel properties for the tested conditions. For both the JP-8 and SPK portion fuels, the lubricity enhancer used to treat the fuel was the QPL approved Innospec Fuel Specialties DCI-4A. Fuel was treated at the minimum effective treat rate of 9ppm as outlined in QPL-25017 to provide a "worst case" scenario for testing. Prior to testing, fuel samples were collected of each test fuel and analysis completed for documentation. Selected results can be seen in Table 2.

Property	**Units**	**Method**	**Results**			
			DF2	**JP-8**	**50/50**	**SPK**
Density at 15°C	g/mL	D4052	0.858	0.802	0.796	0.736
Flashpoint	°F	D56	154	127	115	111
Kinematic Viscosity at 40°C	cSt	D445	3.0	1.2	1.0	0.9
Cetane Number	—	D613	47.2	42.2	53.7	64
Heat of Combustion	BTU/lb	D240	19460	19769	20038	20364
	BTU/gal	Calc.	139340	132314	133111	125080
Sulfur	ppm	D5453	8.6	1.6	1.5	3.5
HFRR	mm	D6079	0.444	0.675	0.695	0.840
BOCLE	mm	D5001	0.46	0.69	0.72	0.76

Table 2 – Test Fuel Chemical & Physical Analysis

Parameter	**Units**	**Results**			
		DF2	**JP-8**	**50/50**	**SPK**
Engine Speed	rpm	2800.0	2800.0	2800.0	2800.0
Torque	lbf·ft	601.86	594.10	575.37	580.89
Power	bhp	320.87	316.73	306.75	309.69
BSFC	lb/bhp·hr	0.411	0.406	0.407	0.396
Coolant Out (primary loop)	°F	203.0	203.0	203.0	203.0
Coolant In (secondary loop)	°F	100.0	100.1	100.0	100.0
Oil Sump	°F	239.6	243.7	246.2	247.3
Fuel In	°F	89.5	84.7	90.9	92.9
Pump Drain	°F	106.4	101.9	107.8	109.2
Fuel Return	°F	102.0	100.0	101.4	102.4
Intake Air	°F	75.6	75.4	76.4	77.6
Exhaust Port (Avg)	°F	1392.7	1404.8	1452.0	1358.2
Oil Galley	psig	56.1	54.9	54.6	52.9
Intake Restriction	psig	0.53	0.51	0.41	0.48
Exhaust Restriction	psig	10.7	10.5	10.3	10.7
Fuel Rail	psig	19346	19399	19382	19407

Table 3 – Engine Operating Summary

RESULTS

All four tests completed the full 210-hr test cycle without experiencing any unusual fuel related operating conditions. In addition, no fuel system hardware failures were experienced during testing, despite the much lower viscosity and lubricity levels of some of the test fuels. Selected operating conditions can be seen for the rated test segments in Table 3. This shows the consistency achieved between each test.

Engine Powercurve Analysis

As previously stated, engine powercurves were completed at the start and end of testing to determine overall engine performance variation over the test duration. Figures 3, 4, 5, and 6 show the pre-and post-test full load powercurve for ULSD, JP-8, 50/50 JP-8/SPK, and SPK test fuels respectively. Full load power degradation remained similar throughout testing. It is worth mentioning that during testing, problems with the engine's turbocharger assembly were experienced, resulting in continuous engine boost degradation throughout the first three tests.

The problem was later identified to be an issue with vane movement on the variable geometry turbo (VGT), and was not attributed to testing conditions. At the completion of the third test (50/50 JP-8/SPK), the engine's turbocharger assembly was replaced in an effort to avoid any PCM commanded de-rating due to its inability to meet desired boost targets.

As expected, this phenomenon was the primary cause of engine power variation across testing, and masked any real quantification of engine power degradation due to fuel system impacts. Despite this phenomenon, engine fueling was consistently maintained throughout testing, thus avoiding the invalidation of the overall test goals to determine the fuels interaction with the fuel system. Over the test duration, engine fuel consumption rates, generated rail pressure, and fuel system control commands remained consistent providing a good comparison for fuel system compatibility between each fuel tested. Despite the boost pressure degradation experienced, no major differences in engine output were noted between fuels, or across the test duration for each tested fuel.

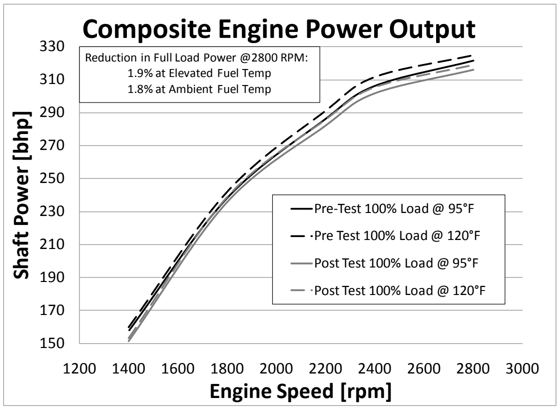

Figure 3 – ULSD Powercurves

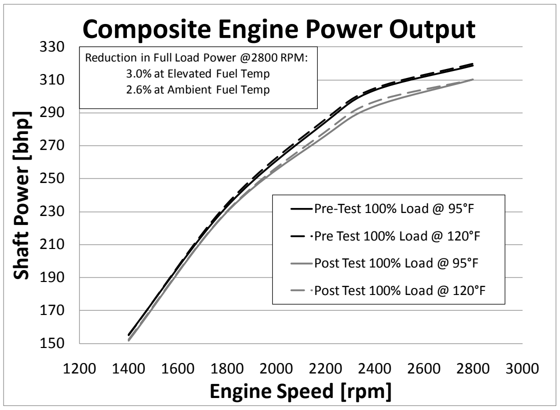

Figure 4 – JP-8 Powercurves

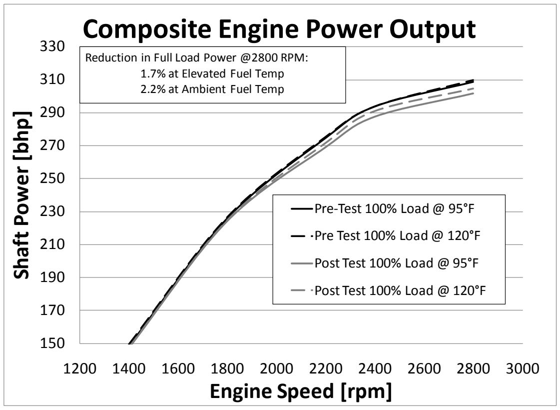

Figure 5 – 50/50 JP-8/SPK Powercurves

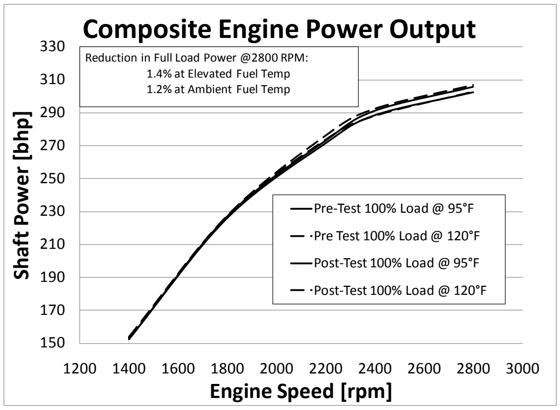

Figure 6 – SPK Powercurve

Post-Test Fuel System Analysis

The post-test teardown of the fuel injection hardware yielded, although minor, some changes between each tested fuel. Overall, no catastrophic wear or trends were found in any of the components tested on military fuels, which supports the ability of this fuel system to operate satisfactorily in military applications.

As previously stated, the fuel injection pump was completely disassembled to document internal wear. All components were compared across each test, as well as compared to a new set of unused hardware to fully document condition, and quantify wear due to each fuel's use. In general, no significantly different wear patterns were noted between the different tested fuels. Some of the typical wear seen during the ULSD test was slightly more pronounced on the remaining lower lubricity fuels tested, but not to the extent to raise concern over its ability to properly function. Table 4 contains a summary of the fuel injection pump inspection for all four tests.

One exception to the similar wear noted in all tests was a wear pattern identified on a single roller from the 50/50 JP-8/SPK test. On the left hand assembly, the roller experienced severe end wear on the roller into the follower assembly (see Figure 7). This appeared to be an isolated problem as it did not occur in any other tests. There is no evidence to support that it is a problem related to fuel lubricity, as the final SPK test with lower lubricity levels did not reproduce this issue, and its post-test condition appeared overall similar to the JP-8 and ULSD components. Other possible causes for this type of wear pattern could be due to a manufacturing defect. For example, a slightly tapered roller, or a canted bore machined into the pump body can preload the roller causing it to be forced against the follower wall increasing the loading and friction resulting in higher wear. At this time, there is no accurate way to determine the root cause of the problem. Despite this, no other tests showed this particular wear pattern in relation to any of the critical fuel properties. Thus, this appears to be an isolated case.

Figure 7 – Roller Wear into Follower, 50/50 JP-8/SPK

Part	DF2	JP-8	50/50	SPK
Pump Bore	very light polish, top & bottom	very light polish, top & bottom	light polish, light scuffing, top & bottom	light polish, very light scuffing, top & bottom
Camshaft	light polish, seal contact wear	light polish, very light burnish, seal contact wear	light polish, light burnish, seal contact wear	light polish, light burnish, seal contact wear
Roller (L)	light polish	light polish, very light burnish	light polish, light burnish, heavy roller end wear	light polish, very light burnish
Roller (R)	light polish	light polish, very light burnish	light polish, light burnish	light polish, very light burnish
Shoe (L)	new, polish from plunger button	new, polish from plunger button	new, polish from plunger button	new, polish from plunger button
Shoe (R)	new, polish from plunger button	new, polish from plunger button	new, polish from plunger button	new, polish from plunger button
Follower (L)	very light polish	polish, very light scuffing	polish, light scuffing	polish, very light scuffing
Follower (R)	very light polish	polish, very light scuffing	polish, light scuffing	polish, very light scuffing
Plunger (L)	as new, very light polish on button, more than right	as new, light polish on button, more than right	as new, light polish on button, more than right	as new, light polish on button, more than right
Plunger (R)	as new, light polish on button	as new, light polish on button	as new, light polish on button	as new, light polish on button
Barrel (L)	as new	as new	as new	as new
Barrel (R)	as new	as new	as new	as new
Inlet Check (L)	as new	as new	as new	as new
Inlet Check (R)	as new	as new	as new	as new

Table 4 – Fuel Injection Pump Inspection

As shown in the table, wear patterns produced in the pump body bore were overall similar in size and severity. Figure 8 and Figure 9 show the bore polish areas of the ULSD and SPK test respectively. As shown, the location and size was similar overall, with the 50/50 JP-8/SPK and SPK markings showing a slight scuffing tendency that was not noted in the ULSD or JP-8 test. Despite this, the differences in wear seen in the JP-8, 50/50 JP-8/SPK, and SPK test from the baseline ULSD test did not suggest any major incompatibility, and did not have any operational impact on the fuel system performance during testing.

Figure 8 – Post-test ULSD Pump Body Bore Polish

Figure 9 – Post-test SPK Pump Body Bore Polish

Figure 10 – Post-test ULSD Follower

Figure 11 – Post-test SPK Follower

Figure 10 and Figure 11 show the post-test ULSD and SPK follower assemblies. Again, markings shown on the follower surface were consistent with the wear trends seen in the pump bores, overall similar in size and location.

Camshafts removed from the used pumps completed a dimensional trace across the lobe peak to determine if any significant wear patters could be found between each test. The tested camshafts showed no greater variation in surface condition than that found on the new unused camshaft. Apart from the slight burnish seen on the JP-8, 50/50 JP-8/SPK, and SPK test, no other differences were noted in condition from the baseline ULSD components.

Consistent with the high pressure fuel pump inspection, fuel injectors from each test were removed and disassembled for inspection and photographs. 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 baseline diesel test and the JP8 and SPK tests. From the inspection, the only internal injector components showing any appreciable wear patterns were the upper piston of the hydraulic coupling. 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 surface. This wear scar was seen in each of the test fuels, and was found to be overall similar in size and condition between baseline and military fuels. Figure 12, 13, 14, 15, and 16 shows the magnified photo of the upper hydraulic coupler piston for the new, ULSD, JP-8, 50/50 JP-8/SPK, and SPK test respectively.

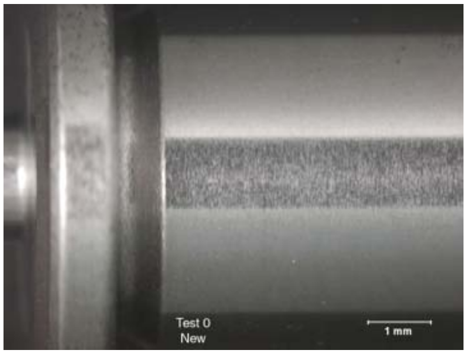

Figure 12 – Upper Piston, Injector Hydraulic Coupler, New

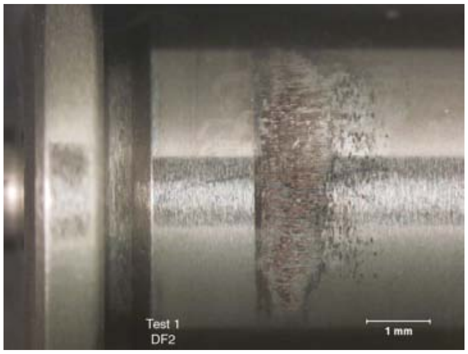

Figure 13 – Upper Piston, Injector Hydraulic Coupler, ULSD

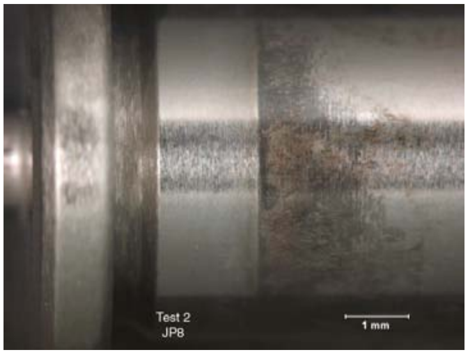

Figure 14 – Upper Piston, Injector Hydraulic Coupler, JP-8

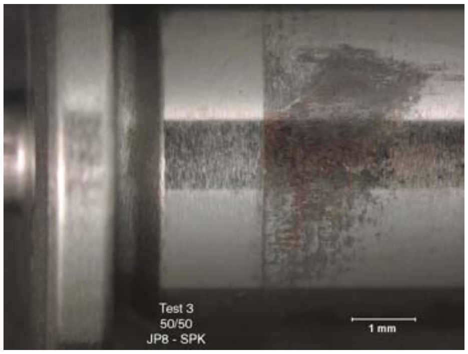

Figure 15 – Upper Piston, Injector Hydraulic Coupler, 50/50 JP-8/SPK

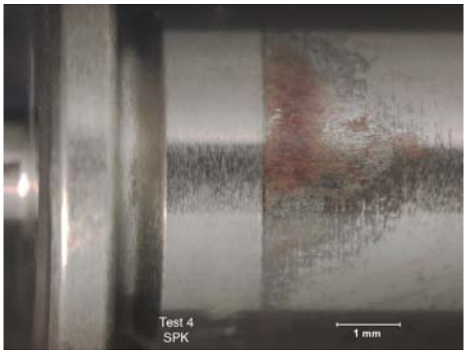

Figure 16 – Upper Piston, Injector Hydraulic Coupler, SPK

Although this wear did not impact the testing at hand, this type of wear is typical of types 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, both requiring immediate fuel injector replacement to ensure proper engine operation.

CONCLUSIONS

In conclusion, testing conducted to date supports that modern fuel-lubricated high pressure common rail fuel injection systems can be successfully operated using military specified fuels. Even at minimal lubricity-enhancing treat rates, JP-8 and synthetic based fuels provided adequate component protection and system performance compared to a baseline ULSD fuel in the tested application. No unusual operating conditions were experienced throughout testing, and engine performance remained consistent throughout.

Recommendations

Due to the minimal differences seen in component conditions at the end of testing, it would be beneficial to conduct future testing using more stringent conditions to further differentiate each fuel's performance and system compatibility. This could be achieved through additional testing utilizing longer test durations, as well as increased fuel inlet temperature specifications to determine impact on fuel systems at desert like conditions.

REFERENCES

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