THE USE OF SYNTHETIC JP-8 FUELS IN MILITARY ENGINES

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ABSTRACT

In an effort to reduce Army dependence on foreign oil there has been a push to include synthetic fuel and synthetic fuel blends for use in military vehicles. Currently there is an ASTM specification to include up to a 50-50% blend by volume of synthetic Fischer Tropsch (FT) JP-8 and JP-8. Before such fuels are deployed throughout the entire fleet, testing has been under way to investigate the potential impact of such fuels on heavy duty military engines. Initial results show that the two military engines tested did operate on a 50-50 blend of JP-8 and synthetic JP-8 without any major failures though there was a power loss at each operating condition. Through the use of a single cylinder research engine this study will investigate the combustion differences between the different fuels and try to identify potential benefits and risks associated with the use of alternative fuels in military diesel engines.

1. INTRODUCTION

In 1988 the Army adopted the single fuel forward initiative mandating that JP-8 be used as the fuel in all Army vehicles. However, recently there has been a push to decrease the United States dependency on foreign oil by finding alternative, renewable energy solutions. One possible solution is the use of synthetic fuels and synthetic fuel blends known as Fischer Tropsch fuels. These fuels can be created from coal, biomass or natural gas feedstock using the Fischer Tropsch process. The Army has taken strides to allow the use of the synthetic blends of JP-8 in military vehicles by testing various relevant diesel engines .The commercial sector is also exploring the use of such synthetic fuel and in 2009 the ASTM International specification for jet fuel changed to allow the use of a blend of JP8 and FT-JP8 up to a 50-50 % blend by volume.

The studies performed thus far on Army vehicles have looked into large scale issues such as power loss and component failures. Unfortunately, typical engine out performance type measurements do not reveal much about the combustion process. A more detailed analysis must be performed in order to truly understand the combustion differences between the fuels.

One such apparatus that enables such a study is a single cylinder research engine that allows for precise control of the intake conditions and injection event. The research engine also was equipped to take both high speed and low speed measurements including temperatures, pressures, and injection needle lift. These capabilities allow for the study of the combustion process to help quantify the results seen on the multi-cylinder military engines.

Last, modern engines are not designed to handle the broad range of property specifications for JP-8. Synthetic fuels and synthetic fuel blends tend to have much narrow property ranges than JP-8, but nevertheless are important for closing the knowledge gap of how certain fuel properties affect the combustion process in military diesel engines. Performing detailed combustion calculations in a controlled environment is the first step to gaining an understanding of the different fuels and how such fuels affect the combustion process is affected.

2. EXPERIMENTAL DIESEL ENGINES

The Army has been testing the use of alternative fuels in military engines in order to investigate the possible use of such fuels in the field. Testing has been completed on diesel fuel (DF-2), JP-8 and a 50-50 blend of JP-8 and S-8 fuels in both the GEP 6.5L (HMMWV) and a Cummins V903 engines (Bradley Fighting Infantry Vehicle). In order to study the fuel affects on the

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In an effort to reduce Army dependence on foreign oil there has been a push to include synthetic fuel and synthetic fuel blends for use in military vehicles. Currently there is an ASTM specification to include up to a 50-50% blend by volume of synthetic Fischer Tropsch (FT) JP-8 and JP-8. Before such fuels are deployed throughout the entire fleet, testing has been under way to investigate the potential impact of such fuels on heavy duty military engines. Initial results show that the two military engines tested did operate on a 50-50 blend of JP-8 and synthetic JP-8 without any major failures though there was a power loss at each operating condition. Through the use of a single cylinder research engine this study will investigate the combustion differences between the different fuels and try to identify potential benefits and risks associated with the use of alternative fuels in military diesel engines.

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engines the same test procedure was followed for both engines. Data was collected at various loads and speed to document the performance of the engines.

Since the military multi-cylinder engines were not instrumented to record high speed cylinder pressure, the AVL single cylinder research engine was used to provide a more in-depth analysis of the combustion process using the same three fuels. In addition, a 100% synthetic JP-8 known as S-8 and a low cetane Fischer Tropsch (FT) JP-8 referred to as Sasol were included in this study. A summary of the engine characteristics used in this study are given in Table 1.

Table 1: Engine Specifications

Engine Parameter	AVL	GEP 6.5	Cummins 903
Injection System	IRI BETA	Pump Line Nozzle (PLN)	Step timing control, Pressure Time (PT)
Peak Injection Pressure [bar]	1600	700	1300
Nozzle Geometry [mm]	7 x 0.191	single hole	7 x 0.190
Bore x Stroke [mm]	120 x 120	103 x 97	140 x 120
Peak Firing Pressure [bar]	200	-	-
Compression Ratio	16	20.2	14.5
Displacement [L]	1.4	6.5	14.8
Swirl Number	Variable	NA	-
Operating Speeds	800-3000	1500-3400	800-2900
Cylinders	1	8	8
Boost System	Shop air	Turbocharger	Turbocharger
Rated Power		190 hp @3400 rpm	600 @ 2600
Rated Torque		375 ft-lbs @ 1800 rpm	1200 @ 2600

2.1 Test Conditions

Two multi-cylinder production engines (HMMWV GEP 6.5L and Bradley FIV Cummins VTA903) were evaluated over two 400 hour NATO evaluation test cycles using both JP-8 and a 50% blend of JP-8 and 50% SPK (synthetic paraffinic kerosene) FT JP-8 by volume. Both engines were performance benchmarked over their full load operating speed range using DF-2 after the manufacturer prescribed break-in period and then subsequently performance was evaluated over their full load operating speed range using either JP-8 or the blend fuel at each 100 hour test point until completion of the 400 hour NATO test cycle. The ambient air temperature was set at 77˚ F and fuel temperature was kept constant at 86˚F. Full load data is recorded at 100%, 75% and 60% of the rated speed as well as the max torque speed. The 903 was also run at elevated temperatures for an endurance test but only the ambient conditions were considered for this study.

This type of procedure was used to assess the performance of each engine as a function of time to assess any looming internal wear or component degradation process. Each engine was subsequently torn down and inspected for signs of wear and potential failure modes after each 400 NATO durability test.

In order to better understand the results obtained during the multi-cylinder military engine tests, experiments were run on an AVL, single cylinder, research engine. The research engine included precise control and measurement of the intake air system, injection event, in-cylinder pressure, and exhaust manifold condition such that heat release analysis could be readily performed to assess combustion variances between the various test fuels.

The strategy for evaluating each fuel was to calibrate the single cylinder engine at selected high load points using DF-2 for best fuel consumption characteristics while avoiding visible smoke and then subsequently operate the engine using the other test fuels with the same calibration strategy. It is important to note that the chosen calibration strategy was a simple single injection event that allowed only for variance in start of injection and injected quantity as function of speed and load. A test matrix, Table 2, was created such that experiments would be run at conditions seen in a military heavy duty truck engine.

Table 2: Test Matrix for AVL Research Engine Testing

Speed [RPM]	Intake Pressure [psi]	Exhaust Pressure [psi]	Oil Rail Pressure [psi]	Intake Temperature [F]	Pulse Width [ms]	Injection Timing bTDC [deg]
1250	16.5	9.7	3500	145	4	19
1400	27	18.4	4500	177	4.2	18.5
1600	26	21	4000	195	4.2	19.35
1800	26.7	26.7	4000	210	3.5	20.25
2000	28.2	29.3	4800	213	3.3	18.8
2200	30	36	4800	213	3.1	21.35

This test matrix was first run using DF-2 baseline case and then the same matrix was run keeping all the parameters the same but changing the fuel type including JP-8, the 50-50 blend, S-8 and Sasol. A variety of high and low speed measurements were acquired during this test protocol including start and end of injection, fueling rate, in-cylinder pressure, fuel injection system dynamics (rail pressure and control valve control command/current), manifold thermodynamic conditions, engine load and speed, and various engine system temperature and pressures. These measurements were used to conduct heat release analysis (combustion event behavior) and to determine the ignition delay. The results of this analysis will show the impact of fuel dependent ignition quality, evaporation characteristics, and injection system dynamics on the combustion event and any measured performance variances.

2.2 Fuel Analysis

A fuel analysis was performed on each of the test fuels. The information collected includes, cetane number, aromatic content, gas chromatograph, viscosity, density and boiling points. This data was summarized in Table 3. The fuel properties play a role in how the fuel spray forms, the breakup of the liquid, the evaporation, quantity of injected fuel, the ignition and the heat release profile.

Table 3: Fuel Properties

Fuel	Cetane Number	Density	Viscosity	Viscosity	T90 Boiling Point	Lower Heating Value	Aromatics % Volume	Sulfur Content
	[ ]	[kg/L] @ 15 C	[mm^2/s] 40	[mm^2/s] -20	[C]	[MJ/kg]	%	[ppm]
DF2	42.8	0.8655	2.688		317.1	42.6	45.74	390
JP8	44.9	0.8026	1.39	4.96	234.4	43.4	14.69	23
50/50	47.3	0.7923	1.2925	4.397	232.1	43.4	14.05	30
S8	62.4	0.7554	1.2862	4.42	248	44.1	0	1.6
Sasol JP8	25.2	0.7612		3.4775	205.3	44	0.89	-

2.3 Combustion Analysis

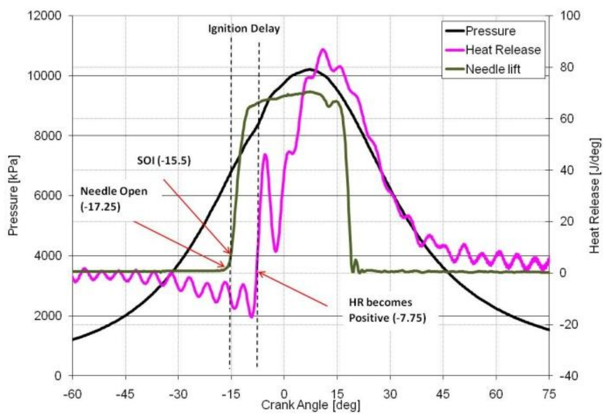
The AVL engine measurements allow for combustion analysis to be performed on each of the different fuels. Using the first law of thermodynamics and the pressure trace, the heat release was calculated using an in-house code called NETHEAT (Schihl and Hoogterp, 2008). The experimental pressure traces were post processed with a low pass digital filter before being run through the heat release code to reduce the noise caused by a recessed pressure transducer. The first law of thermodynamics is shown below:

$$\frac{dQ}{d\theta} = \frac{k}{k-1} P \frac{dV}{d\theta} + \frac{1}{k-1} V \frac{dP}{d\theta} \qquad (1)$$

where Q was the net heat release rate, k was the specific heat ratio, P was the combustion chamber pressure, V was the combustion chamber volume and θ was the crank shaft rotation angle (Schihl and Hoogterp, 2008).

The ignition delay period was calculated using the results from the heat release analysis. The start of injection (SOI) was determined using the measured needle lift profile and was determined to be a short time (when the needle lift profile realizes a 15% change) after the needle opens based on experiments conducted in an injector test rig. The injection rate was unknown, but it can be assumed that there was a small amount of time for the fuel injection pressure to reach a level high enough to overcome the injector needle spring force thus causing the delay in SOI in comparison to the start of injection command. The start of combustion (SOC) was determined to be the point when the heat release becomes positive and thus ignition delay was determined based on the elapsed time from start of injection to start of combustion. Figure 1 shows a sample calculation of ignition delay.

Figure 1: SOI, SOC and ignition delay period as



determined in engine experiments

3. EXPERIMENTAL RESULTS

Both the GEP 6.5L and the Cummins VTA 903 engine testing showed a reduction of power for both JP-8 and the blend fuel in comparison to DF-2 due to the lower volumetric energy density of such fuels, variances in the combustion process, and variances in the fuel injection system behavior. This power loss was the most significant difference between the two fuels operating in the engines. There were no component failures and upon inspection at the tear downs, no significant damage to the engines was noticed. The HMMWV test found that the power loss while running on JP-8 when compared to DF-2 was between 6% and 14%, and when the 50-50 blend was compared to DF-2 the power loss was found to be between 12% and 19%. The Cummins 903 had a power loss for JP-8 over DF-2 between 2% and 4% and the power loss seen while running the 50-50 blend when compared to DF-2 was 3%-5%. These results can be seen in Table 4.

Table 4: Torque Measurements for Cummins 903 and the GEP HMMWV Engine

Engine	Engine Speed [RPM]	Torque with DF-2	Torque with JP-8	Torque with 50-50 blend	% Decrease for JP8	% Decrease for 50-50
903	2600	1264.67	1209.67	1197.33	4.36	5.32
903	2400	1300.67	1253.67	1242.67	3.59	4.43
903	2200	1294.33	1254.67	1238.67	3.04	4.30
903	1800	1236.00	1208.33	1189.33	2.24	3.77
903	1600	1164.67	1142.00	1119.67	1.93	3.82
HMMWV	1800	381.76	357.02	336.66	14.18	19.08
HMMWV	2100	376.39	346.32	330.62	8.00	12.17
HMMWV	2400	362.90	333.40	316.31	8.13	12.83
HMMWV	2700	341.82	317.35	300.71	7.16	12.03
HMMWV	3000	325.72	303.07	286.22	6.95	12.13
HMMWV	3200	315.14	292.05	275.75	7.33	12.51
HMMWV	3400	301.80	281.75	263.93	6.64	12.56

The single cylinder research engine experiments also revealed a power loss for the fuels tested when compared to DF-2. These results are summarized in Table 5. The reduction in torque when compared to DF2 is between 1-8% for JP-8, 2-10% for the 50-50 blend, 1-9% for S-8 and 1-13% for the Sasol.

These results are similar to what was seen in both military engine tests. The AVL tests were set up so that the air intake conditions (air temperature and pressure) and fuel injection parameters (timing, pulse width, number of pulses and oil rail pressure) were all held constant. Thus the changes in the power were a result of the fuel properties.

Table 5: Torque Measurements for the AVL Engine at Various Engine Speeds

Engine Speed	1250	1250	1400	1400	1600	1600
Fuel	Torque [ft-lbs]	% Decrease WRT DF-2	Torque [ft-lbs]	% Decrease WRT DF-2	Torque [ft-lbs]	% Decrease WRT DF-2
DF2	128.67	0.00	159.43	0.00	146.45	0.00
JP8	118.19	8.14	162.28	-1.79	141.12	3.64
50-50	115.62	10.14	149.77	6.06	146.79	-0.23
S8	116.06	9.80	154.71	2.96	144.10	1.60
Sasol	123.73	3.84	137.93	13.49	140.90	3.79
Engine Speed	1800	1800	2000	2000	2200	2200
Fuel	Torque [ft-lbs]	% Decrease WRT DF-2	Torque [ft-lbs]	% Decrease WRT DF-2	Torque [ft-lbs]	% Decrease WRT DF-2
DF2	120.10	0.00	116.73	0.00	108.40	0.00
JP8	112.93	5.97	112.01	4.04	106.64	1.62
50-50	114.55	4.62	113.88	2.44	105.46	2.71
S8	111.32	7.31	122.55	-4.99	99.41	8.29
Sasol	118.19	1.59	116.14	0.51	103.14	4.85

3.2 Fuel composition effects

It was not enough however, to only look at the change in torque for the given fuels. More information was needed to understand why there was a loss in power. However, this is a very complex question. To begin exploring this question, the energy input of the individual fuels into the combustion system was investigated. Energy input of the fuel was defined as follows:

$$E_f = \rho_f \times LHV \qquad (2)$$

where ρ_f was the fuel density, LHV was lower heating value and E_f was the energy input of the fuel.

The results are summarized in Table 6. This information implies that DF-2 was more energy dense than the other four fuels. This means barring any experimental error it would be expected that DF-2 would create more power than the other fuels since the injection parameters were held constant.

Table 6: Energy Input Calculated for the Five Fuels Tested

Fuel	Energy Input	Ratio to DF2
	[J/m^3]	
DF2	36870.3	1.00
JP8	34832.84	0.94
50/50	34385.82	0.93
S8	33304.32	0.90
Sasol JP8	33492.8	0.91

The density of the fuel affected the fuel injection rates. Table 3 showed that DF-2 had the highest density. This means that since the injection parameters were held constant, the higher fuel density caused DF-2 to have a higher quantity mass of fuel injected for the same command period. Thus, DF-2 had a higher fuel consumption rate and thus generated more torque in comparison to fuels with a lower fuel density. The fuel density also had a large effect on the mixing and evaporation of the fuels which becomes more evident later in the heat release analysis.

Table 7 summarizes the fuel consumption for the fuels at different speeds. This again mimics the results that were found in the multi-cylinder engine tests. Table 8 shows the Cummins 903 fuel consumption numbers recorded during the testing.

Table 7: Fuel Consumption Measurements Taken on the AVL Research Engine at Various Engine Speeds

Engine Speed	1250	1250	1400	1400	1600	1600
Fuel	Fueling Rate [lbs/hr]	Ratio to DF2	Fueling Rate [lbs/hr]	Ratio to DF2	Fueling Rate [lbs/hr]	Ratio to DF2
DF2	10.67	1	14.542	1	16.087	1
JP8	9.32	0.873477	13.427	0.923326	14.826	0.921614
50-50	8.97	0.8406748	12.989	0.893206	14.864	0.923976
S8	8.847	0.8291471	12.557	0.863499	14.4	0.895133
Sasol	8.88	0.8322399	11.634	0.800028	13.668	0.84963
Engine Speed	1800	1800	2000	2000	2200	2200
Fuel	Fueling Rate [lbs/hr]	Ratio to DF2	Fueling Rate [lbs/hr]	Ratio to DF2	Fueling Rate [lbs/hr]	Ratio to DF2
DF2	14.077	1	15.689	1	16.073	1
JP8	12.805	0.9096398	14.904	0.949965	15.037	0.935544
50-50	13.027	0.9254102	14.646	0.93352	14.858	0.924407
S8	11.93	0.8474817	14.26	0.908917	14.449	0.898961
Sasol	12.622	0.8966399	14.199	0.905029	14.729	0.916382

Table 8: Fuel Consumption Measurements for the Cummins 903 Engine at Various Engine Speeds

Engine Speed	2600	2600	2400	2400	2200	2200
Fuel	Fuel Consumption [lb/hr]	Ratio to DF2	Fuel Consumption [lb/hr]	Ratio to DF2	Fuel Consumption [lb/hr]	Ratio to DF2
DF2	222.07	1.00	205.23	1.00	187.25	1.00
JP8	209.74	0.94	197.71	0.96	178.77	0.95
50-50	208.01	0.94	194.07	0.95	174.42	0.93
Engine Speed	1800	1800	1600	1600		
Fuel	Fuel Consumption [lb/hr]	Ratio to DF2	Fuel Consumption [lb/hr]	Ratio to DF2		
DF2	149.32	1.00	130.24	1.00		
JP8	145.73	0.98	126.01	0.97		
50-50	142.44	0.95	124.16	0.95		

The fuel viscosity affects atomization, fuel pump performance as well as the durability of the fuel system. Low viscosity fuel will result in finer atomization, but will also cause shorter penetration and less fuel air mixing; such effects are minimal when compared to injector nozzle geometry, swirl and injection pressure (Wong and Steere, 1982). There may also be changes in the behavior of the injector needle due to lower viscosities which reduces friction in the injector (Lepperhoff et al, 2006). This thought has not been thoroughly studied and still needs to be investigated further as the type of fuel injection system may cause these effects to be more or less noticeable.

The viscosity of a fuel was also responsible for lubrication to the fuel pump which affects the longevity of the moving parts. If a low lubricity fuel was used long term, an additive package would be needed to prolong the life of the fuel pump and injector. However, prior knowledge of the current fuel properties in the tank must be known in order to implement this strategy. If the fuels are being mixed in theater the chances of having a detailed fuel analysis is unlikely. Blending two fuels adds to the complexity of the problem as it would not ensure the new fuel created had a linear relationship of fuel properties between the two fuels that had been blended.

The fuel properties that have the largest effect on the ignition and combustion of the fuel were the cetane number and volatility of the fuel. A recent study conducted showed that a reduction of 10 in the cetane number can increase the ignition delay by as much as 30% in some cases (Schihl et al, 2006). The cetane number was the largest contributor to the chemical delay portion of the ignition delay. Figure 2 shows these trends. In general terms, the low cetane Sasol fuel had the longest ignition delay while the S-8 had the shortest ignition delay times. The DF-2, S-8 and 50-50 are fairly similar.

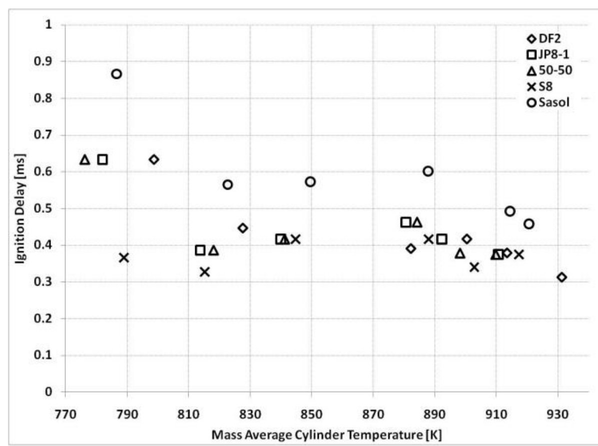


Figure 2: Ignition delay values at different ambient cylinder temperatures for the AVL 521 research engine

3.3 Heat Release Analysis

As previously noted earlier in this submission, the fuel properties also play a large role on the combustion by affecting the fuel spray formation, mixing and vaporization. To gain insight into these differences, a heat release analysis was performed for each fuel at each associated engine operating condition. Looking at the heat release for the fuels in Figures 3 and 4 at 2200 rpm, there are some noticeable differences. The heat release consists of both the premix spike and diffusion controlled burn region of combustion. During the premix spike, depicted in Figure 3, the fuel around the liquid fuel is entrained with hot cylinder gas and ignites.

During this phase of combustion it is possible to achieve high pressure rise rates that can be detrimental to the engine based on combustible fuel trapped in the jet mixing layer. Figure 4 shows the entire heat release profile for the five different fuels at 2200 rpm.

It can be seen in Figure 3 that the DF-2 and JP-8 had a very similar premix spike in regards to the slope and magnitude of the curve. The 50-50 blend was slightly less in magnitude than the DF-2 and JP-8 while the S-8 ignites sooner and had a smaller energy release. The Sasol fuel takes longer to ignite and had a higher premix region. This pattern follows what would be expected when looking at the cetane numbers alone. The S-8 had a high cetane number of 65 explaining the early combustion where Sasol has a low cetane number of 25 causing the lag in start of combustion.

The higher cetane fuels had less premix combustion characteristics resulting in the lower rates of pressure rise. While it was not measured in any of these tests it had been noted that this behavior results in improved acoustic performance of the engine (Lepperhoff et al, 2006). Extreme pressure rise rates can have detrimental effects on a diesel engine if allowed to go too high which is a concern for lower quality fuels. JP-8 does not currently have a cetane specification and has been reported as low as 29 in certain parts of the world during the past decade. This could cause severe pressure rise rates due to the long ignition delays and can cause engine failures.

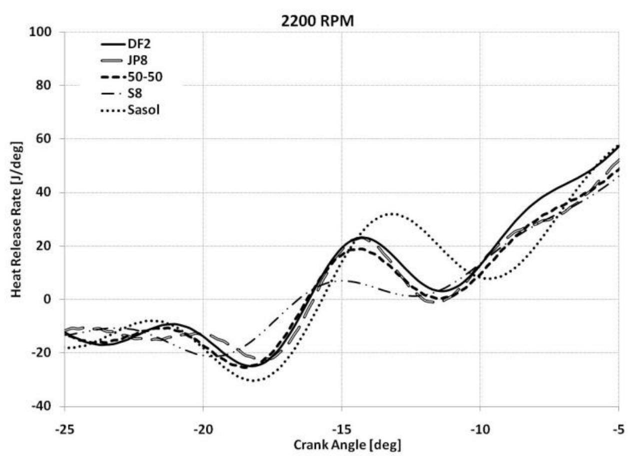


Figure 3: The premix region of the heat release analysis in the AVL research engine operating at 2200 rpm

Looking at the diffusion burn portion of the heat release in Figure 4, DF-2 still had the highest heat release again followed closely by JP-8 and the 50-50 blend. S-8 lags behind the Sasol to reach its maximum value, however, reaches approximately the same peak as the 50-50 blend. The Sasol then declined at a quicker rate. This was likely due to the fact that the Sasol burns more fuel in the premix phase while having a lower injection velocity and less injected fuel energy compared to the other fuels leaving less fuel in the diffusion burn.

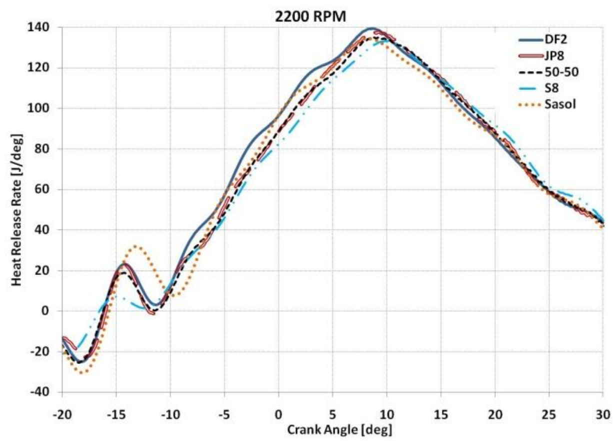


Figure 4: Heat release analysis for five different fuels in the AVL research engine operating at 2200 rpm

The DF-2, JP-8 and 50-50 blend had fuel properties that were closer in values to each other than the Sasol and S-8 which made these three fuels easier to compare. A decreasing boiling point causes the fuel to evaporate quicker while lower density causes more rapid mixing of air and fuel. The result is heat release profiles that remained similar in magnitude and shape for the DF-2, JP-8, and 50-50 blend.

The S-8 and Sasol fuels have interesting behavior. While the S-8 ignites much quicker it had a lower premix spike and a lower diffusion burn period. The peak of the diffusion burn was also delayed when compared to the other fuels. This was the opposite from what was observed from the Sasol. The Sasol fuel takes longer to ignite but reaches the peak of the diffusion burn quicker than the other fuels. The differences in both these fuels were caused by the same properties. The S-8 had a high cetane number, and a lower volatility causing the mixture to ignite easily, but needing more time for all the fuel to evaporate and reach a combustible equivalence ratio. The Sasol has the opposite problem.

It has a low cetane number but a high volatility. This caused the Sasol to take longer to combust but it then evaporated quicker causing the diffusion burn to happen in a shorter period of time.

The rate of heat release was integrated in order to provide further insight concerning engine performance variances. The integrated heat release rate (IHRR) at exhaust valve open shows the difference in the total energy released during combustion. In Table 9 it was seen hat DF-2 had the highest energy released when compared to the other fuels. JP-8 follows DF-2, then the 50-50 blend, and finally S-8. The Sasol fuel was more erratic with its performance. This was in line with the observations made regarding torque and energy input from the fuel.

Table 9: Peak Integrated Heat Release Rate at Exhaust Valve Close in the AVL Research Engine

Engine Speed	1250	1250	1400	1400	1600	1600
Fuel	IHRR [J]	Ratio to DF2	IHRR [J]	Ratio to DF2	IHRR [J]	Ratio to DF2
DF2	4407.14	1.00	5409.35	1.00	5430.84	1.00
JP8	4169.08	0.95	5293.17	0.98	5173.40	0.95
50-50	3994.99	0.91	5152.76	0.95	5221.60	0.96
S8	3865.27	0.88	5012.74	0.93	4968.92	0.91
Sasol	4025.78	0.91	4590.83	0.85	4762.24	0.88
Engine Speed	1800	1800	2000	2000	2200	2200
Fuel	IHRR [J]	Ratio to DF2	IHRR [J]	Ratio to DF2	IHRR [J]	Ratio to DF2
DF2	4363.81	1.00	4423.27	1.00	4220.46	1.00
JP8	4198.88	0.96	4318.24	0.98	4135.13	0.98
50-50	4055.32	0.93	4252.73	0.96	3943.54	0.93
S8	3950.83	0.91	4155.60	0.94	3935.47	0.93
Sasol	4128.67	0.95	4059.11	0.92	4007.53	0.95

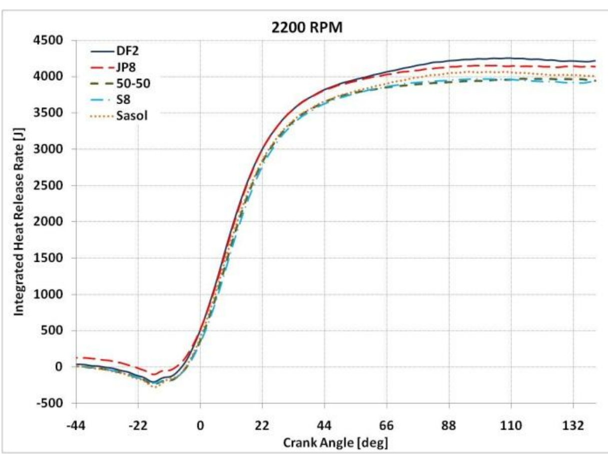


Figure 5: The integrated heat release rate at 2200 RPM for the AVL research engine

The IHRR also explains the torque variations between S8 and the 50-50 blend. It can be seen in Figure 5 that around 65 – 105 degrees after TDC (top dead center) S-8 has a slightly higher IHRR. After 110 degrees after TDC the 50-50 had a higher magnitude. In all, both fuels were very similar in their behavior, causing slight variations in the experiments to cause a lack of a clear trend.

3.4 Exhaust Temperatures

Exhaust temperatures affect the formation of emissions and performance of the turbocharger. Exhaust temperatures are also important to the Army vehicles as they will affect the thermal signature of a vehicle. The exhaust temperatures were compared to the DF-2 case as shown in Table 10. It was found that DF-2 and JP-8 had very similar exhaust temperatures while the other fuels are lower.

Table 10: Experimental Results for Exhaust Temperature Using Five Different Fuels in a Single Cylinder Engine

Engine Speed	1250	1250	1400	1400	1600	1600
Fuel	Exhaust Temperature [F]	Ratio to DF2	Exhaust Temperature [F]	Ratio to DF2	Exhaust Temperature [F]	Ratio to DF2
DF2	1042.11	1.00	1112.94	1.00	1267.08	1.00
JP8	1047.04	1.00	1105.77	0.99	1262.61	1.00
50-50	953.49	0.91	1079.89	0.97	1181.12	0.93
S8	973.13	0.93	1037.91	0.93	1165.60	0.92
Sasol	993.70	0.95	964.88	0.87	1077.65	0.85
Engine Speed	1800	1800	2000	2000	2200	2200
Fuel	Exhaust Temperature [F]	Ratio to DF2	Exhaust Temperature [F]	Ratio to DF2	Exhaust Temperature [F]	Ratio to DF2
DF2	1073.28	1.00	1087.72	1.00	1001.08	1.00
JP8	1066.76	0.99	1102.39	1.01	980.78	0.98
50-50	1047.64	0.98	1069.24	0.98	970.42	0.97
S8	1005.67	0.94	1054.91	0.97	951.37	0.95
Sasol	1022.37	0.95	1005.25	0.92	940.47	0.94

Table 11: Exhaust Temperatures in both the Cummins 903 and GEP 6.5 HMMWV Engines

Engine	Engine Speed [RPM]	Exhaust Temps with DF-2 [F]	Exhaust Temps with JP-8 [F]	Exhaust Temps with 50-50 [F]	JP-8 ratio to DF2	50-50 ratio to DF-2
903	2600	1171.90	1158.73	1155.73	0.99	0.99
903	2400	1178.13	1169.70	1167.30	0.99	0.99
903	2200	1200.70	1190.00	1189.73	0.99	0.99
903	1800	1301.37	1287.50	1288.87	0.99	0.99
903	1600	1365.47	1354.30	1350.60	0.99	0.99
HMMWV	1800	1033.68	963.54	930.82	0.93	0.90
HMMWV	2100	1094.94	1002.99	977.67	0.92	0.89
HMMWV	2400	1172.89	1080.44	1046.54	0.92	0.89
HMMWV	2700	1222.37	1141.51	1106.21	0.93	0.90
HMMWV	3000	1303.29	1222.80	1193.50	0.94	0.92
HMMWV	3200	1355.40	1272.72	1235.78	0.94	0.91
HMMWV	3400	1397.15	1320.35	1277.87	0.95	0.91

Both the fueling rate and energy content of the fuel drive the differences in exhaust temperatures. The higher the energy content shown in Table 6 leads to higher IHRR adding to the higher exhaust temperatures. It is also seen in Table 7 that both DF-2 and JP-8 had higher fuel consumption which caused lower air fuel ratios and higher exhaust temperatures. The HMMWV had more pronounced differences due to the fueling rate changes between fuels being more pronounced for this engine. The combustion phasing seen in the heat release profile of Figure 4 will also affect the temperatures in cylinder as well as exhaust temperatures.

CONCLUSION

Overall, all the fuels operated in the engine without any major mechanical issues despite being calibrated for DF-2. There was a power loss when using JP-8 or the synthetic fuels over DF-2 that can be reduced with a fuel specific recalibration of the engine. However, it should also be noted that while the fuels all ran in the research engine it does not necessarily mean they are acceptable for long term use in all military diesel engines; more investigation is needed at this point in time. Cold starting could cause major issues for synthetic and blended fuels that have low cetane or high volatility numbers. The effects of hot fuel on fuel injection system behavior that might be seen in desert conditions has not been included in this study, and there is also a known lubricity issue with the synthetic fuels. The main concern for fuels that are being mixed for ground vehicle use while in theater is the chance of mixing two poor ignition quality fuels. JP-8 does not have a strict specification for the cetane number or lubricity. A low lubricity fuel can degrade and ultimately damage the injection system. There are lubricity additives that can be used to remedy this looming issue, but if the properties of the fuels being used are unknown then the additives cannot be easily employed.

The cetane number and volatility can pose an even greater risk. If two fuels are blended that have a low ignition quality there may be starting and low to medium load combustion stability issues. There also is the possibility to exceed maximum pressure rise rates and peak firing pressure limits that could destroy a given engine due to excessive ignition delay. While injection timing strategies could be used to combat this problem it is not easily performed in a field environment. The fuel properties needed to perform such calibrations must be tested in a lab and thus would be unknown from a real world field point of view thus making the correct calibrations nearly impossible. This challenge with fuel flexibility use points toward the need for advanced combustion sensors to enable closed loop control of military diesel engines.

While the NATO testing and research results indicated use of the synthetic fuels may be possible, more research is needed in the area of synthetic fuels. Future work will include the use of a gas to liquid diesel fuel known as GTL as well as blends of the fuels included in this submission. Such future work will include more focus on part load conditions.

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REFERENCES

Lepperhoff, G., Korfer, Th., Pischinger, S., Busch, H., Keppeler, S., Schaberg, P., and Schnell, M., 2006, “Potential of Synthetic Fuels in Future Combustion Systems for HSDI Diesel Engines”, SAE Paper 2006-01-0232.

Schihl. P., and Hoogterp, L., 2008, “On the Ignition and Combustion Variances of Jet Propellant-8 and Diesel Fuel in Military Diesel Engines”, 26th Army Science Conference, 2008.

Schihl, P., Hoogterp, L., and Pangilinan, H., 2006, “Assessment of JP-8 and DF-2 Evaporation Rate and Cetane Number Differences on a Military Diesel Engine”, SAE Paper 2006-01-1549.

Wong, C.L., and Steere, D.E., 1982, “The Effects of Diesel Fuel Properties and Engine Operating Conditions on Ignition Delay”, SAE Paper 821231.

Zannis, T., Hountalas, D., Papagiannakis, R., and Levendis, Y., 2008, “Effect of Fuel Chemical Structure and Properties on Diesel Engine Performance and Pollutant Emissions: Review of the Results of Four European Research Programs”, SAE Paper 2008-01-0838.