ADA

TACTICAL/COMBAT ENGINES CETANE WINDOW EVALUATION

INTERIM REPORT
TFLRF No. 436

by
Gregory A. Hansen, Douglas Yost, & Edwin A. Frame
U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

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

Contract No. W56HZV-09-C-0100 (WD0004 – Tasks VIII & XIII)

January 2013

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14. ABSTRACT

The European Stationary Cycle 13 Mode test was performed on a turbocharged inline 6-cylinder diesel engine and a 6.5L turbocharged V-8 diesel engine for every test fuel. Full engine instrumentation was employed including in-cylinder pressure measurements. Engine operating parameters and exhaust gas emissions were recorded.

For each engine, clear trends for cetane-related performance were observed in the exhaust gas emissions, and potential cetane-related problems were identified at various conditions. Other fuel properties such as density, and bulk modulus also impacted engine performance. For each engine tested, an appropriate cetane window was identified.

15. SUBJECT TERMS
Cetane Number, Synthetic Fuel, JP-8, diesel engine, combustion

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EXECUTIVE SUMMARY

A fuel's cetane number is very important for the operation of modern diesel engines. The U.S. military currently uses petroleum-based jet fuels in diesel engine-powered ground vehicles and is studying the use of alternative jet fuels obtained from a variety of sources. Currently there is no cetane number specification for jet fuels as this property holds no significance for turbine engine operation. Therefore, it is of interest to identify a window, or range, of cetane number which would be acceptable to ensure the reliable operation of diesel engine-powered military ground vehicles.

The TARDEC Fuels and Lubricants Research Facility located at Southwest Research Institute identified 15 candidate fuels with cetane numbers ranging from 28 to 78. The fuels selected include diesel, jet, and various synthetic fuels. A cetane improver was used to fill out range. The European Stationary Cycle 13 Mode test was performed on a turbocharged inline 6-cylinder diesel engine and a 6.5L turbocharged V-8 diesel engine for every test fuel. Full engine instrumentation was employed including in-cylinder pressure measurements. Engine operating parameters and exhaust gas emissions were recorded.

For each engine, clear trends for cetane-related performance were observed in the exhaust gas emissions, and potential cetane-related problems were identified at various conditions. Other fuel properties such as density, and bulk modulus also impacted engine performance. For each engine tested, an appropriate cetane window was identified, as were other fuel properties that should also be of interest. Further work on this topic should include other major diesel engine families. The results from this work should help the military integrate emerging and future fuels into the supply chain.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period April 2009 through January 2013 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler served as the TARDEC contracting officer's technical representative. Ms. Patsy Muzzell of TARDEC served as project technical monitor.

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

2-EHN	2-Ethylhexyl Nitrate
50MFB	50-Percent Mass Fraction Burned
ATDC	After Top Dead Center
BM	Bulk Modulus
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CA50	Crank Angle 50 Timing (or the crank angle at which the 50% MFB occurs)
CAD	Crank Angle Degrees
CN	Cetane Number
CO	Carbon Monoxide
DCN	Derived Cetane Number
ESC	European Stationary Cycle
FTDSA	Fischer Tropsch Diesel from South Africa
FTDSH	Fischer Tropsch Diesel from Shell
HC	Hydrocarbon
H/C	Hydrogen Atom to Carbon Atom Ratio
HCCI	Homogeneous Charge Compression Ignition
HRR	Heat Release Rate
IVC	Intake Valve Close
J/CAD	Joules per Crank Angle Degree
KVis	Kinematic Viscosity
LPP	Location of Peak Pressure
MFB	Mass Fraction Burned
MHRR	Maximum Heat Release Rate
NOx	Oxides of Nitrogen (consisting of NO and NO2)
PQIS	Petroleum Quality Information System
RPM	Revolutions Per Minute
SOI	Start of Injection
TDC	Top Dead Center

1.0 HISTORICAL BACKGROUND

A fuel's cetane number is critically important for the operation of modern diesel engines. The U.S. military currently uses petroleum-based jet fuels in its ground vehicles. The U.S. military is currently studying the use of alternative jet fuels obtained from a variety of sources. Unfortunately there is no cetane number specification for jet fuels as this property holds no significance for turbine engine operation. As an example, data in the Petroleum Quality Information System (PQIS) database and from SwRI's own fuel inventory have been used to graph the large variety in cetane index, (and for the alternative fuels, cetane number) versus energy density in currently available jet-type fuels.

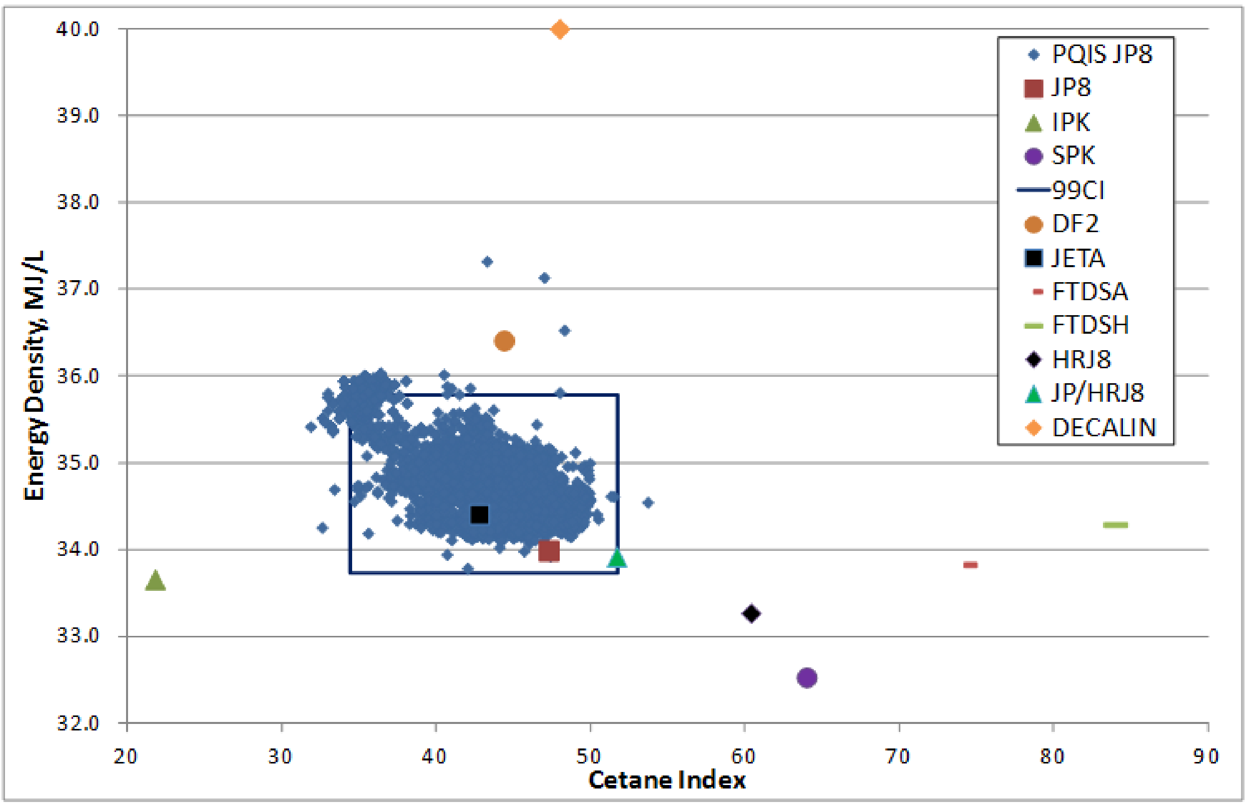

Figure 1. Historical Energy Density of JP-8 and Various Alternative Fuels vs. Cetane Index

2.0 INTRODUCTION

For each engine studied in this program, the goal was to observe cetane-related performance trends and specifically measure power, combustion characteristics, and exhaust gas emissions. It was also important to identify potential cetane-related issues. Other fuel properties were measured such as density, and bulk modulus to determine their specific impacts on engine performance.

At the end of testing a cetane window, or range of cetane number, acceptable for reliable operation of diesel engine-powered military ground vehicles was identified.

TARDEC Fuels and Lubricants Research Facility identified 15 candidate fuels with cetane numbers ranging from 28 to 78 to be used for this program. The fuels selected included diesel, jet, and various synthetic fuels. A cetane improver was used to fill gaps in range.

3.0 EQUIPMENT

The engines used for this program were a Caterpillar (CAT) C7 (inline 6 cylinder, turbocharged, after cooled, direct injected diesel engine), and a General Engine Products (GEP) 6.5T (V-8, turbocharged, indirect injected diesel engine).

3.1 MAINTENANCE

Prior to testing, each engine was fully rebuilt with new parts and measured to ensure tolerances met the manufacturers' specifications. Total test time on each engine was less than 50 hours, so no maintenance items were performed during the testing period.

4.0 EUROPEAN STATIONARY CYCLE OPERATING SYSTEM

4.1 LOAD STEPS

Each of the 13 modes of the ESC (see Figure 2) are governed by a mathematical formula, as explained below, for calculating the engine speeds A, B, & C. Each operating point also has a weighting value assigned to it for calculating the cycle average emissions.

CAT C7 Engine Speeds
A = 1602 RPM
B = 1991 RPM
C = 2380 RPM

GEP 6.5T Engine Speeds
A = 1928 RPM
B = 2641 RPM
C = 2995 RPM

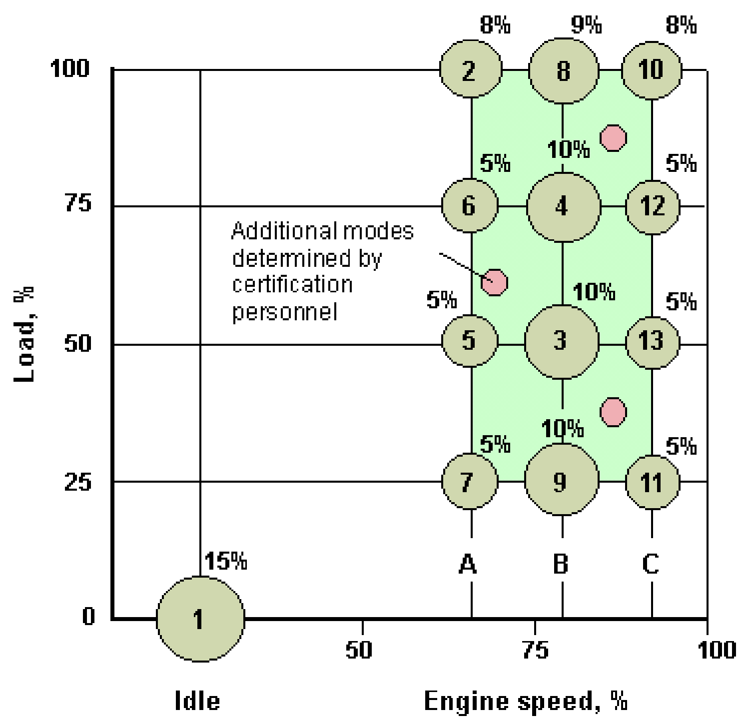

Figure 2. ESC 13 Mode Cycle Description

The engine speeds are defined as follows:

1. The high speed n_{hi} is determined by calculating 70% of the declared maximum net power. The highest engine speed where this power value occurs (i.e. above the rated speed) on the power curve is defined as n_{hi}.

2. The low speed n_{lo} is determined by calculating 50% of the declared maximum net power. The lowest engine speed where this power value occurs (i.e. below the rated speed) on the power curve is defined as n_{lo}.

3. The engine speeds A, B, and C to be used during the test are then calculated from the following formulas:

   $A = n_{lo} + 0.25(n_{hi} - n_{lo})$; $B = n_{lo} + 0.50(n_{hi} - n_{lo})$; $C = n_{lo} + 0.75(n_{hi} - n_{lo})$

4.2 CONTROLS

On the CAT C7 engine, the coolant and fuel temperatures were closed loop controlled and the manifold temperature was open loop controlled at a constant percentage value. The oil temperature was not directly controlled due to the use of the onboard oil/coolant heat exchanger, but the oil temperatures were tightly grouped for each mode due to the control of the coolant temperature. The engine operating points for each ESC mode can be seen in Table 1.

Table 1. CAT C7 Engine Operating Conditions

Caterpillar C7						
ESC MODE	Speed	Load	Coolant Temp	Oil Temp	Manifold Temp	Fuel Temp
	RPM	Ft-Lb	°F	°F	°F	°F
1	700	4	180	195	78	95
2	1602	781		205	97	
3	1991	356		208	92	
4	1991	534		214	99	
5	1602	391		209	88	
6	1602	586		211	92	
7	1602	195		205	81	
8	1991	712		215	102	
9	1991	178		209	87	
10	2380	648		220	110	
11	2380	162		215	93	
12	2380	486		220	107	
13	2380	324		217	102	

On the GEP 6.5T engine, the coolant, oil, inlet air, and fuel temperatures were all closed loop controlled. The engine operating points for each ESC mode can be seen below in Table 2.

Table 2. GEP 6.5T Engine Operating Conditions

GEP 6.5T						
ESC MODE	Speed	Load	Coolant Temp	Oil Temp	Inlet Air Temp	Fuel Temp
	RPM	Ft-Lb	°F	°F	°F	°F
1	950	9	190	200	72	95
2	1928	341		220		
3	2641	161				
4	2641	242				
5	1928	170				
6	1928	256				
7	1928	85				
8	2641	322				
9	2641	81				
10	2995	289				
11	2995	72				
12	2995	217				
13	2995	144				

5.0 INSTRUMENTATION

Full engine instrumentation was employed including in-cylinder pressure. All relevant engine operating temperatures, pressures and exhaust gas emissions were recorded.

5.1 ENGINE SETUP

The high speed instrumentation for the CAT C7 consisted of the following:

- Kistler Cylinder Pressure Transducer, 6041A
- Kistler 5011 Charge Amplifier
- BEI Shaft Encoder (0.2 CAD)
- Wolff Instrumented Injector
- PEM CWT Rogowski Current Waveform Transducer

The high speed instrumentation for the GEP 6.5T consisted of the following:

- 2x Kistler Cylinder Pressure Transducer, 6056A (Pre-Chamber) & 6052B(Main-Chamber)
- Kistler 5011 & 5018 Charge Amplifiers
- Kistler Fuel Line Pressure Transducer, 4065A1000 with matching pre-calibrated amplifier
- BEI Shaft Encoder (0.2 CAD)
- Wolff Instrumented Injector

The high speed data was recorded and post-processed by a SwRI High Speed DAQ. A SwRI PRISM DAQ system was used for engine control and data recording of the slow speed instrumentation. A Horiba MEXA 1600D emissions bench was also used, (Figure 3).

Figure 3. Horiba MEXA 1600D Emissions Bench

5.2 HIGH SPEED PRESSURE TRANSDUCERS - GEP 6.5T & CAT C7

The Number 2 cylinder was instrumented for pressure on the GEP 6.5T engine. This was done because it was both closest to the front of the engine where the shaft encoder was mounted and because the high pressure fuel line (coming out of the injection pump) was more accessible than the Number 1 cylinder line.

Figure 4 shows the location of the fuel line pressure transducer. It is located at the outlet of the injection pump.

Figure 4. Injection Line Pressure Transducer (GEP 6.5T)

Figure 5 shows the location in the head of the pre-chamber pressure transducer (which uses the glow plug port), the main chamber pressure transducer, and the instrumented injector.

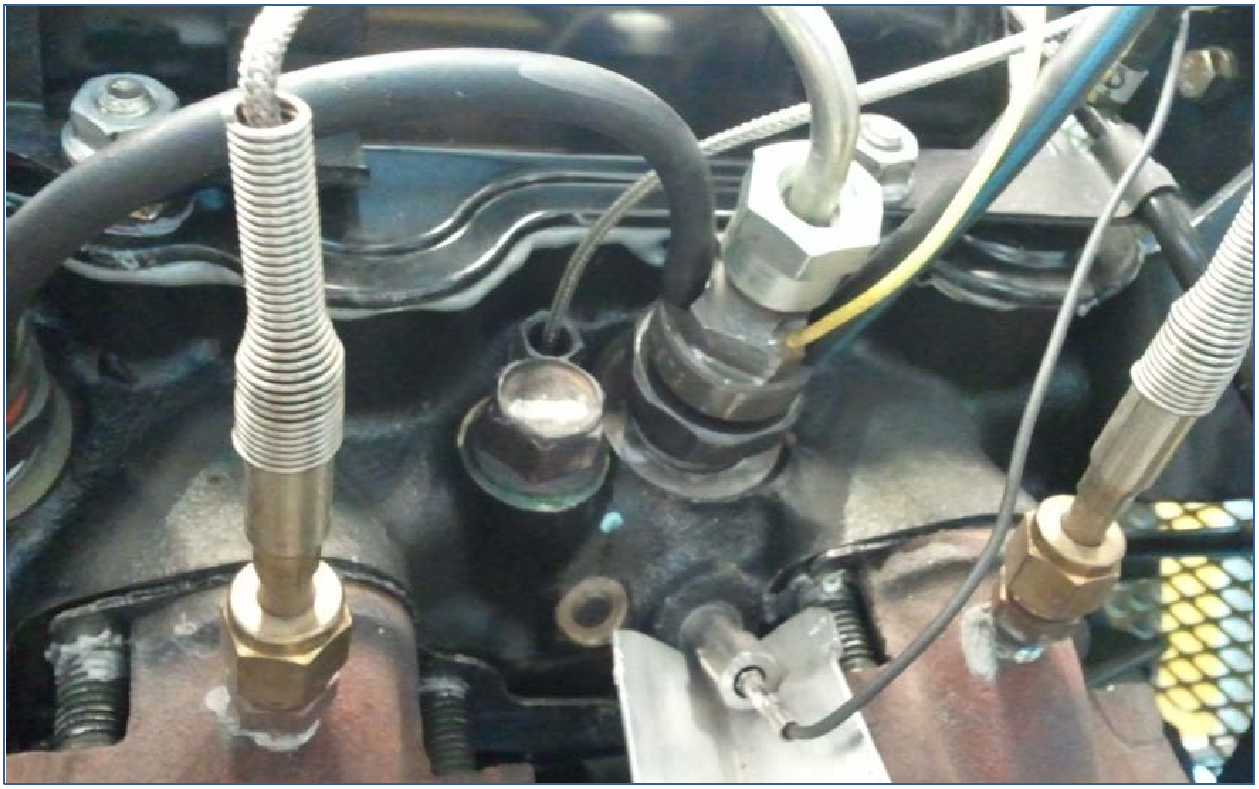

Figure 5. GEP 6.5T Cylinder Pressure Transducers and Instrumented Injector

Figure 6 is a sectioned view of the head for the GEP 6.5T engine and shows the location of the main chamber pressure transducer in relation to the intake valve port and the pre-chamber port.

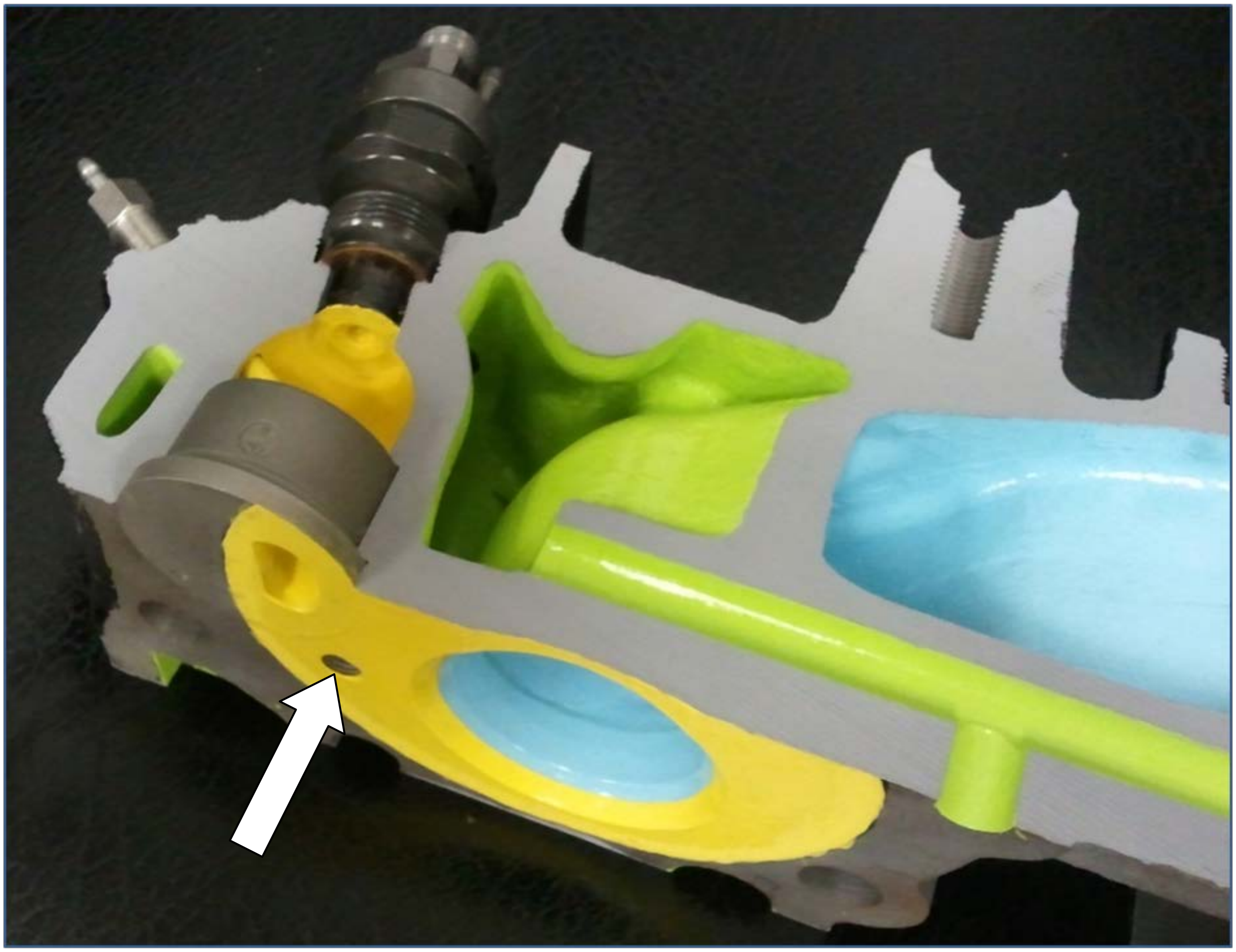

Figure 6. GEP 6.5T Head Cut Away with Main Chamber Pressure Transducer Location Indicated

Caterpillar supplied TFLRF with drawings of their model CAT C7 engine cylinder head indicating the Cylinder Number 1 pressure transducer location and dimensions. A custom 2-piece adaptor was made (as seen in Figure 7) and fitted with O-ring seals for water jacket penetration.

Figure 7. CAT C7 Pressure Transducer Adaptor Sleeve

Figure 8 shows the CAT C7 Number 1 injector and the pressure transducer adaptor located at the left of the image. A short piece of tubing was used to seal the adaptor so oil could not reach the pressure transducer.

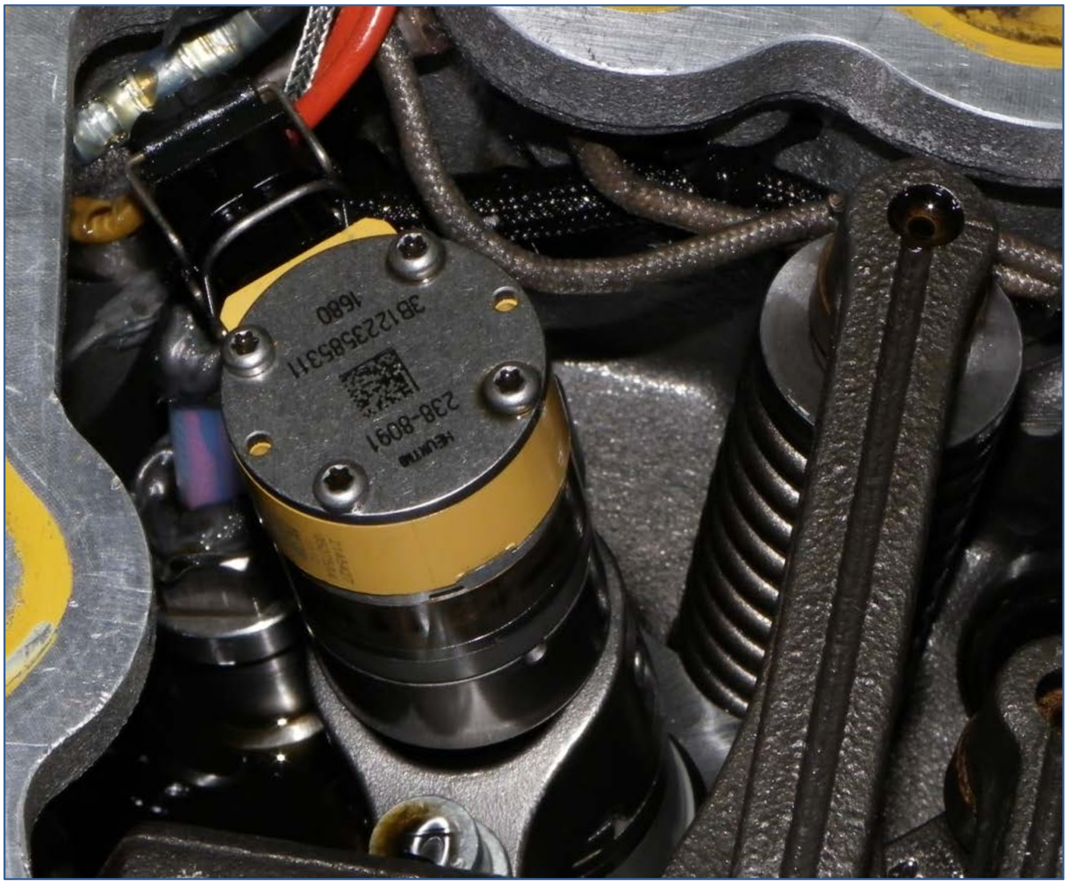

Figure 8. CAT C7 Adaptor Sleeve Location

5.3 INSTRUMENTED INJECTORS – CAT C7 & GEP 6.5T

The CAT C7 HEUI-B injector was instrumented for needle lift. During the process of instrumentation, the internals (see Figure 9) were modified slightly to allow room for the sensor and sensor wire. Upon initial testing of the injector, it was discovered that engine lubricant was migrating to fuel side internally. The injector was returned to the supplier for evaluation. It was determined that there was no simple fix, and that the work was done correctly according to the drawings supplied.

Figure 9. Fully Disassembled CAT C7 HEUI-B Injector

A high speed current transducer was evaluated as an alternative to using the leaky injector in order to indicate SOI. The following plot shows the relation between the injector coil current, injector needle lift, and in-cylinder Heat Release Rate (HRR). It was observed (see Figure 10) that there is a steady fixed offset between the coil current and the needle lift. This offset gave confidence to the use of coil current to determine SOI.

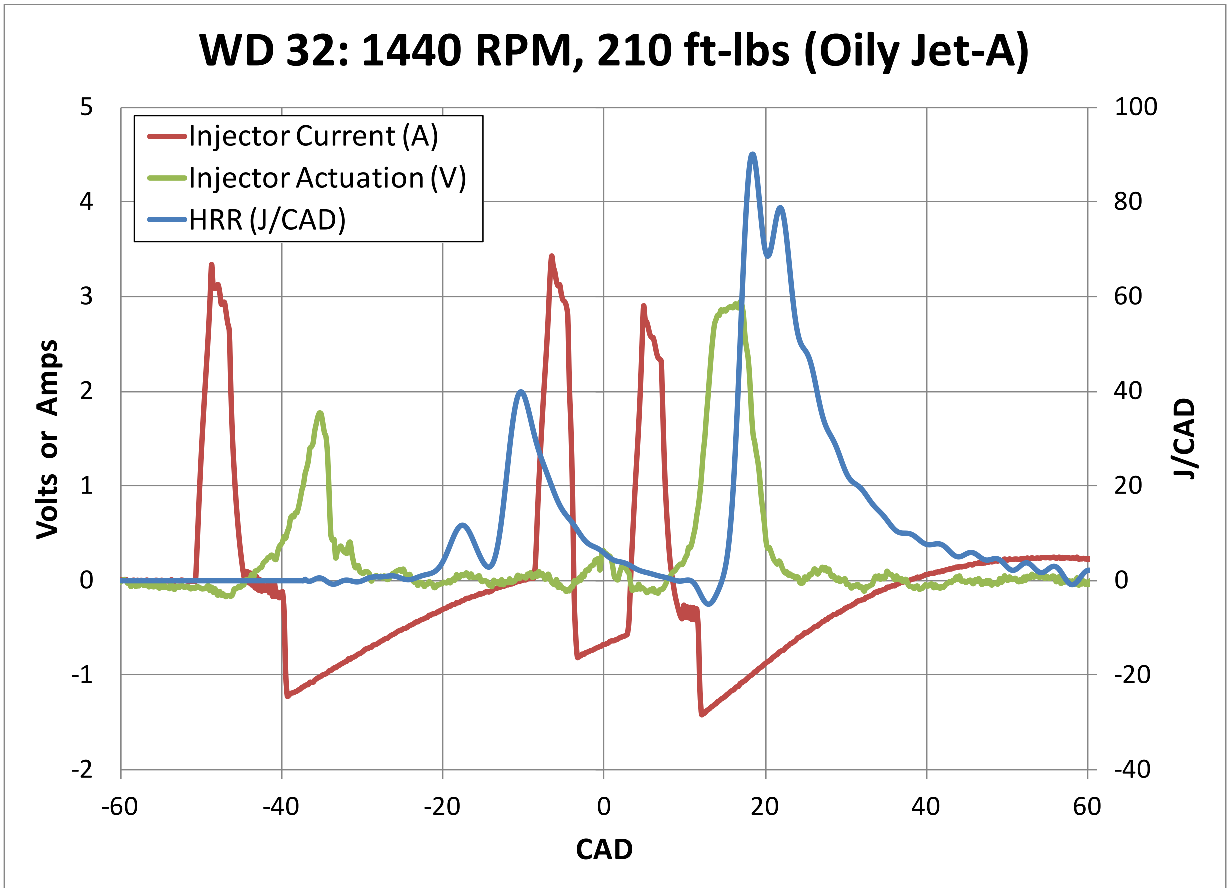

Figure 10. CAT C7 Comparison of Needle Lift and Coil Current with HRR Overlay

Figure 11 shows the difference in heat release rates between injectors and fuels. The line labeled "Oily Jet A" was a test performed with the leaky instrumented injector. The other two lines are with a known good, but non-instrumented injector. The leaky instrumented injector was showing some of the combustion characteristics of the diesel fuel and it was concluded to not use the leaky injector as the program results would be negatively impacted.

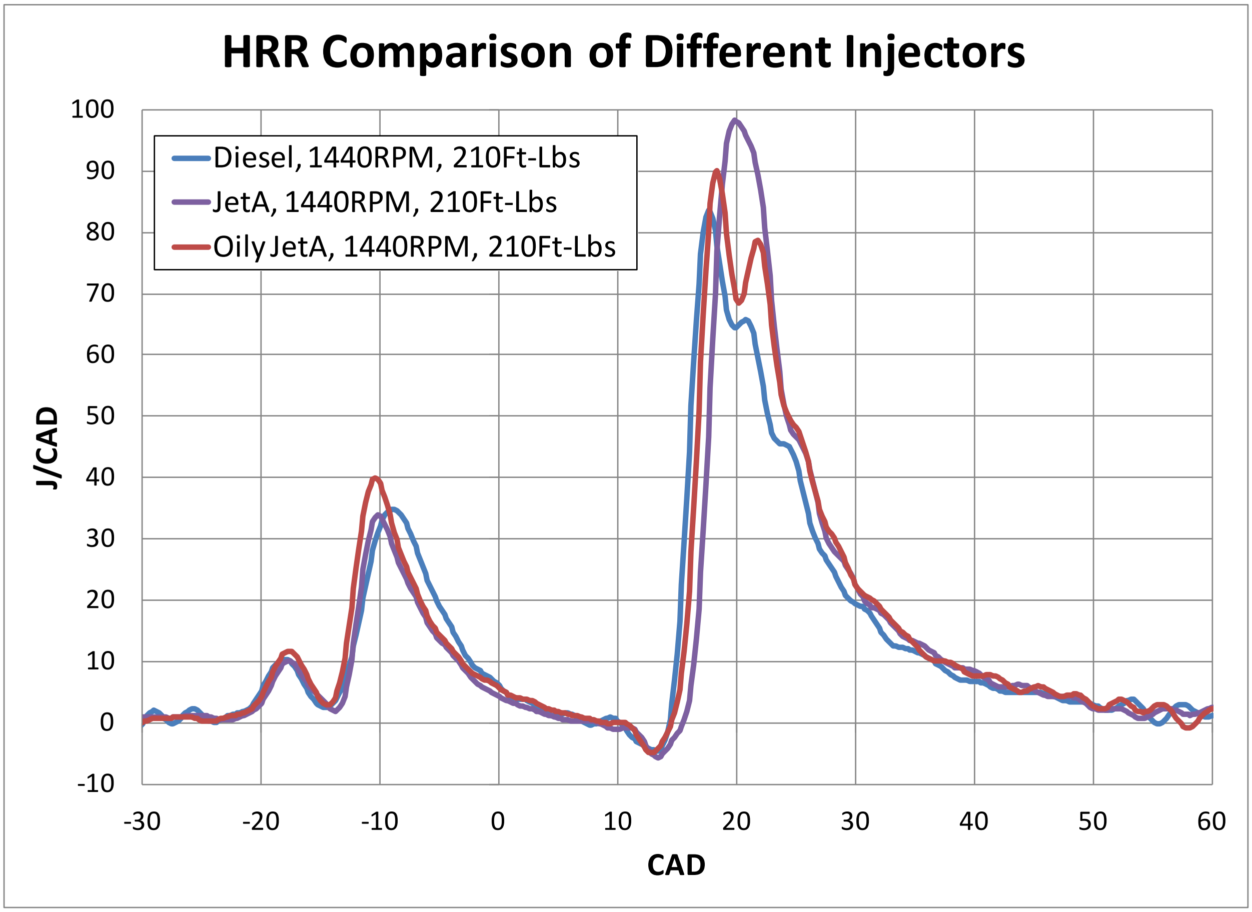

Figure 11. CAT C7 Verification of Oil Leaking in Instrumented HEUI-B Injector

During initial testing on the GEP 6.5T engine, it was observed that the injector, at almost every operating condition, opened more than once. This was found to be the direct result of a reflected pressure wave in the fuel line. The following chart, Figure 12 shows the reflected pressure wave as having the same amplitude as the primary wave. The injector open time however is very different between the two events. This is most likely the result of two items. The first is the pulse width of the pressure wave between 1600 and 1700 psi, which is the opening pressure range for the injector. The second is after the initial injection event, there is not any bulk fluid motion in the high pressure line due to the regular increment of the pump to the next cylinder. Mode 7 in the ESC was a medium speed light load step that exhibited the highest amplitude pressure wave reflection.

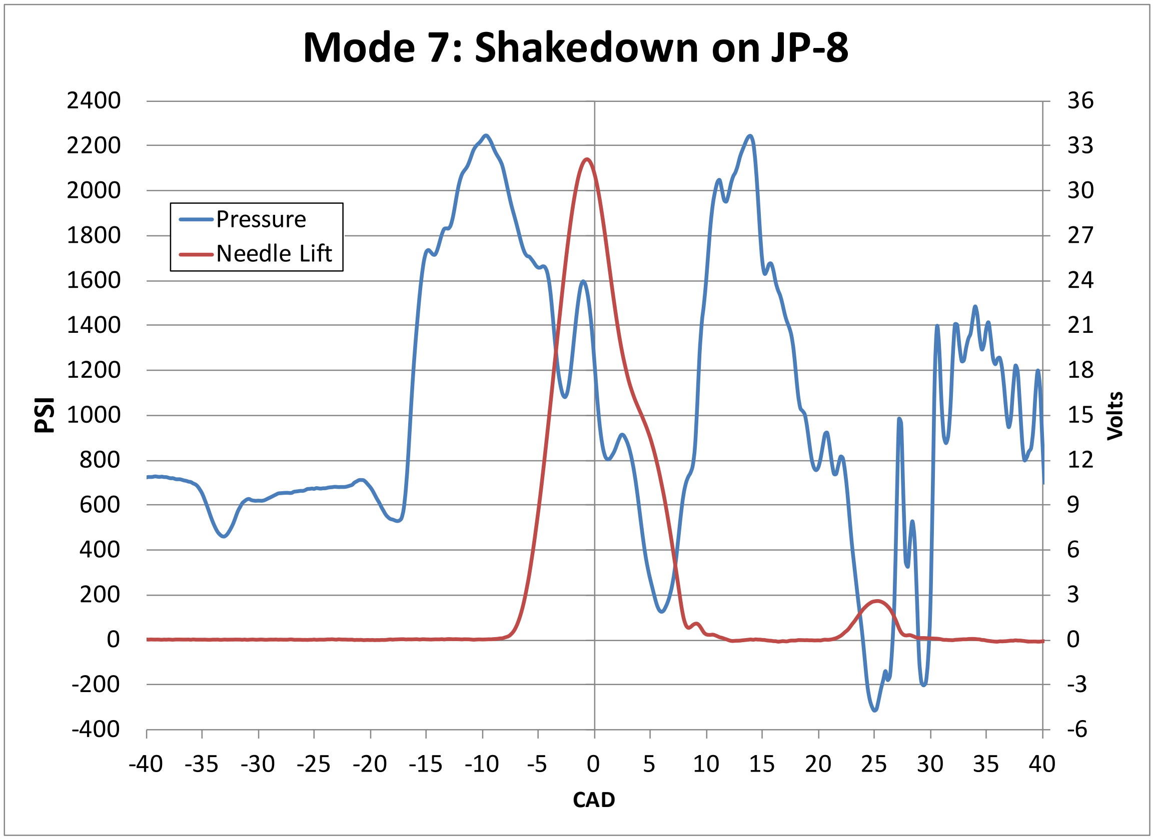

Figure 12. GEP 6.5T ESC Mode 7 Injection Pressure and Needle Lift

The results of this late injection opening would be a decrease in the cycle thermal efficiency and an increase in emissions, particularly Carbon Monoxide (CO) and Hydrocarbon (HC).

6.0 FUEL PROPERTIES

Included in this report is a selection of fuel properties from the fifteen fuels used in the program. For the full analysis of each fuel, please refer to Appendix A. Table 3 lists the fuels used sorted by cetane number from lowest to highest. The fuels selected encompass a broad range of middle distillates, synthetics, and synthetic blends.

The lower end of the cetane range is comprised of custom diesel fuels typically used in Homogeneous Charge Coupled Ignition (HCCI) research engines. These fuels are characterized by a very heavy percentage of aromatic compounds. For cetane numbers in the mid-40's, Jet A was obtained from a fungible supply pipeline and a certified diesel test fuel were used.

For the cetane range from 50 to 60 the certified diesel was additized with 2-Ethylhexyl Nitrate (2-EHN) cetane improver and 2 blends of jet fuel and synthetic jet fuel were used with varying degrees of 2-EHN cetane improver. The synthetic HRJ8 showed a cetane of 60.4 and the higher cetane fuels were comprised of full synthetic Fischer-Tropsch (FT) fuels with varying degrees of 2-EHN cetane improver. FT Diesel #2, used as a blending agent, had aromatic and sulfur components, whereas the FT Diesel #1 had none.

Table 3. Fuel Descriptions with Cetane Number

Cetane # by D613	Description
28.0	Custom Diesel Formulation #1
36.6	50/50 Blend of Custom Diesel #1 & #2
38.5	Custom Diesel Formulation #2
42.8	Jet A (pipeline)
44.4	2007 Certified Diesel
49.9	47/53 Blend S8 & JP8 (used at Ft. Bliss)
51.7	50/50 Blend HRJ8 & Jet-A (used with Generator Sets)
54.3	2007 Cert. Diesel & 0.3% Cetane Improver
55.9	Ft. Bliss Blend & 0.1% Cetane Improver
60.5	Ft. Bliss Blend & 0.3% Cetane Improver
60.4	HRJ8
64.0	Shell FT (low density)
71.7	Shell FT & 0.4% Cetane Improver
74.2	Fischer Tropsch Diesel #1
78.2	21/79 Blend of FT Diesel #1 & #2 & 0.3% Cetane Improver

Distillation range played a role in the results from the CAT C7 engine so a plot of fuel distillation can be seen in Figure 13. The data are arranged in the order they were operated in the program, with HRJ8 being the first fuel tested, and so forth. Of note, the distillation differences among the fuels are very large, especially when comparing the two highest neat cetane fuels. They are both from the Fischer-Tropsch process.

The additized FT-SPK fuel from Shell exhibited the narrowest boiling range with a T90-T10 temperature value of only 22.4 °C. Whereas the FT Diesel fuel which was obtained from the Air Force exhibited a T90-T10 value of 144.7 °C. The differences in combustion caused by the varying distillation ranges will be discussed further.

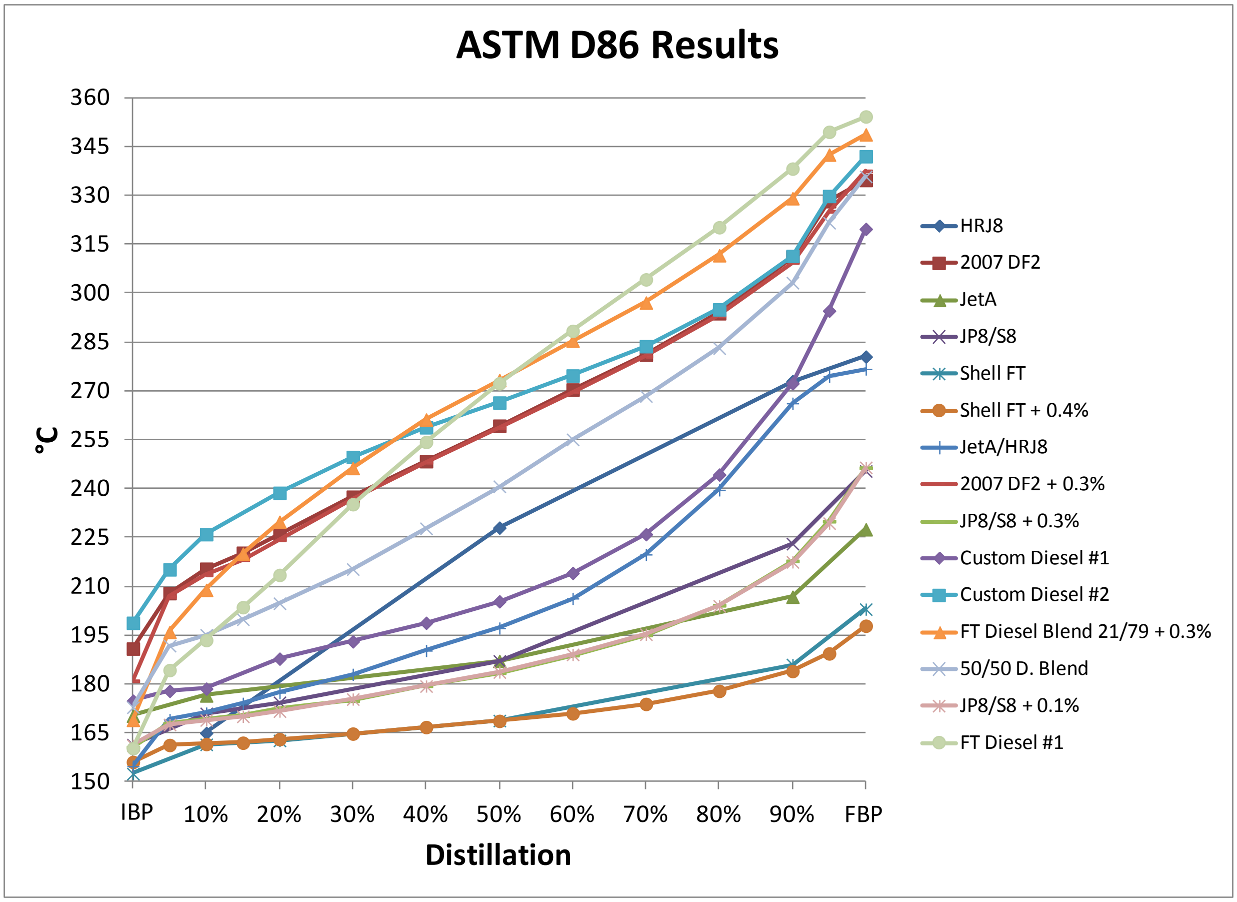

Figure 13. Fuel Distillation Characteristics

In order to compare the power output of the engines for each of the fuels, it was important to compare the energy content of the fuel. In Figure 14, the various fuels tested (minus the cetane improved fuels) are compared on a normalized basis. The certified diesel fuel has the highest energy density, so it was designated as 100% for this program. All the other fuels exhibited lower energy densities on a volumetric basis. Volumetric energy density is more important than mass based energy density as the fuel systems for the engines used in this program utilize constant volume injections.

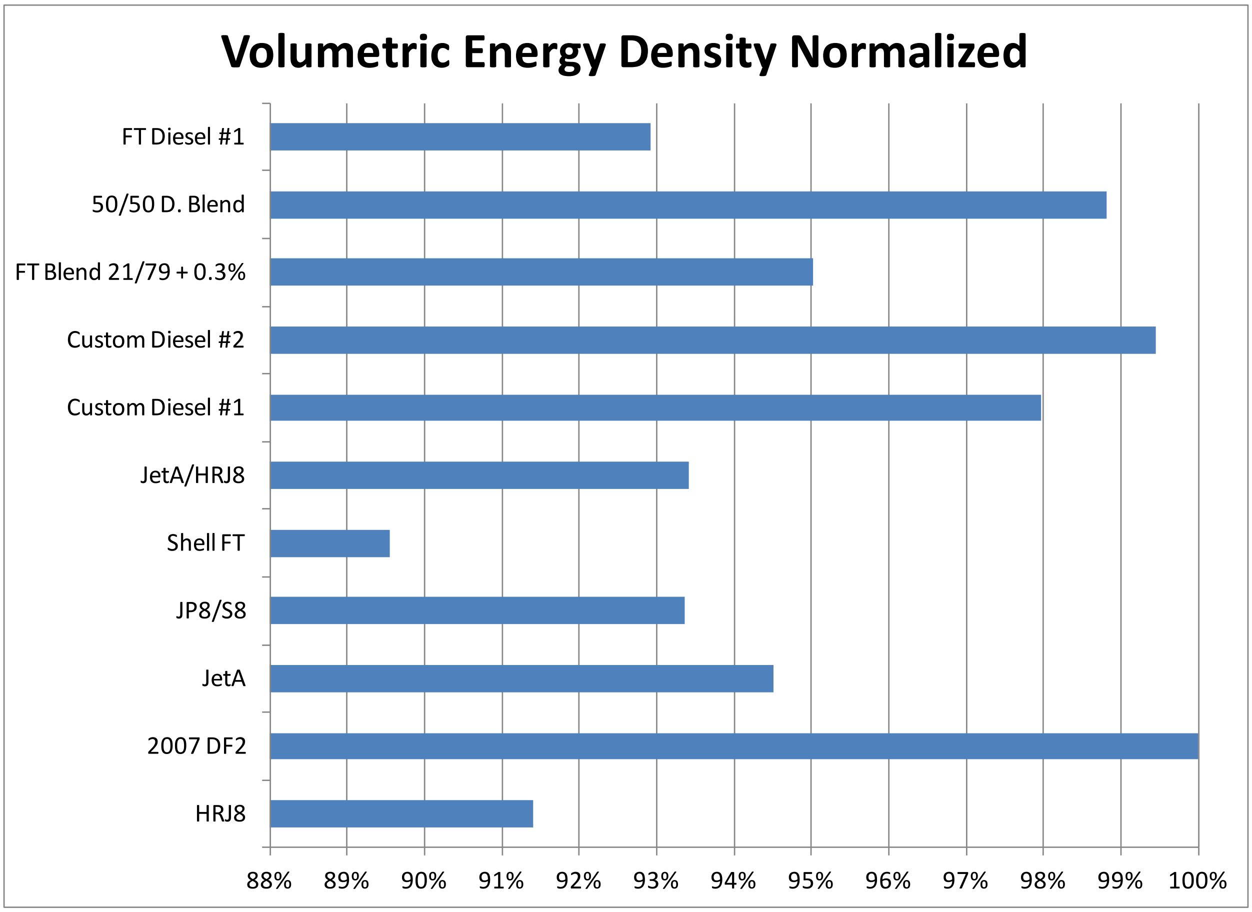

Figure 14. Fuel Normalized Volumetric Energy Density

To evaluate how effective the 2-EHN cetane improver was when it was used on the fuels in this program, the cetane number results were compared to a different program performed under Work Directive 017, Task 2.9. The cetane response for this program (as seen in Figure 15) appears to be less than that of similar fuels on the WD 017 program. This is most likely due to the highly volatile nature of 2-EHN. The cetane improver used for this program was of unknown age when purchased, and was not kept in a cold storage room prior to use.

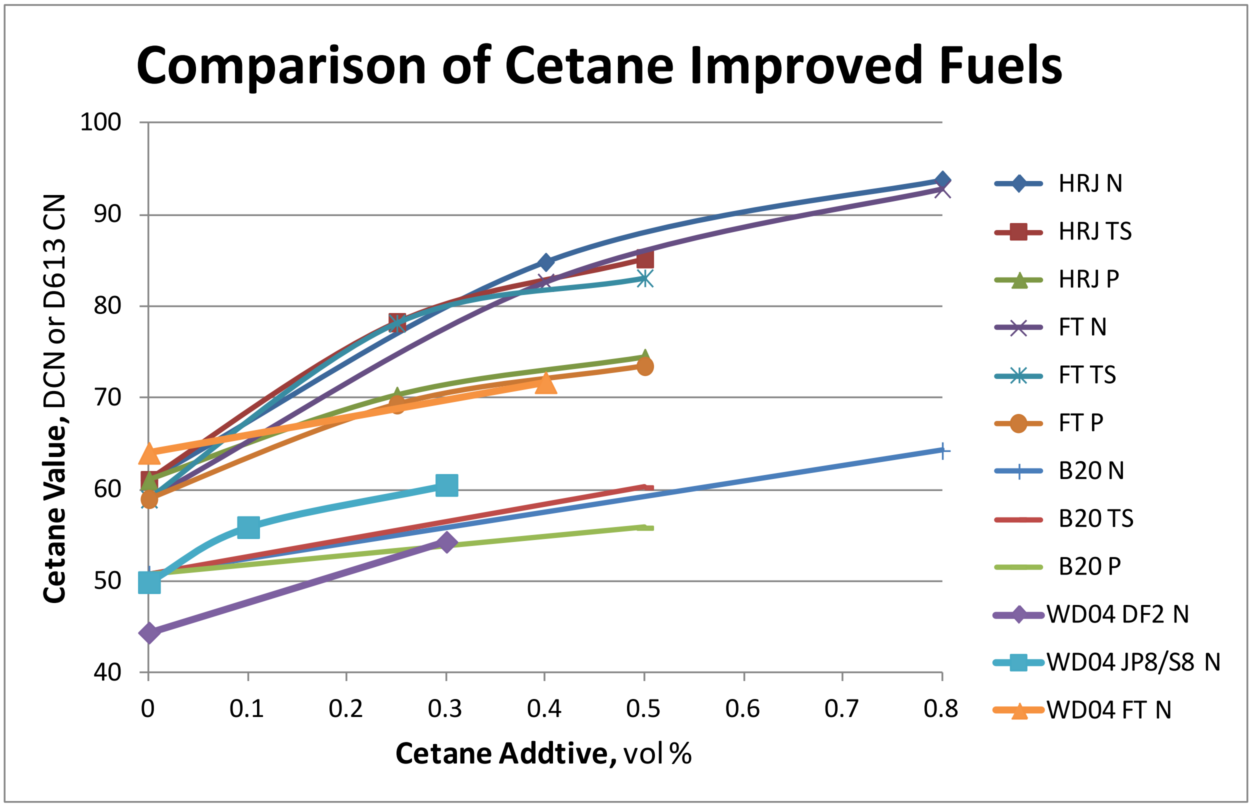

Figure 15. Comparison of Cetane Improved Fuels – WD004 vs WD017

7.0 PEAK POWER

For the CAT C7 engine, there was a weak correlation with cetane number but a strong correlation with density as seen in Figure 16 and Figure 17. If the DF-2 and Shell FT-SPK fuels are compared, there an 11.8% power loss between them. 10.5% of that loss is a direct result of the difference in volumetric energy density. The remainder is ECM modifying injection timing to control NOx emissions.

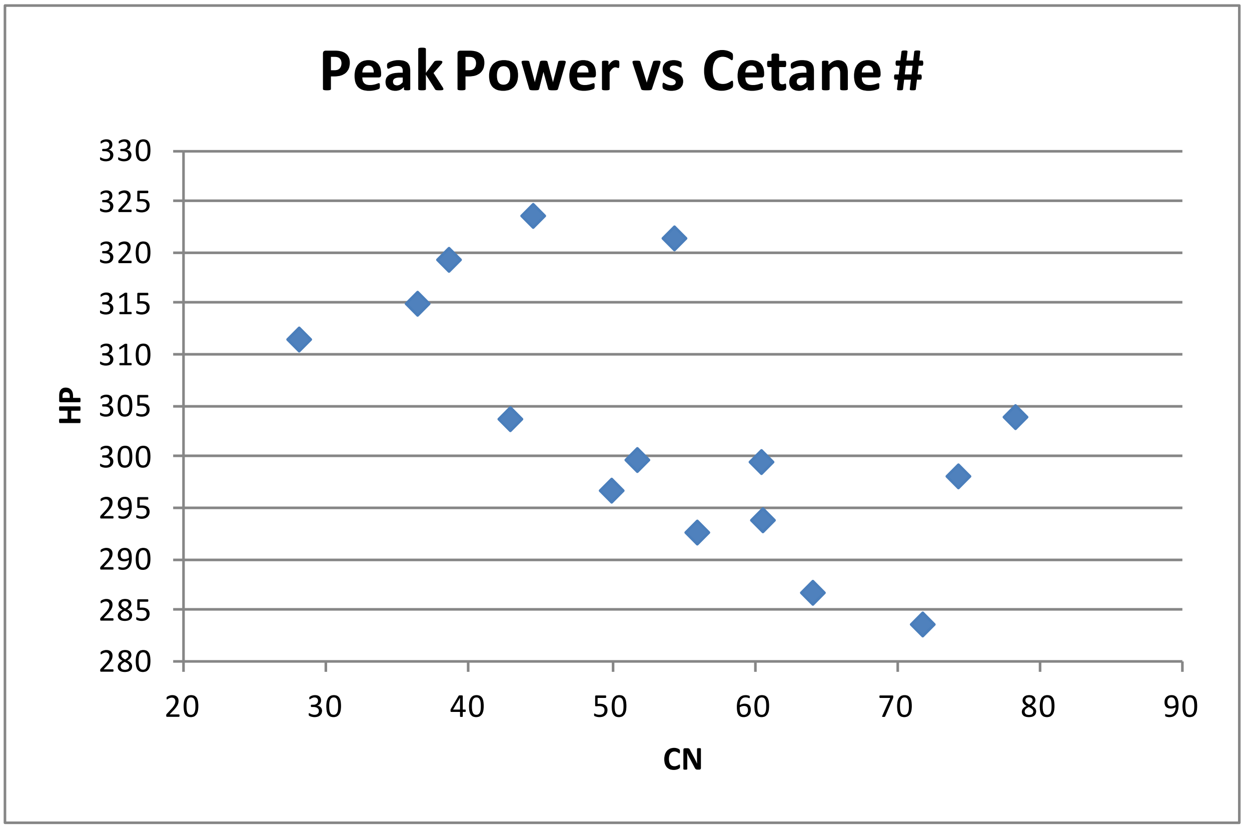

Figure 16. CAT C7 Peak Power vs. Cetane Number

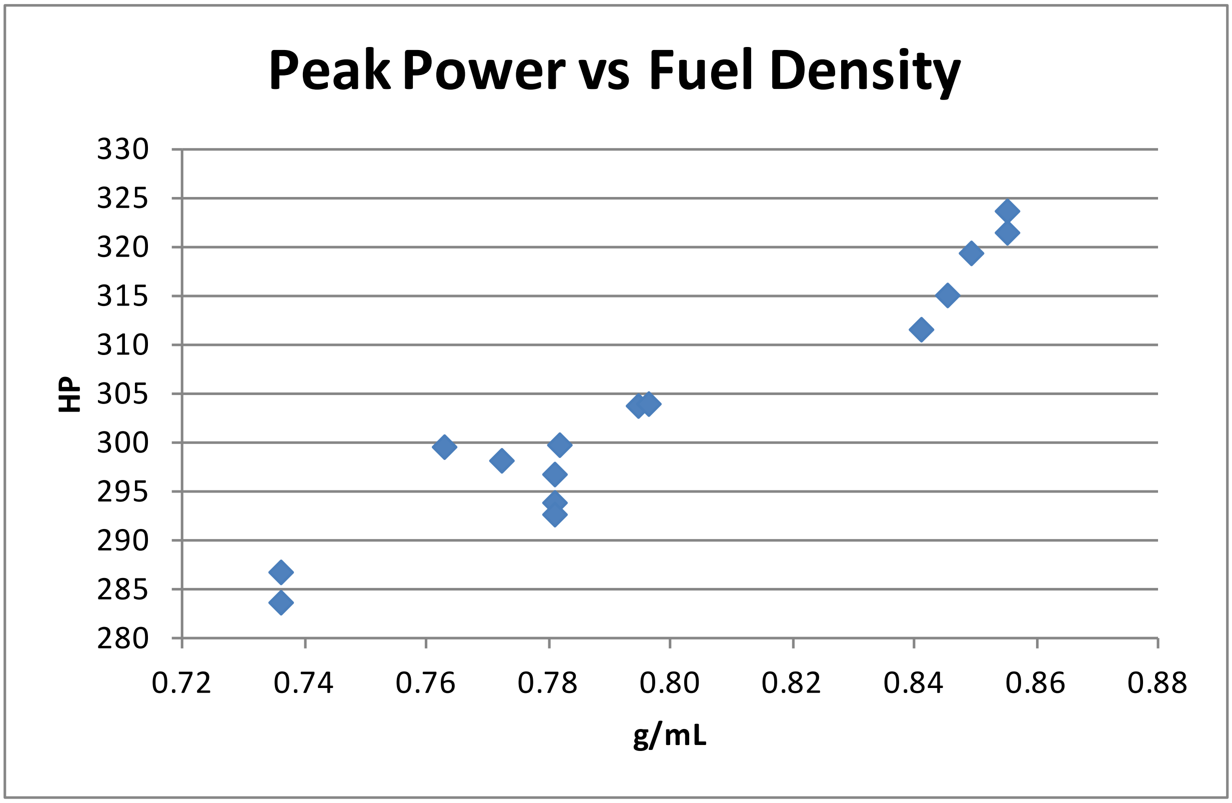

Figure 17. CAT C7 Peak Power vs. Fuel Density

In Figure 18 and Figure 19, as seen in the GEP 6.5T engine, there is a very weak correlation with cetane number and a strong correlation with density. If DF-2 and Shell FT-SPK fuels are compared, there is a 20.5% power loss. 10.5% of which is a direct result of the difference in volumetric energy density. The remainder of the loss is the bulk modulus effects on timing which is discussed in further detail in section 11.2.

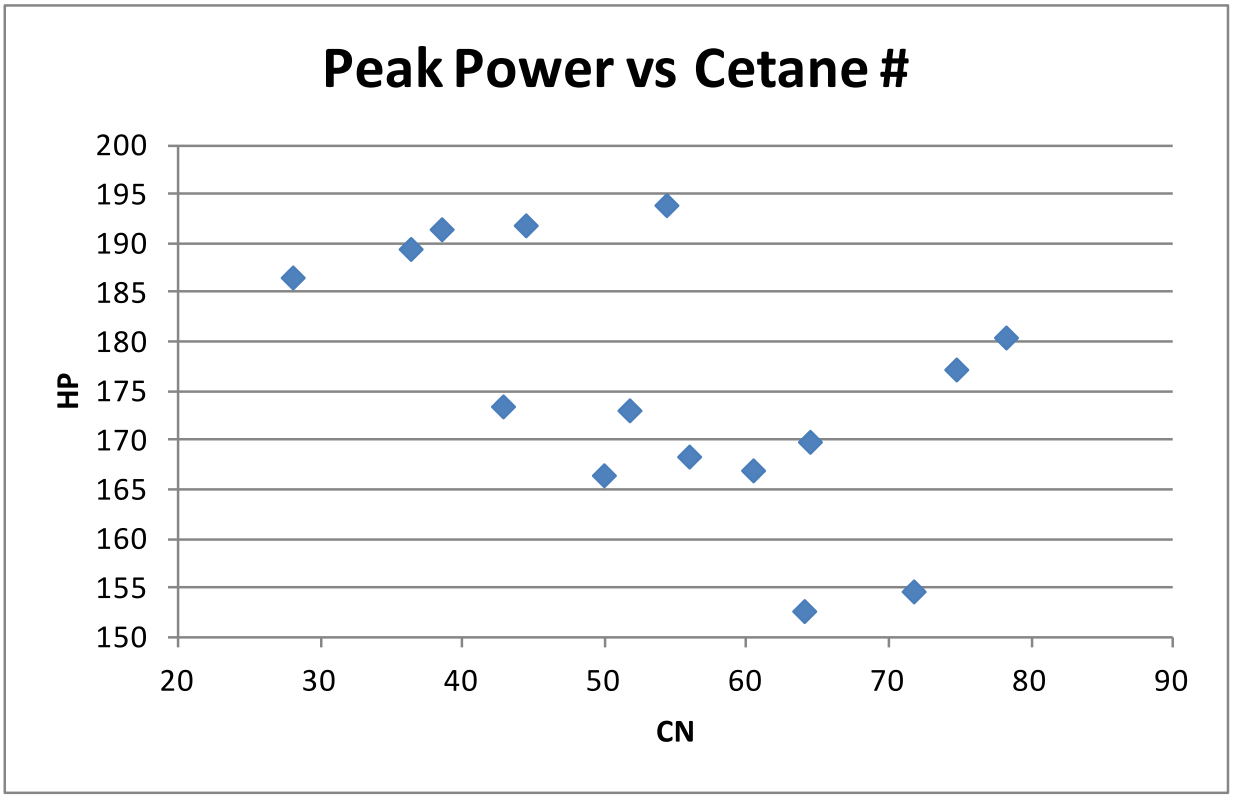

Figure 18. GEP 6.5T Peak Power vs. Cetane Number

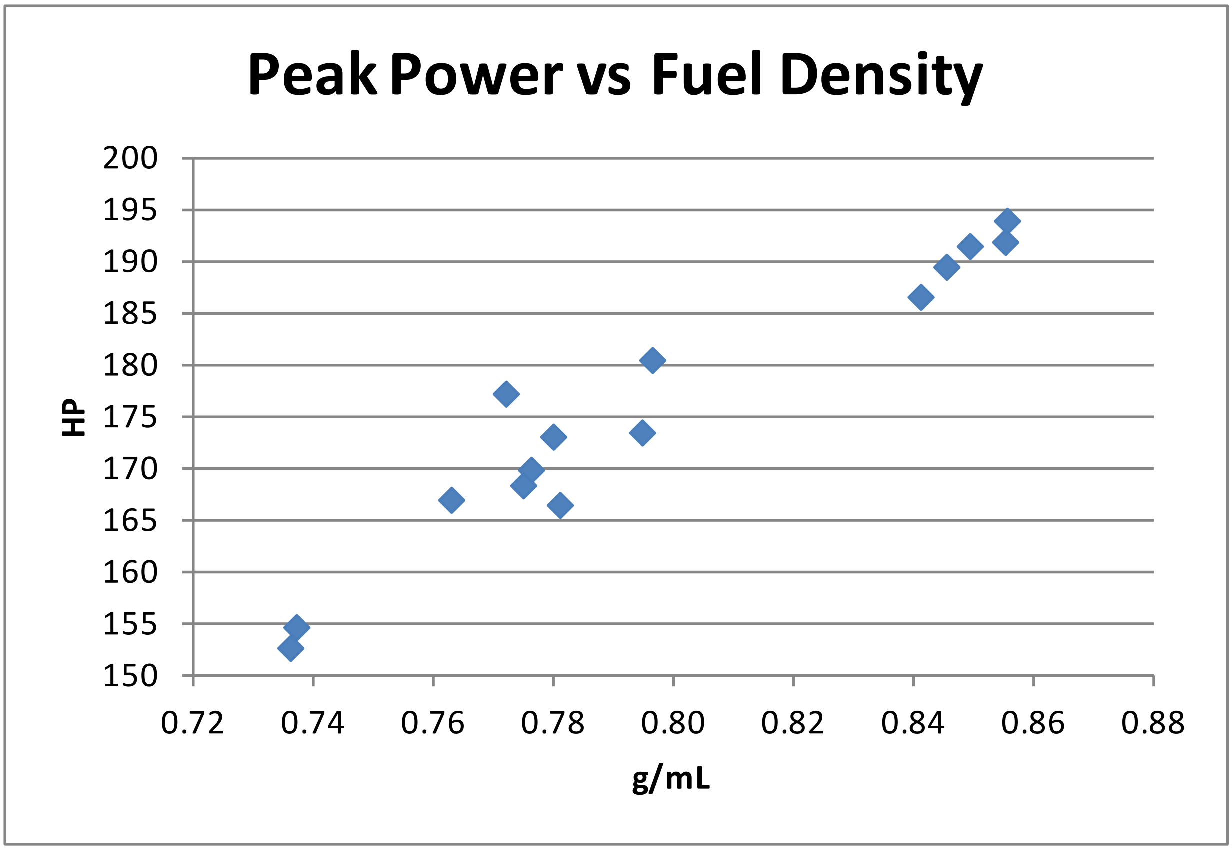

Figure 19. GEP 6.5T Peak Power vs. Fuel Density

8.0 EMISSIONS

The CAT C7 ECM controls NOx formation well. The observed emissions levels (as seen in Figure 20) were below the Non-Road Tier 1 standard of 6.9 g/bhp-hr NOx. For cetane numbers below 38, HC and CO emissions exceed the Non-Road Tier 1 standards of 1.0 g/bhp-hr HC and 8.5 g/bhp-hr CO.

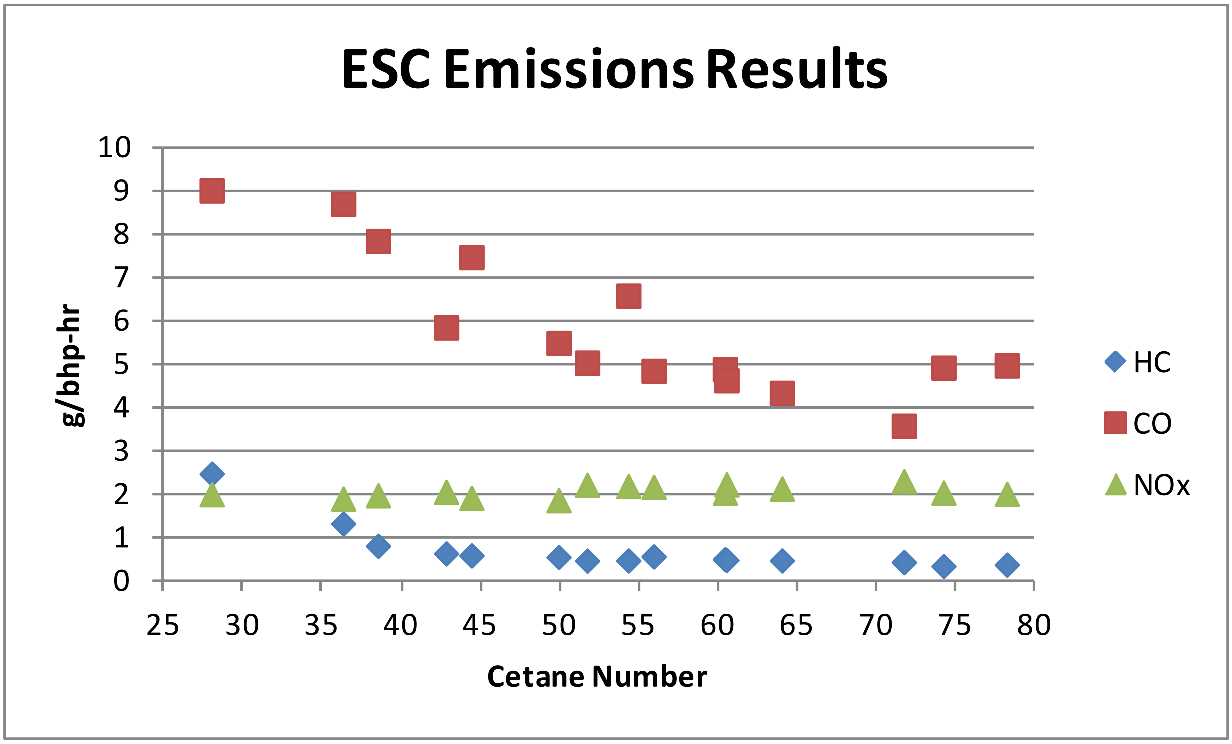

Figure 20. CAT C7 ESC Emissions Results

As compared to the CAT C7 engine, the GEP 6.5T emits very low HC and CO but very high NOx (as seen in Figure 21). However, the observed emissions levels were all still within Non-Road Tier 1 standards.

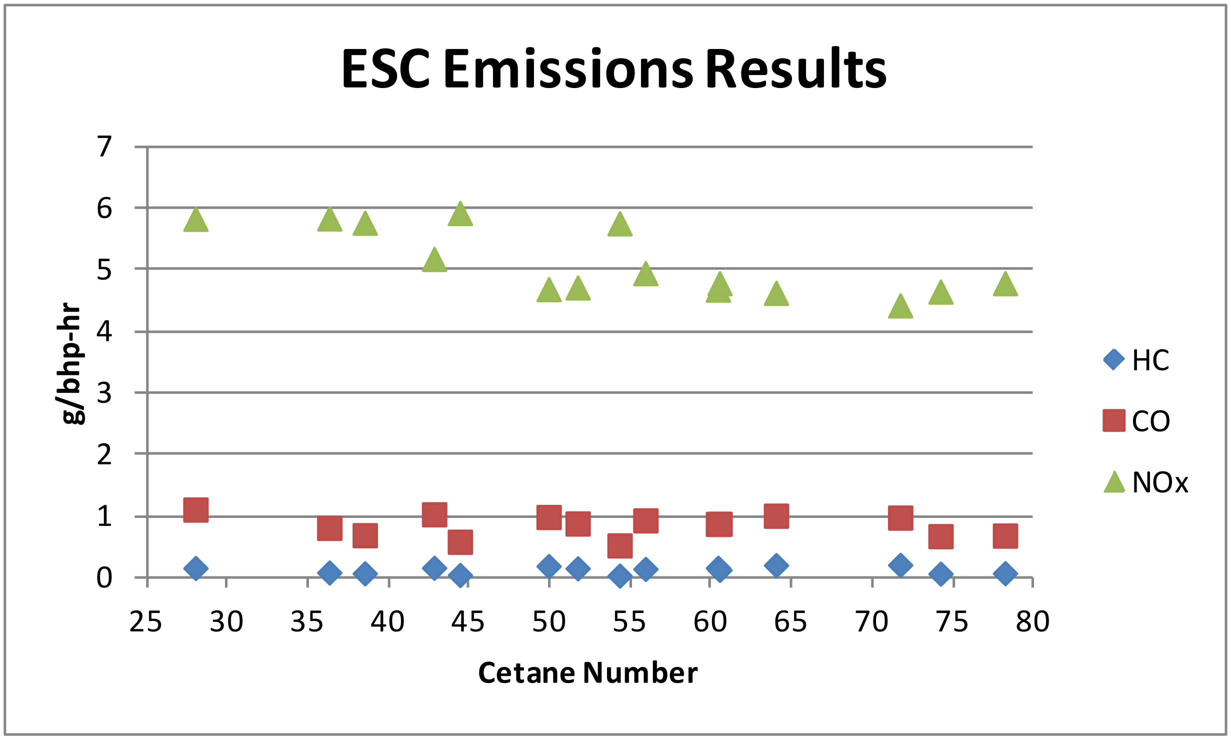

Figure 21. GEP 6.5T ESC Emissions Results

9.0 IGNITION DELAY

Although engine combustion characteristics were more sensitive to cetane on the CAT C7 engine, the GEP 6.5T exhibited a larger percentage change in ignition delay. Figure 22 illustrates the differences in ignition delay between the two engines. The Arrhenius temperatures as plotted on the x-axis were calculated from the manifold conditions at Intake Valve Closing (IVC), and the position of the piston at Start of Injection (SOI). Due to the low energy output, and shifted injection timing, the engine idle conditions have been easily highlighted for comparison as well.

Also in Figure 22, the fuels have been arranged from lowest cetane number to highest cetane number so an easy comparison can be made between ignition delay and cetane number.

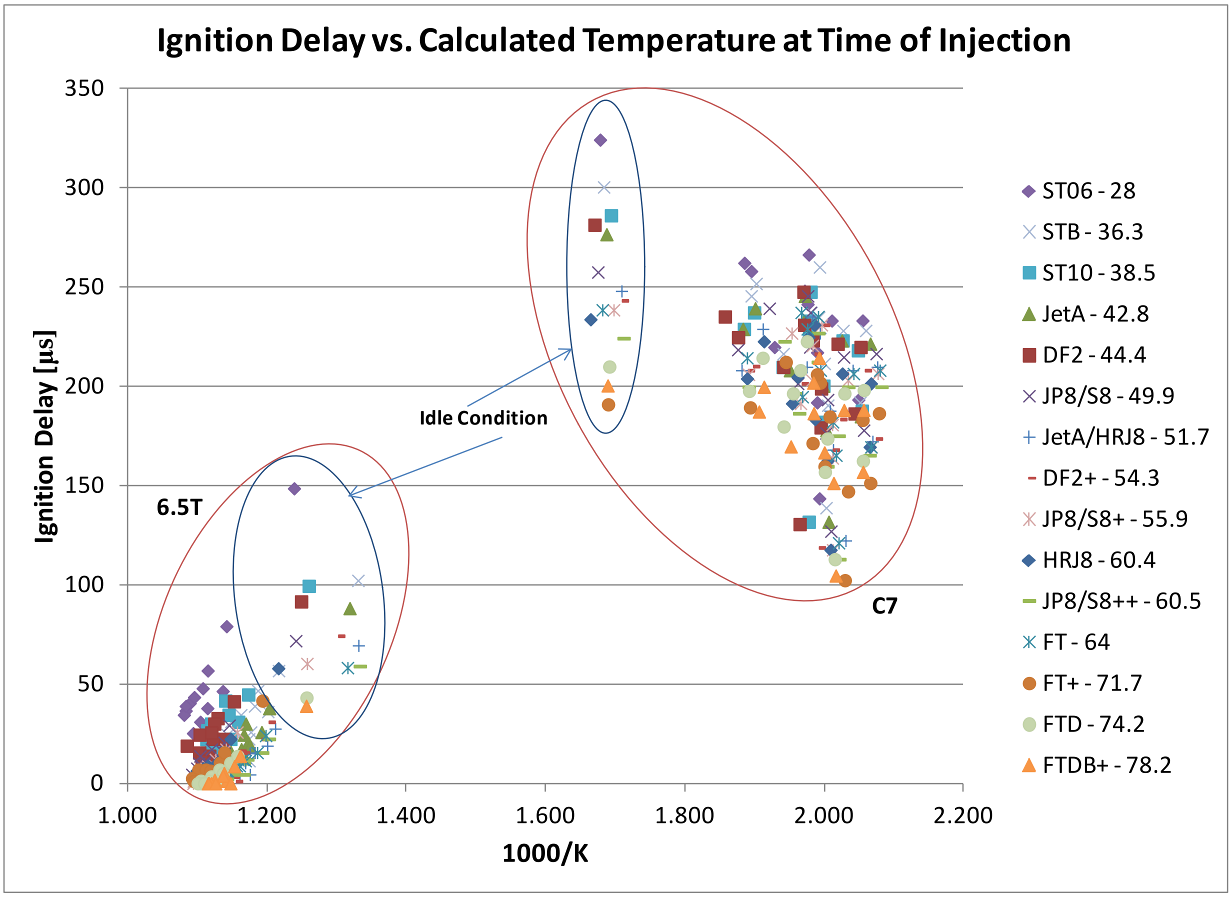

Figure 22. CAT C7 and GEP 6.5T Ignition Delay Comparison

10.0 COMBUSTION CHARACTERISTICS

10.1 CAT C7 ENGINE

On the CAT C7 engine there was a small decrease in peak power (as seen in Table 4) due to increasing cetane number. This was caused by a decrease in cycle thermal efficiency, and the CAT C7 ECM changing the timing of the main injection to control NOx emissions.

Table 4. CAT C7 Peak Power and NOx

Fuel #	Fuel Descr.	Peak Power	ESC Mode 10 NOx g/hp-hr
2	2007 DF-2	323.7	2.406
8	2007 DF-2 + 0.3%	321.5	2.806
5	FT-SPK	286.8	2.880
6	FT-SPK + 0.4%	283.7	3.098
4	JP8/S8	296.8	2.468
14	JP8/S8 + 0.1%	292.7	2.858
9	JP8/S8 + 0.3%	293.9	2.920

In Figure 23, the ESC Mode 10 is shown for the fuels in Table 4 above. This mode is operated at 2380 rpm and constant Brake Mean Effective Pressure (BMEP) close to full throttle. It can be seen that the pre-injection heat release is cetane number dependent. However, the ECM controls the main-injection so the main heat release event is not phased too early. This is the control strategy for preventing excessive NOx formation.

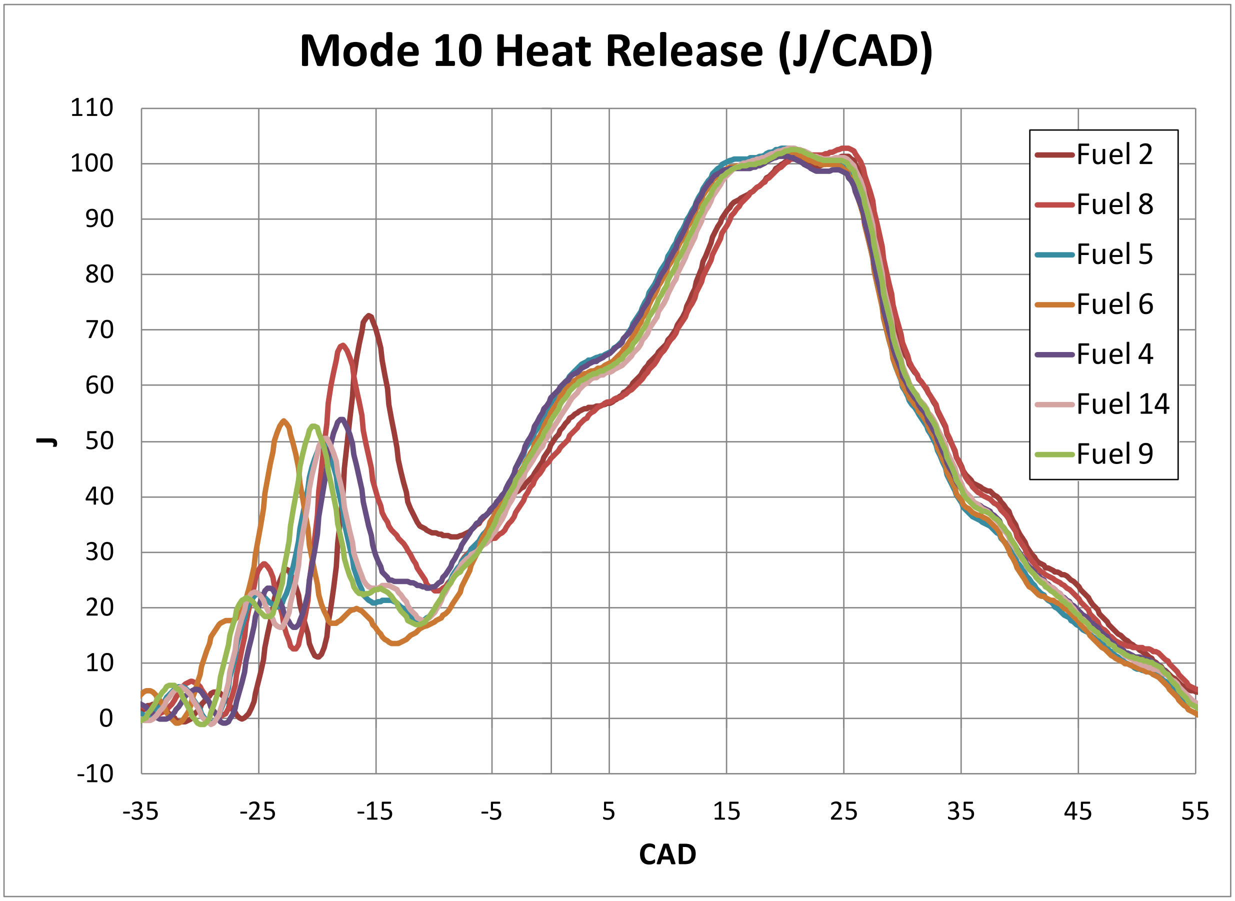

Figure 23. CAT C7 ESC Mode 10 HRR Comparison

Mode 2 on the CAT C7 engine (as seen in Figure 24), which is very near to peak-torque, shows the ECM working very well at high load to shift the timing of the main heat release curve for the widest range of cetane number fuels tested. This is the main reason for the near constant Brake Specific NOx (BSNOx) results from the ESC cycle.

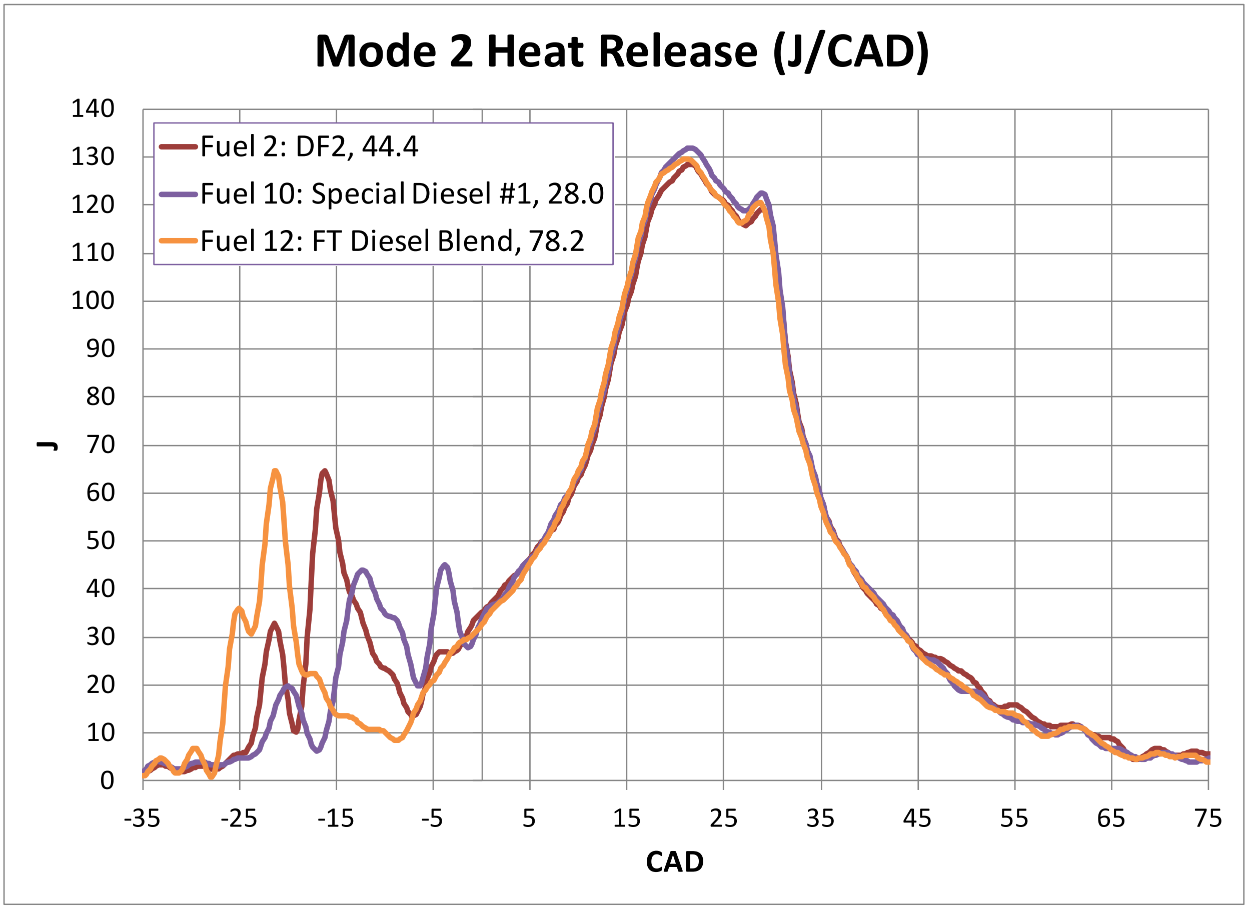

Figure 24. CAT C7 ESC Mode 2 HRR Comparison

Another observed performance characteristic was an audible difference in idle quality between the high & low cetane fuels. The high cetane fuel exhibited roughest idle. As seen in Figure 25, a large amount of heat was released before TDC with the high cetane fuel. This heat release constitutes 40% of the cycle fuel mass burned.

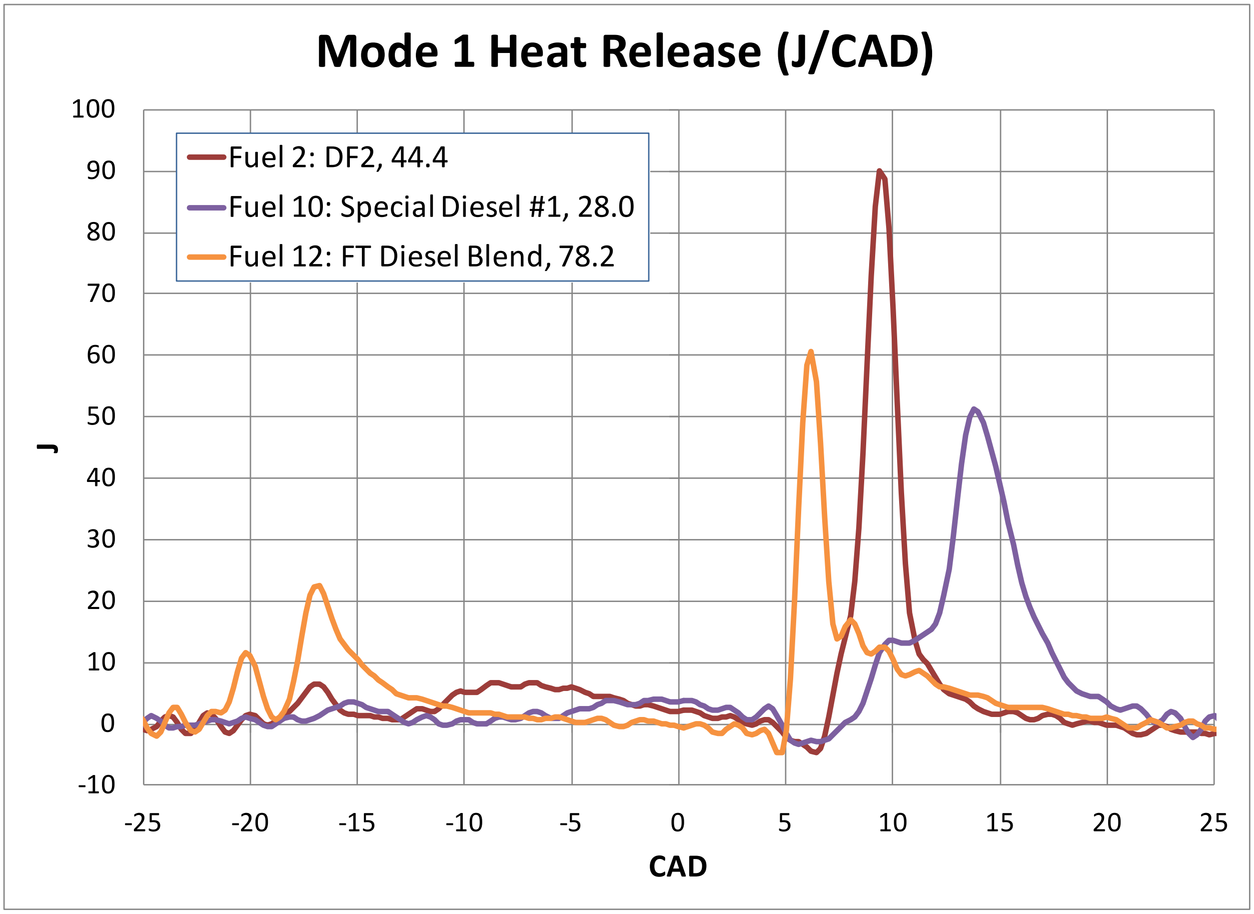

Figure 25. CAT C7 ESC Mode 1 HRR Comparison

Mode 11 was the most challenging to execute. For the three lowest cetane fuels, the throttle actuation controls were modified to produce a very over-damped torque response in order to smooth out engine operation. Prior to modification, the high speed DAQ could not average the data taken due to the large variation in instantaneous speed. Mode 11 was the largest contributor to raw engine out CO. The values ranged from 1240 to 3550 ppm CO. The ECM was also not able to completely control the main heat release event, as compared with the control on Mode 2, at this light load, high speed engine condition as seen in Figure 26.

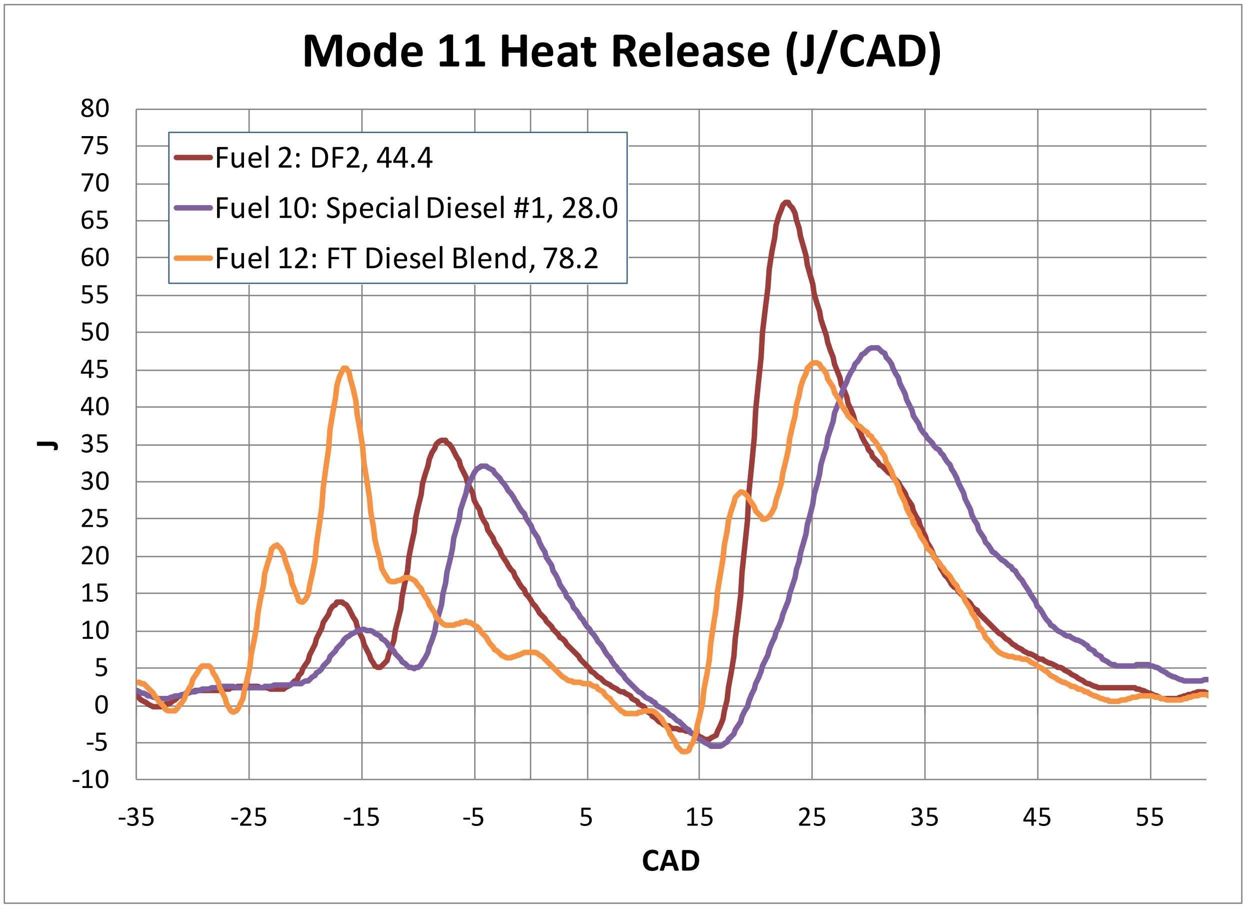

Figure 26. CAT C7 ESC Mode 11 HRR Comparison

10.2 GEP 6.5T ENGINE

Reversing the trend seen previously, improving the cetane number of a given fuel will increase the peak power output on the GEP 6.5T engine (refer to Table 5).

Table 5. GEP 6.5T Cetane Number and Peak Power

Fuel #	Fuel Descr.	Cetane #	Peak Power
2	2007 DF-2	44.4	191.9
8	2007 DF-2 + 0.3%	54.3	194.0
5	FT-SPK	64.0	152.7
6	FT-SPK + 0.4%	71.7	154.7
4	JP8/S8	49.9	166.5
14	JP8/S8 + 0.1%	55.9	168.4
9	JP8/S8 + 0.3%	60.5	169.9

On the GEP 6.5T engine, because the injection timing is set statically, cetane number has a direct impact on fuel consumption. As seen in Figure 27, there is a 5% spread in BSFC due to cetane number. However, these values are slightly negatively influenced by the injection delay caused from the generally decreasing bulk modulus values with increasing cetane number.

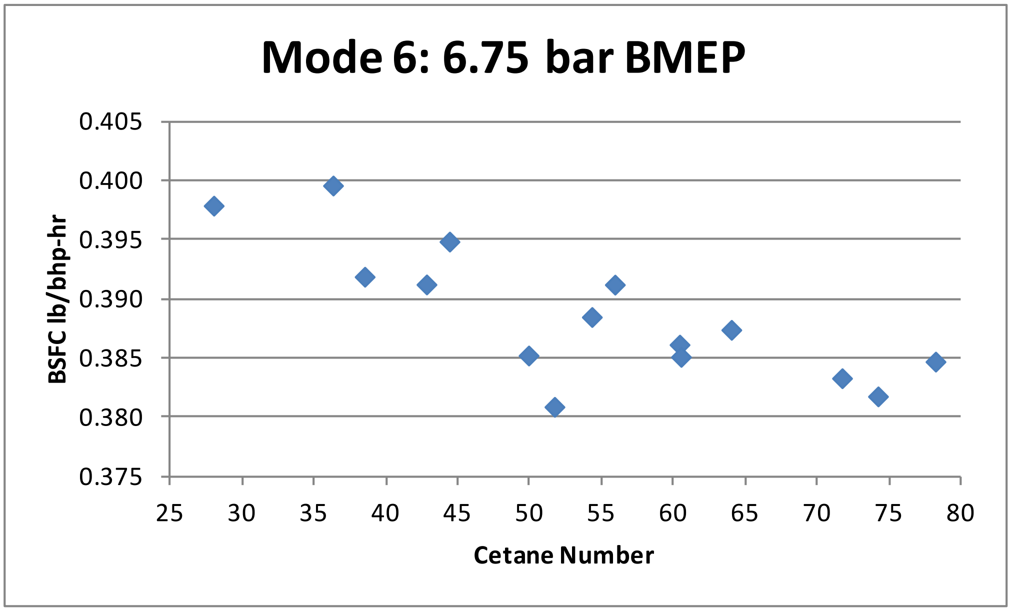

Figure 27. GEP 6.5T ESC Mode 6 -- BSFC vs. Cetane Number

When mode 5 on the ESC was run (as seen in Figure 28), the heat release rate for the cetane number 28 fuel was observed to be almost double that of the cetane number 64 fuel. This large maximum HRR can be detrimental to the engine as combustion noise and hardware component stress scales with HRR.

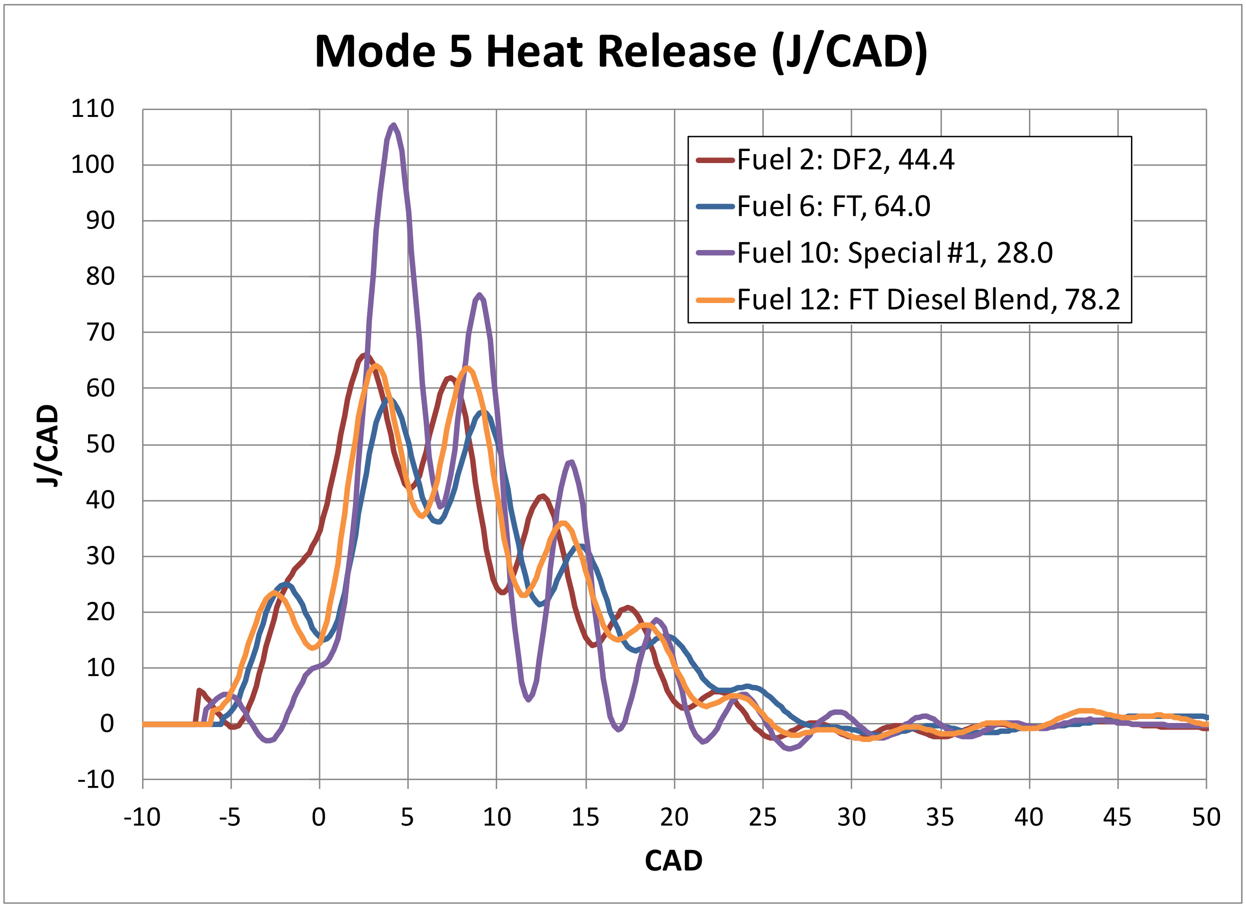

Figure 28. GEP 6.5T ESC Mode 5 HRR Comparison

For the combustion data presented and analyzed on the GEP 6.5T engine, only the pre-chamber data was used. This is due largely to the ignition event taking place inside the pre-chamber. When a few of the main-chamber combustion data sets were analyzed early in the program, TFLRF staff wanted to know if the physical transport delay between the pre and main chambers could be characterized to simplify potential engine models. When an extreme of engine loads, speeds, and fuels are compared, in Table 6, the transport time delay between pre and main chamber remains relatively constant regardless of engine condition or fuel.

Table 6. GEP 6.5T Physical Transport Delay from Pre to Main Chamber

Transport Delay from Pre to Main Chamber				
	Fuel 3: Jet-A		Fuel 10: 28 CN	Fuel 12: 78 CN
	CAD	µs	µs	µs
Mode 1	1.2	21.2		
Mode 2	3.0	25.8		
Mode 11	4.0	22.6	19.2	20.3

Note: Mode 1 is idle, mode 2 is close to peak torque, mode 11 is high speed & light load.

Figure 29 and Figure 30 illustrate the entire combustion event characteristics for Mode 1 and Mode 2 on the GEP 6.5T engine operating on Jet A fuel. These plots also include needle lift and injection pressure traces.

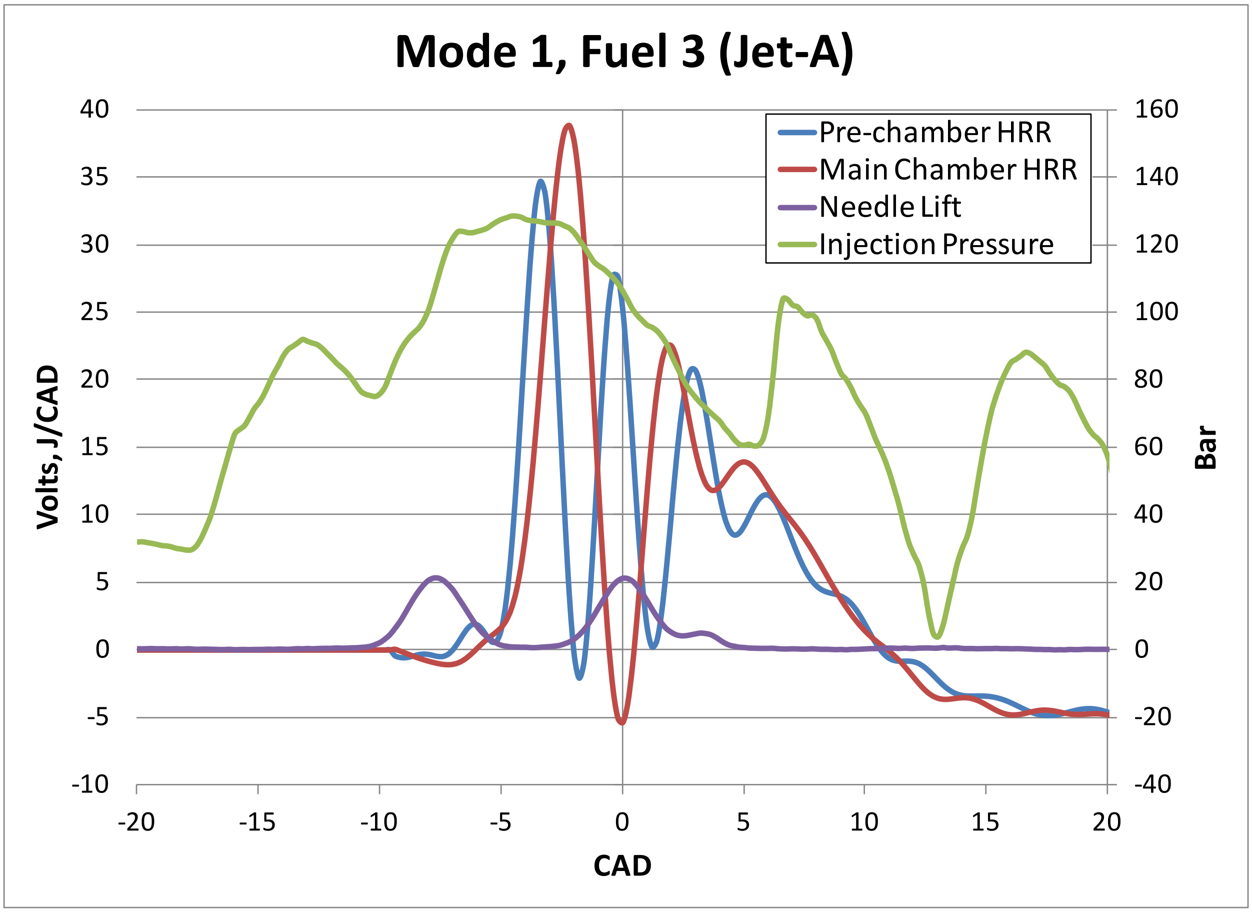

Figure 29. GEP 6.5T ESC Mode 1 with Jet A Fuel

In both Figure 29 and Figure 30, the main chamber pressure trace can be seen to lag behind the pre chamber pressure trace as expected. The main chamber pressure trace also exhibits both a lower ringing frequency and less amplitude in the ringing frequency. This can be directly attributed to the differences in geometry between the pre and main combustion chambers.

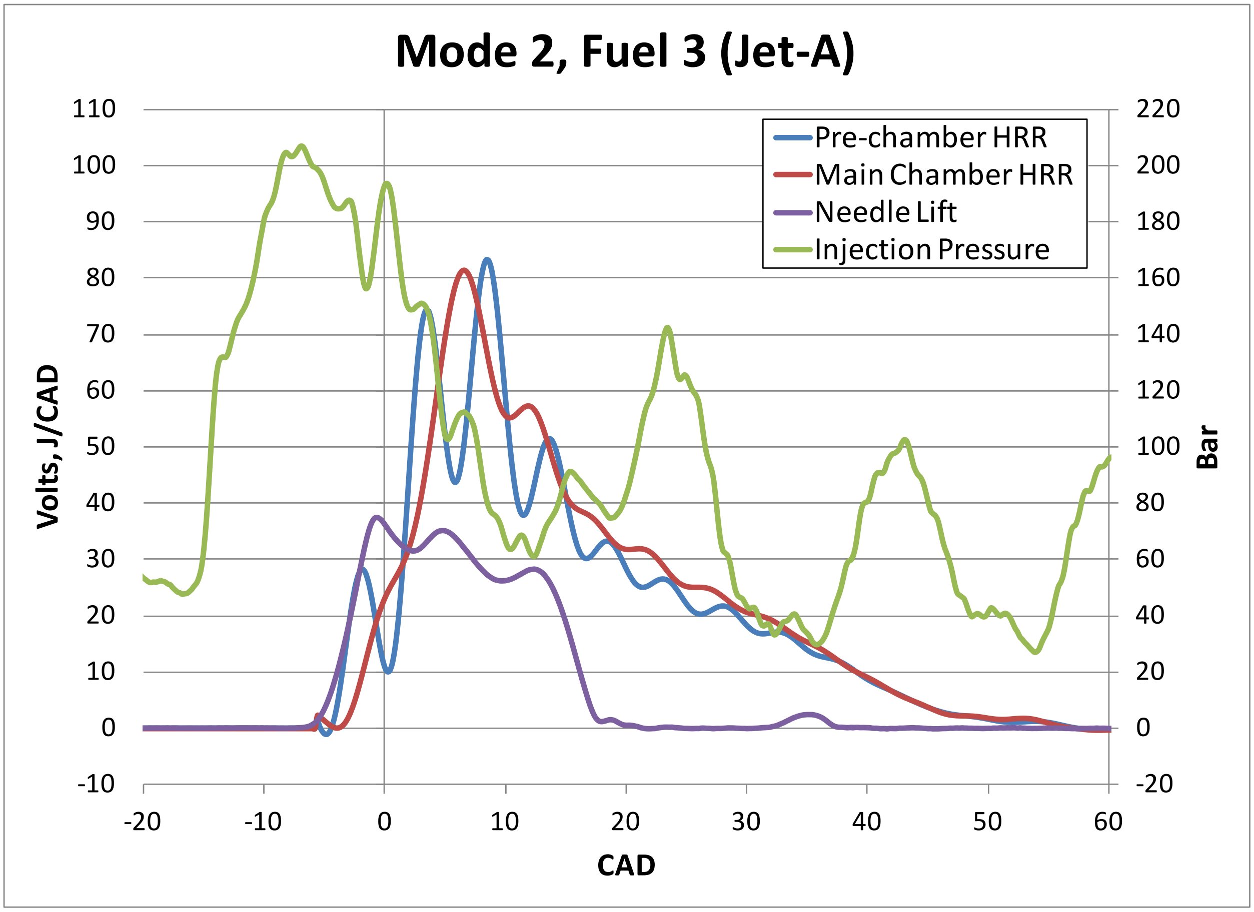

Figure 30. GEP 6.5T ESC Mode 2 with Jet A Fuel

11.0 FUEL PROPERTY EFFECTS ON PERFORMANCE

The slate of 15 fuels used for the cetane window testing had not only large variations in cetane number, but also variations in other fuel properties such as viscosity, boiling range, bulk modulus, lubricity, hydrogen/carbon atom ratio, and fuel structure type. The engine performance and combustion data was compared to the fuel property data to determine any significant fuel property variations for either the CAT C7 or GEP 6.5T engines.

All fuel and engine performance data were entered into a spreadsheet. A correlation worksheet function was used to calculate the correlation coefficient between measurement variables when measurements on each variable were observed for each of N subjects. The computation of the correlation coefficient is the ratio of covariation in the X and Y variable, to the individual variability in X and the individual variability in Y. Covariation is meant as the amount that X and Y vary together. So, the correlation looks at how much the two variables vary together relative to the amount they vary individually. If the covariation is large relative to the individual variability of each variable, then the relationship and the value of r is strong. The value of any correlation coefficient must be between -1 and +1 inclusive, whether large values of one variable tend to be associated with large values of the other (positive correlation), whether small values of one variable tend to be associated with large values of the other (negative correlation), or whether values of both variables tend to be unrelated (correlation near 0 (zero)).

The correlation coefficients for the fuel property variables for the test fuels are shown in Table 7 with highlighted values representing +/-0.90 or greater correlation coefficients. Some of the test fuels differed from other fuels only due to the addition of a cetane improver additive.

Fuel density is important for fuel injection, as most fuel injection systems have a fixed metering volume, thus lower density fuels could result in lower power output. The fuel density shows correlation with fuel bulk modulus, net heat of combustion, the carbon and hydrogen content, and fuel hydrocarbon type. Fuel structure has a major effect on the fuel density.

Fuel ignition quality is determined by the fuel property variables Cetane Number (CN) and Derived Cetane Number (DCN). The cetane number 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 (TDC). The DCN correlates the measured ignition delay characteristics of a fuel with the cetane number as defined by the primary reference fuels blends in a combustion bomb. It is noted CN and DCN are highly correlated, as they are both defined by reference fuel blends, but do not appear to correlate well with other fuel properties. 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 fuel injection.

Several different fuel variables are a measure of fuel structure, those being the carbon content, hydrogen content, hydrogen/carbon atom ratio (H/C), the aromatics content, 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. The fuel Bulk Modulus (BM) is a measure of fuel compressibility, and effects fuel injection dynamics. Typically as the saturate content of a fuel increases, there are more highly branched molecule chains, the fuel is more compressible, and the bulk modulus would be lower. This fuel property data set did not show a strong correlation between BM and saturate content.

The test fuels boiling point data from are a measure of fuel volatility; higher boiling point temperatures indicate a less volatile fuel. The distillation temperatures appear to correlate with each other and the fuel viscosity. In addition the T90-10 temperature range is an indicator of the breadth of the distillation cut that can affect engine performance and idle stability, and correlates with the T90 distillation temperature. The fuel kinematic viscosity for the fuel property set appear to correlate with the distillation data and flashpoint. The fuel flashpoint correlates with the T10 distillation temperature.

Table 7. Fuel Property Cross Correlation Table

	Density	CN	DCN	BM	Kvis	NHofC	C	H	H/C	Aromatics	Olefins	Saturates	Sulfur	Nitrogen	Flash	T10	T50	T90	T90-10	HFRR
Density	**1**																			
CN	-0.6828	**1**																		
DCN	-0.6205	**0.9606**	**1**																	
BM	**0.9438**	-0.5237	-0.4807	**1**																
Kvis	0.7042	-0.0810	-0.0399	0.8243	**1**															
NHofC	**-0.9791**	0.7687	0.6987	**-0.9132**	-0.5956	**1**														
C	**0.9308**	-0.6906	-0.6296	0.8225	0.5535	**-0.9221**	**1**													
H	**-0.9621**	0.7822	0.6989	-0.8736	-0.5517	**0.9902**	**-0.9427**	**1**												
H/C	**-0.9622**	0.7746	0.6928	-0.8712	-0.5538	**0.9870**	**-0.9546**	**0.9992**	**1**											
Aromatics	**0.9508**	-0.7939	-0.7264	0.8307	0.4929	**-0.9573**	0.8944	**-0.9419**	**-0.9387**	**1**										
Olefins	0.6097	-0.5828	-0.4909	0.5428	0.5241	-0.6061	0.4599	-0.5877	-0.5747	0.5986	**1**									
Saturates	**-0.9503**	0.8041	0.7296	-0.8318	-0.5225	**0.9557**	-0.8776	**0.9391**	**0.9343**	**-0.9933**	-0.6869	**1**								
Sulfur	0.4289	0.2197	0.1968	0.5023	0.5475	-0.3179	0.3343	-0.2701	-0.2778	0.2975	-0.0958	-0.2562	**1**							
Nitrogen	-0.1883	0.5572	0.6298	-0.2000	-0.0415	0.2509	-0.1849	0.2672	0.2602	-0.1703	-0.2398	0.1890	0.4113	**1**						
Flash	0.8347	-0.3348	-0.3164	0.8472	**0.9042**	-0.7211	0.7288	-0.6881	-0.6942	0.6892	0.6039	-0.7121	0.5360	-0.0873	**1**					
T10	0.8032	-0.2039	-0.1555	0.8480	**0.9588**	-0.6858	0.6893	-0.6549	-0.6610	0.6260	0.5607	-0.6486	0.6190	0.0021	**0.9694**	**1**				
T50	0.6252	0.0193	0.0556	0.7931	**0.9675**	-0.5310	0.4712	-0.4875	-0.4880	0.3970	0.3576	-0.4116	0.5577	-0.0608	0.8046	0.8808	**1**			
T90	0.6509	-0.0675	-0.0148	0.8235	**0.9140**	-0.5875	0.5068	-0.5498	-0.5484	0.4407	0.3587	-0.4514	0.4885	-0.1423	0.7255	0.8128	**0.9656**	**1**		
T90-10	0.4542	0.0226	0.0691	0.6719	0.7356	-0.4326	0.3167	-0.3974	-0.3918	0.2600	0.1820	-0.2620	0.3315	-0.2021	0.4634	0.5689	0.8536	**0.9415**	**1**	
HFRR	-0.7351	0.3053	0.2438	-0.7670	-0.7979	0.7104	-0.7396	0.7332	0.7418	-0.5383	-0.4963	0.5598	-0.2982	0.2369	-0.7317	-0.7798	-0.7827	-0.8044	-0.6845	**1**

11.1 CAT C7 ENGINE RESPONSE TO FUEL VARIABLES

11.1.1 CAT C7 Emissions, Peak Power, and Idle

Data from Table 8 are the weighted average regulated gaseous emission response, peak power produced, and idle combustion parameter relationships with fuel properties for the CAT C7 engine. The Table 8 highlighted values represent +/-0.80 or greater correlation coefficients. The weighted average emission values use the European Stationary Cycle (ESC) weighting factors for the calculation. The emissions data for the CAT C7 engine indicate that CO emissions are the only species whose response are impacted significantly by the fuel properties. The CO emission response increase as fuel density increases, fuel bulk modulus increases, carbon content and aromatic content increase. The CO emission response decrease as CN increases, Net Heat of Combustion (NHofC) increases, hydrogen content, H/C, and saturate content increase. The NHofC, aromatics, and saturates have the greatest impact on the CAT C7 engine weighted average CO emissions.

The CAT C7 engine Peak Power fuel property correlation data from Table 8 indicate density, BM, carbon content, aromatics, flashpoint, and T10 distillation temperature all reveal peak power increases with fuel property value increases. Antagonistic fuel property effects on CAT C7 engine power are NHofC, hydrogen content, H/C, and saturates content. One would expect peak power to increase with fuel heating value, the heating value units for this data set are MJ/kg (energy/unit mass), whereas power is more likely a function of the energy/unit-volume of the fuel due to fuel injection systems injecting on a volume basis. In addition as discussed previously the CAT C7 engine appears to have a NOx control strategy that alters combustion phasing to control NOx emissions that may impact peak power.

Included in Table 8 are selected combustion parameters for the ESC idle mode for the CAT C7 engine. The combustion parameter peak pressure in units of bar, is indicative of the piston loadings at idle for the slate of test fuels. There were not any significant fuel property correlations for the CAT C7 cylinder pressure at idle. The Location of Peak Pressure (LPP) with respect to engine Top Dead Center (TDC) has impacts on engine efficiency and idle roughness. A reasonable correlation exists for an advancing of LPP timing at idle with the fuel properties of CN, DCN, NHofC, and saturates. As the fuel CN increase the fuel becomes more reactive, and combustion occurs closer to TDC. The data also suggest that as fuel aromatic content increase the LPP timing retards from TDC.

The parameter Maximum Heat Release Rate (MHRR) in Joules/° from Table 8 indicate the level of premixed combustion that has been associated with knock, piston shock loading, and increased NOx emissions. At an idle mode the combustion in the engine is barely overcoming friction to keep the engine running, the heat release rate effects are muted. At the CAT C7 engine idle mode there is not any correlation of fuel properties with MHRR. The combustion parameter 50 Percent Mass Fraction Burned Angle (50MFB) attempts to condense the engine heat release profile curve into a single quantitative value. It is the crank angle with respect to engine TDC at which 50-percent of the energy released by the combustion event has occurred. A slight correlation exists for an advancing of 50MFB timing at idle with the fuel property CN.

Table 8. Fuel Property effects on CAT C7 Weighted Average Emissions, Peak Power, and Mode 1 Combustion

			Weighted Average Emissions, Peak Power, and Idle Combustion - Fuel Property Correlation Coefficients for Caterpillar C7 Engine																		
	Units	*Engine Condition*	*Density*	*CN*	*DCN*	*BM*	*Kvis*	*NHofC*	*C*	*H*	*H/C*	*Aromatics*	*Olefins*	*Saturates*	*Sulfur*	*Nitrogen*	*Flash*	*T10*	*T50*	*T90*	*T90-10*
HC	*gr/hp-hr*	*13-Mode Weighted Average*	0.4839	-0.7299	-0.6024	0.3631	-0.0033	-0.5951	0.3722	-0.5901	-0.5663	0.6508	0.5147	-0.6644	-0.2186	-0.3062	0.0640	0.0345	-0.0272	0.1084	0.1331
CO	*gr/hp-hr*	*13-Mode Weighted Average*	**0.8980**	**-0.8490**	-0.7698	**0.8124**	0.5011	**-0.9278**	**0.8102**	**-0.9114**	**-0.9021**	**0.9337**	0.6697	**-0.9434**	0.1058	-0.4241	0.6372	0.5741	0.4339	0.5037	0.3790
NOx	*gr/hp-hr*	*13-Mode Weighted Average*	-0.4996	0.4489	0.4299	-0.4862	-0.4343	0.4994	-0.4616	0.5040	0.5023	-0.4189	-0.3170	0.4256	-0.0938	0.5956	-0.4924	-0.4329	-0.4634	-0.4666	-0.4083
Power	*BHP*	*Rated*	**0.9706**	-0.6072	-0.5837	**0.9775**	0.7778	**-0.9349**	**0.8669**	**-0.9026**	**-0.9017**	**0.8757**	0.5616	**-0.8752**	0.4890	-0.2463	**0.8807**	**0.8448**	0.7199	0.7256	0.5356
Mode 1 Peak Pressure	*bar*	*IDLE, 700-RPM*	-0.0431	0.5748	0.5371	0.1635	0.4149	0.0986	-0.0163	0.0852	0.0721	-0.2890	-0.3391	0.3110	0.4609	0.2328	0.1839	0.3027	0.5432	0.4887	0.5149
Mode 1 Location of Peak Pressure	*°ATDC*	*IDLE, 700-RPM*	0.7814	**-0.8770**	**-0.8128**	0.7016	0.3844	**-0.8234**	0.6654	-0.7891	-0.7759	**0.8268**	0.7619	**-0.8597**	0.0106	-0.4150	0.5568	0.4640	0.2718	0.3245	0.1896
Mode 1 Maximun Heat Release Rate	*J/°*	*IDLE, 700-RPM*	0.2519	-0.2927	-0.4671	0.2570	0.1211	-0.2441	0.3556	-0.2301	-0.2451	0.1986	-0.0170	-0.1777	0.0712	-0.2799	0.3190	0.1690	0.0816	-0.0031	-0.1022
Mode 1 50 Percent Mass Fraction Burn Angle	*°ATDC*	*IDLE, 700-RPM*	0.4132	**-0.8028**	-0.7170	0.2534	-0.1240	-0.5168	0.3020	-0.5107	-0.4867	0.5958	0.5337	-0.6173	-0.3189	-0.4033	0.0313	-0.0479	-0.1935	-0.0880	-0.0965

11.1.2 CAT C7 Engine ESC A-Speed Modal Response to Fuel Variables

The European Stationary Cycle (ESC) includes an idle mode previously discussed, and four load conditions (100%, 75%, 50% 25%) at three engine speeds. The three engine speeds are calculated based on a formula that takes into consideration the power and the speed at the rated condition. For the CAT C7 engine the ESC A-Speed of 1602 rpm is close to the peak torque speed of 1440 rpm, and the torque curve in the 1400-1600 rpm speed range is fairly flat. Mode 2 is 100%, Mode 6 is 75%, Mode 5 is 50%, and Mode 7 is 25% loads respectively.

The A-Speed combustion correlations with fuel properties are shown in Table 9 for the CAT C7 engine. The Table 9 highlighted values represent +/-0.80 or greater correlation coefficients. Mode 2 (100% load) peak cylinder pressure shows increasing cylinder pressure with increases values in fuel density, BM, Kinematic Viscosity (KVis), flashpoint, and T10, T50, and T90 distillation temperatures. The fuel BM followed by the T90 point showed the most significant fuel property effect on peak pressure. The Mode 2 LPP advances towards TDC with increasing NHofC and increasing fuel hydrogen content. There are not any fuel properties that show a significant relationship to either the MHRR or the 50MFB angle for Mode 2 for the CAT C7 engine.

Mode 6 (75% load), Table 9, peak cylinder pressure shows increasing cylinder pressure with increases in values of BM, KVis, flashpoint, and T10, T50, and T90 distillation temperatures. The T10 point followed by the BM showed the most significant fuel property effect on peak cylinder pressure. The Mode 6 LPP advances towards TDC with increasing fuel saturates content. There are not any fuel properties that show a significant relationship to either the MHRR or the 50MFB angle for Mode 6 for the CAT C7 engine.

Mode 5 (50% load), Table 9 peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel sulfur. The fuel sulfur effect on peak pressure is likely a reflection on how some of the test fuels were processed. The Mode 5 LPP advances towards TDC with increasing fuel CN, a result that was initially anticipated for all modes due to increasing fuel reactivity with increasing CN. There are not any fuel properties that show a significant relationship with the MHRR. The 50MFB angle for Mode 5 with the CAT C7 engine advances towards TDC with increasing CN and DCN values.

There are not any fuel properties that show a significant relationship to peak cylinder pressure for CAT C7 Mode 7 (25% load), Table 9. The Mode 7 LPP advances towards TDC with increases in the following fuel properties: CN, NHofC, hydrogen content, H/C, and saturates content. The LPP retards with increasing fuel aromatic content. The saturates, aromatics, followed by CN have the most significant effects on LPP. There are not any fuel properties that show a significant relationship with either the MHRR or the 50MFB angle for Mode 7 with the CAT C7 engine.

For the ESC A-Speed with the CAT C7 engine, the combustion parameters of peak pressure and LPP, at high loads (100%, 75%) appeared to be impacted mostly by fuel bulk modulus and fuel distillation. At lower loads (50%, 25%) the combustion was impacted mostly by cetane number and fuel structure.

Table 9. CAT C7 European Stationary Cycle A-Speed fuel property effects on Modal Combustion Variables

	Units	Engine Condition	European Stationary Cycle A Speed (1602-RPM) Modal Combustion Fuel Property Correlation Coefficients for Caterpillar C7 Engine																		
			Density	CN	DCN	BM	Kvis	NHofC	C	H	H/C	Aromatics	Olefins	Saturates	Sulfur	Nitrogen	Flash	T10	T50	T90	T90-10
Mode 2 Peak Pressure	bar	100% LOAD	**0.8417**	-0.2656	-0.2134	**0.9215**	**0.8808**	-0.7871	0.7470	-0.7726	-0.7751	0.6664	0.4001	-0.6621	0.6117	-0.0958	**0.8251**	**0.8820**	**0.8913**	**0.9089**	0.7729
Mode 2 Location of Peak Pressure	°ATDC	100% LOAD	0.7881	-0.7918	-0.7282	0.7559	0.4380	**-0.8128**	0.7049	**-0.8031**	-0.7951	0.7789	0.5505	-0.7859	0.1675	-0.4401	0.6196	0.5291	0.3873	0.4148	0.2794
Mode 2 Maximun Heat Release Rate	J/°	100% LOAD	-0.2165	-0.2474	-0.2045	-0.2959	-0.3727	0.1386	-0.1427	0.0662	0.0717	-0.1086	0.2146	0.0677	-0.7000	-0.3854	-0.3373	-0.3821	-0.3982	-0.2601	-0.1461
Mode 2 50 Percent Mass Fraction Burn Angle	°ATDC	100% LOAD	0.3354	-0.5132	-0.4898	0.0864	0.0075	-0.3155	0.4066	-0.3263	-0.3322	0.4934	0.4202	-0.5081	-0.2525	-0.1772	0.2476	0.1384	-0.1440	-0.1542	-0.2977
Mode 6 Peak Pressure	bar	75% LOAD	0.7888	-0.1118	-0.0887	**0.8458**	**0.8850**	-0.6821	0.7135	-0.6554	-0.6651	0.6151	0.3030	-0.6016	0.7867	0.1114	**0.8763**	**0.9325**	**0.8588**	**0.8129**	0.6082
Mode 6 Location of Peak Pressure	°ATDC	75% LOAD	0.7034	-0.7743	-0.7303	0.5573	0.2985	-0.7314	0.6004	-0.6997	-0.6878	0.7963	0.6574	**-0.8170**	0.0464	-0.3966	0.4511	0.3895	0.1898	0.2462	0.1222
Mode 6 Maximun Heat Release Rate	J/°	75% LOAD	0.0083	-0.0031	0.0133	-0.0969	0.0783	0.0675	0.0417	0.0735	0.0647	0.0706	0.3570	-0.1154	-0.1544	0.1031	0.1199	0.1390	-0.0958	-0.1076	-0.2323
Mode 6 50 Percent Mass Fraction Burn Angle	°ATDC	75% LOAD	0.2534	-0.3397	-0.3257	0.0341	-0.0985	-0.2585	0.3289	-0.2547	-0.2600	0.4028	0.2136	-0.3961	-0.0079	0.1248	0.0702	0.0499	-0.2424	-0.2695	-0.4094
Mode 5 Peak Pressure	bar	50% LOAD	0.5682	0.1381	0.1245	0.6665	0.7178	-0.4752	0.5154	-0.4536	-0.4647	0.3762	0.0101	-0.3428	**0.8776**	0.2855	0.6624	0.7424	0.7497	0.7023	0.5620
Mode 5 Location of Peak Pressure	°ATDC	50% LOAD	0.5789	**-0.8672**	-0.7974	0.4525	0.0487	-0.6899	0.5255	-0.6828	-0.6660	0.7380	0.5860	-0.7538	-0.2747	-0.4443	0.1772	0.0992	-0.0105	0.1160	0.1064
Mode 5 Maximun Heat Release Rate	J/°	50% LOAD	-0.7216	0.3043	0.1477	-0.7212	-0.6364	0.6939	-0.5688	0.6651	0.6552	-0.6822	-0.3643	0.6713	-0.4350	-0.0455	-0.5796	-0.6441	-0.6612	-0.6919	-0.6041
Mode 5 50 Percent Mass Fraction Burn Angle	°ATDC	50% LOAD	0.5695	**-0.8749**	**-0.8611**	0.4018	-0.0120	-0.6695	0.5912	-0.6889	-0.6805	0.7163	0.4533	-0.7150	-0.1847	-0.4641	0.2395	0.1047	-0.0743	-0.0302	-0.1032
Mode 7 Peak Pressure	bar	25% LOAD	-0.3808	0.7694	0.6864	-0.2399	-0.0403	0.4519	-0.3660	0.4606	0.4495	-0.5112	-0.6831	0.5620	0.5059	0.5467	-0.1740	-0.0905	0.0782	0.0217	0.0829
Mode 7 Location of Peak Pressure	°ATDC	25% LOAD	0.7930	**-0.8619**	-0.7607	0.6930	0.3721	**-0.8395**	0.7017	**-0.8232**	**-0.8104**	**0.8765**	0.6925	**-0.8948**	-0.0486	-0.4200	0.5063	0.4393	0.2958	0.3831	0.2867
Mode 7 Maximun Heat Release Rate	J/°	25% LOAD	0.4227	-0.7235	-0.6668	0.2785	0.0861	-0.4358	0.5318	-0.4630	-0.4710	0.5119	0.4948	-0.5355	-0.4047	-0.4248	0.3375	0.1926	-0.0465	-0.0334	-0.1586
Mode 7 50 Percent Mass Fraction Burn Angle	°ATDC	25% LOAD	-0.3048	-0.1398	-0.0437	-0.3992	-0.5756	0.1830	-0.3216	0.1754	0.1945	-0.0752	-0.0310	0.0727	-0.5373	-0.0143	-0.6163	-0.6171	-0.5291	-0.3907	-0.1945

11.1.3 CAT C7 Engine ESC B-Speed Modal Response to Fuel Variables

The ESC includes an idle mode previously discussed, and four load conditions (100%, 75%, 50% 25%) at three engine speeds. For the CAT C7 engine the ESC B-Speed of 1991 rpm represents an intermediate speed between peak torque and peak power. Mode 8, Mode 4, Mode 3, and Mode 9 are the 100%, 75%, 50%, and 25% loads respectively.

The B-Speed combustion correlations with fuel properties are shown in Table 10 for the CAT C7 engine. The Table 10 highlighted values represent +/-0.80 or greater correlation coefficients. Mode 8 (100% load) does not show any significant correlation of fuel properties with any of the combustion parameters of peak cylinder pressure, LPP, the MHRR, and the 50MFB angle for the CAT C7 engine.

Mode 4 (75% load), Table 10, peak cylinder pressure shows increasing cylinder pressure with increases in values of KVis, sulfur, and T10, T50, and T90 distillation temperatures. The T10 and T50 points followed by the KVis showed the most significant fuel property effect on peak cylinder pressure increase. Fuel properties that show a significant relationship to advancing the Mode 4 LPP are NHofC, hydrogen content, H/C, and saturates content. Fuel properties that retard the LPP are fuel density, bulk modulus, and aromatics content. The MHRR did not reveal any significant fuel property effects. Fuel properties that advance the Mode 4 50MFB angle are NHofC, hydrogen content, H/C, and saturates content. Fuel properties that retard the 50MFB angle are fuel density, BM, carbon content, and aromatics content. From the fuel cross-correlation, Table 10, it is seen that NHofC correlates strongly with H, C, and fuel structure properties; this fuel property cross-correlation may affect the CAT C7 combustion variables correlations.

Mode 3 (50% load), Table 10, peak cylinder pressure does not show a strong correlation with any fuel property. The fuel sulfur effect on peak pressure is likely a reflection on how some of the test fuels were processed. The Mode 3 LPP advances towards TDC with increasing fuel CN, DCN, NHofC, and saturates content. The LPP retards from TDC due to the effects of fuel aromatics content. Fuel properties that show a significant relationship with the MHRR are the

T50 and T90 distillation temperatures and the T90-10 distillation range. The Mode 3 MHRR increases with decreasing distillation values, or higher volatility fuels. The 50MFB angle for Mode 3 with the CAT C7 engine does not show a strong correlation with any fuel property.

There are not any fuel properties that show a significant relationship to peak cylinder pressure for the CAT C7 engine operating at Mode 9 (25% load), Table 10. The Mode 9 LPP advances towards TDC with increases in the following fuel properties: CN, DCN, NHofC, hydrogen content, H/C, and saturates content. The LPP retards with increasing fuel aromatics content. The saturates, aromatics, followed by CN have the most significant effects on the LPP. There are not any fuel properties that show a significant relationship with either the MHRR or the 50MFB angle for Mode 9 with the CAT C7 engine.

For the ESC B-Speed with the CAT C7 engine, the combustion parameters were not affected by fuel property variations at full load. At an intermediate load the combustion was affected by density, BM, NHofC, fuel structure and distillation. At lower loads (50%, 25%) the combustion was impacted mostly by CN, fuel structure, and distillation, with distillation not being important at the lightest load.

Table 10. CAT C7 European Stationary Cycle B-Speed fuel property effects on Modal Combustion Variables

			European Stationary Cycle B Speed (1991-RPM) Modal Combustion - Fuel Property Correlation Coefficients for Caterpillar C7 Engine																		
	Units	Engine Condition	Density	CN	DCN	BM	Kvis	NHofC	C	H	H/C	Aromatics	Olefins	Saturates	Sulfur	Nitrogen	Flash	T10	T50	T90	T90-10
Mode 8 Peak Pressure	bar	100% LOAD	0.4572	0.1946	0.1553	0.6113	0.7665	-0.3349	0.3503	-0.2969	-0.3050	0.2386	0.1391	-0.2365	0.7295	0.2480	0.7235	0.7636	0.7591	0.6574	0.4863
Mode 8 Location of Peak Pressure	°ATDC	100% LOAD	-0.6126	0.0981	0.0108	-0.6347	-0.7319	0.5583	-0.5462	0.5335	0.5362	-0.5212	-0.4372	0.5357	-0.3232	-0.1206	-0.5909	-0.6957	-0.6945	-0.7058	-0.5939
Mode 8 Maximun Heat Release Rate	J/°	100% LOAD	-0.5895	0.0701	0.1128	-0.6592	-0.5995	0.5421	-0.5564	0.5010	0.5094	-0.4484	0.0582	0.3985	-0.7367	-0.0487	-0.5872	-0.6103	-0.6600	-0.6025	-0.4975
Mode 8 50 Percent Mass Fraction Burn Angle	°ATDC	100% LOAD	0.7227	-0.5639	-0.4461	0.6624	0.5498	-0.7511	0.6788	-0.7564	-0.7510	0.7081	0.6133	-0.7307	-0.0382	-0.3313	0.5041	0.5339	0.5164	0.6001	0.5383
Mode 4 Peak Pressure	bar	75% LOAD	0.7070	0.0067	0.0291	0.7924	**0.8542**	-0.6060	0.6263	-0.5810	-0.5898	0.5238	0.2078	-0.5051	**0.8120**	0.1657	0.7906	**0.8722**	**0.8637**	**0.8364**	0.6761
Mode 4 Location of Peak Pressure	°ATDC	75% LOAD	**0.8849**	-0.7853	-0.6959	**0.8335**	0.5684	**-0.9040**	0.7922	**-0.8958**	**-0.8872**	**0.8858**	0.6950	**-0.9036**	0.0852	-0.3480	0.7025	0.6273	0.5062	0.5516	0.4158
Mode 4 Maximun Heat Release Rate	J/°	75% LOAD	0.6850	-0.7205	-0.7096	0.5977	0.3657	-0.6625	0.6735	-0.6644	-0.6669	0.6971	0.5765	-0.7153	-0.0657	-0.3872	0.5777	0.4706	0.2302	0.2806	0.1239
Mode 4 50 Percent Mass Fraction Burn Angle	°ATDC	75% LOAD	**0.8865**	-0.7854	-0.7376	**0.8638**	0.6041	**-0.8983**	**0.8129**	**-0.8924**	**-0.8876**	**0.8242**	0.5933	**-0.8331**	0.1493	-0.5586	0.7196	0.6528	0.5647	0.6215	0.4997
Mode 3 Peak Pressure	bar	50% LOAD	0.3751	0.3604	0.3869	0.4776	0.6805	-0.2635	0.3669	-0.2632	-0.2791	0.1788	-0.0427	-0.1561	0.7798	0.3729	0.5421	0.6758	0.7195	0.6845	0.5753
Mode 3 Location of Peak Pressure	°ATDC	50% LOAD	0.7456	**-0.9003**	**-0.8127**	0.6632	0.3036	**-0.8055**	0.6670	-0.7919	-0.7789	**0.8287**	0.6396	**-0.8438**	-0.1276	-0.4846	0.4668	0.3662	0.2410	0.3187	0.2381
Mode 3 Maximun Heat Release Rate	J/°	50% LOAD	-0.5835	0.0362	-0.0721	-0.7248	-0.8000	0.5545	-0.4073	0.5088	0.4994	-0.4436	-0.3620	0.4545	-0.4684	-0.0339	-0.5788	-0.6970	**-0.8631**	**-0.8793**	**-0.8381**
Mode 3 50 Percent Mass Fraction Burn Angle	°ATDC	50% LOAD	-0.4436	-0.3073	-0.3400	-0.5724	-0.7959	0.3110	-0.3317	0.2553	0.2639	-0.2584	-0.1808	0.2604	-0.7873	-0.4690	-0.6537	-0.7798	-0.7681	-0.7012	-0.5388
Mode 9 Peak Pressure	bar	25% LOAD	-0.5037	0.3956	0.4591	-0.5121	-0.5340	0.4542	-0.4946	0.4478	0.4560	-0.3406	-0.4620	0.3755	-0.1140	0.3950	-0.6767	-0.5822	-0.4302	-0.3235	-0.1199
Mode 9 Location of Peak Pressure	°ATDC	25% LOAD	0.7994	**-0.8882**	**-0.8038**	0.6832	0.3328	**-0.8499**	0.6957	**-0.8285**	**-0.8140**	**0.8950**	0.6868	**-0.9108**	-0.0208	-0.3957	0.4960	0.4198	0.2437	0.3116	0.1971
Mode 9 Maximun Heat Release Rate	J/°	25% LOAD	0.3682	-0.4808	-0.5398	0.2816	0.2431	-0.3035	0.3818	-0.2849	-0.2941	0.3460	0.4882	-0.3841	-0.0205	-0.2908	0.5193	0.3766	0.0505	-0.0511	-0.2900
Mode 9 50 Percent Mass Fraction Burn Angle	°ATDC	25% LOAD	0.1622	-0.5495	-0.4214	0.0450	-0.2099	-0.2623	0.0906	-0.2537	-0.2327	0.3765	0.3952	-0.3984	-0.4488	-0.2426	-0.1550	-0.1987	-0.2387	-0.1248	-0.0613

11.1.4 CAT C7 Engine ESC C-Speed Modal Response to Fuel Variables

The ESC includes an idle mode previously discussed, and four load conditions (100%, 75%, 50% 25%) at three engine speeds. For the CAT C7 engine the ESC C-Speed of 2380 rpm is close to the rated power speed of 2400 rpm. Mode 10 is 100%, Mode 12 is 75%, Mode 13 is 50%, and Mode 11 is 25% loads respectively.

The C-Speed combustion correlations with fuel properties are shown in Table 11 for the CAT C7 engine. The Table 11 highlighted values represent +/-0.80 or greater correlation coefficients. Mode 10 (100% load), the mode closest to engine rated power, the peak cylinder pressure does not show any significant fuel property correlations. The Mode 10 LPP advances towards TDC with increasing BM, KVis, flashpoint, and T10, T50, and T90 distillation temperatures. The KVis and T10 revealed the most significant effect on LPP. There are not any fuel properties that show a significant relationship to the MHRR. Fuel properties that advance the 50MFB angle towards TDC are NHofC, hydrogen content, H/C, and saturates content. Fuel properties that retard the 50MFB angle are fuel density, BM, carbon content, aromatics content, flashpoint and T10 distillation temperature. The fuel density and saturates content have the largest effect on 50MFB for Mode 10 with the CAT C7 engine.

Mode 12 (75% load), Table 11, peak cylinder pressure does not reveal any significant correlation with fuel properties. There are not any fuel properties that show a significant relationship to either the LPP, MHRR, or 50MFB angle for Mode 12 for the CAT C7 engine.

Mode 13 (50% load), Table 11, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel sulfur. The fuel sulfur effect on peak pressure is likely a reflection on how some of the test fuels were processed. The Mode 13 LPP advances towards TDC with increases in the following fuel properties: NHofC, hydrogen content, H/C, and saturates content. The LPP retards from TDC with increasing fuel density and fuel aromatics content. The saturates, aromatics, followed by NHofC are the fuel properties that have the most significant effects on the LPP. There are not any fuel properties that show a significant relationship with either the MHRR or the 50MFB angle for Mode 13 with the CAT C7 engine.

Mode 11 (25% load), Table 11, peak cylinder pressure does not reveal any significant correlation with fuel properties. The Mode 11 LPP advances towards TDC with increases in the following fuel properties: CN, NHofC, hydrogen content, H/C, and saturates content. The LPP retards from TDC with increasing fuel density and fuel aromatics content. The saturates, aromatics, followed by CN have the most significant effects on the LPP. There are not any fuel properties that show a significant relationship to either the MHRR or 50MFB angle for Mode 11 operation of the CAT C7 engine.

For the ESC C-Speed with the CAT C7 engine, the combustion parameter peak pressure does not appear to be influenced by fuel properties. BM, KVis and fuel distillation effect the LPP and 50MFB, at peak load. At lower loads (50%, 25%) the combustion timing as indicated by LPP and were impacted mostly by fuel density, CN, NHofC, and fuel structure.

Table 11. CAT C7 European Stationary Cycle C-Speed fuel property effects on Modal Combustion Variables

	Units	Engine Condition	European Stationary Cycle C Speed (2380-RPM) Modal Combustion - Fuel Property Correlation Coefficients for Caterpillar C7 Engine																		
			Density	*CN*	*DCN*	*BM*	*Kvis*	*NHofC*	*C*	*H*	*H/C*	*Aromatics*	*Olefins*	*Saturates*	*Sulfur*	*Nitrogen*	*Flash*	*T10*	*T50*	*T90*	*T90-10*
Mode 10 Peak Pressure	*bar*	*100% LOAD*	-0.2395	0.6317	0.5240	0.0121	0.2282	0.3127	-0.3104	0.3461	0.3410	-0.4496	-0.4128	0.4673	0.4973	0.2362	0.0580	0.1260	0.3362	0.2806	0.3233
Mode 10 Location of Peak Pressure	*°ATDC*		-0.7987	0.1848	0.1093	**-0.8560**	**-0.9496**	0.6980	-0.6700	0.6620	0.6647	-0.6464	-0.5437	0.6646	-0.5314	-0.0721	**-0.9077**	**-0.9474**	**-0.9026**	**-0.8660**	-0.6745
Mode 10 Maximun Heat Release Rate	*J/°*		0.1133	-0.1381	-0.1044	0.0383	0.0718	-0.0633	0.1984	-0.1030	-0.1146	0.1551	0.3145	-0.1859	-0.1665	-0.0287	0.1457	0.1552	-0.0660	-0.0146	-0.1104
Mode 10 50 Percent Mass Fraction Burn Angle	*°ATDC*		**0.8991**	-0.4962	-0.3845	**0.8554**	0.7841	**-0.8571**	**0.8201**	**-0.8439**	**-0.8438**	**0.8420**	0.6534	**-0.8579**	0.3444	-0.0950	**0.8062**	**0.8350**	0.7075	0.7145	0.5256
Mode 12 Peak Pressure	*bar*	*75% LOAD*	-0.4696	0.6254	0.4881	-0.3857	-0.1105	0.5917	-0.5648	0.6593	0.6570	-0.4807	-0.3469	0.4860	0.3027	0.4056	-0.1217	-0.1090	-0.1445	-0.2806	-0.3330
Mode 12 Location of Peak Pressure	*°ATDC*		-0.5377	0.3028	0.2165	-0.5489	-0.4325	0.5862	-0.6446	0.6551	0.6651	-0.3804	-0.1932	0.3729	-0.1437	0.2306	-0.3653	-0.4236	-0.4856	-0.5686	-0.5577
Mode 12 Maximun Heat Release Rate	*J/°*		-0.5408	0.2252	0.1901	-0.6898	-0.5619	0.5626	-0.5129	0.5808	0.5813	-0.3497	-0.1038	0.3322	-0.3329	0.2969	-0.4600	-0.5060	-0.6650	-0.7184	-0.7214
Mode 12 50 Percent Mass Fraction Burn Angle	*°ATDC*		0.3084	-0.3403	-0.2654	0.0834	-0.0135	-0.3557	0.4961	-0.4170	-0.4311	0.3420	0.2216	-0.3421	-0.0784	0.0616	0.1090	0.0926	-0.0883	-0.0695	-0.1516
Mode 13 Peak Pressure	*bar*	*50% LOAD*	0.3689	0.3467	0.3531	0.5162	0.7076	-0.2362	0.3293	-0.2210	-0.2360	0.1512	-0.0953	-0.1235	**0.8362**	0.2720	0.5912	0.7104	0.7486	0.6946	0.5697
Mode 13 Location of Peak Pressure	*°ATDC*		**0.8057**	-0.7867	-0.7069	0.7307	0.4457	**-0.8486**	0.7153	**-0.8248**	**-0.8134**	**0.8742**	0.6746	**-0.8901**	0.0030	-0.3866	0.5314	0.4835	0.3839	0.4721	0.3868
Mode 13 Maximun Heat Release Rate	*J/°*		-0.3767	-0.0611	-0.1765	-0.3942	-0.5768	0.3459	-0.2897	0.3201	0.3167	-0.3258	-0.3608	0.3474	-0.2206	-0.2531	-0.4199	-0.5032	-0.5871	-0.5429	-0.4754
Mode 13 50 Percent Mass Fraction Burn Angle	*°ATDC*		0.2217	-0.7162	-0.6445	0.1319	-0.2052	-0.3729	0.2450	-0.4072	-0.3920	0.3622	0.3883	-0.3844	-0.6200	-0.6076	-0.1449	-0.2232	-0.1980	-0.0387	0.0744
Mode 11 Peak Pressure	*bar*	*25% LOAD*	-0.3040	0.6324	0.7157	-0.1941	0.0275	0.3304	-0.2936	0.3166	0.3127	-0.3373	-0.2639	0.3440	0.2069	0.5166	-0.2441	-0.0637	0.1135	0.1772	0.2869
Mode 11 Location of Peak Pressure	*°ATDC*		**0.8061**	**-0.8692**	-0.7631	0.6917	0.3252	**-0.8672**	0.7351	**-0.8557**	**-0.8439**	**0.8885**	0.6153	**-0.8946**	0.0197	-0.3706	0.4691	0.4071	0.2646	0.3546	0.2651
Mode 11 Maximun Heat Release Rate	*J/°*		0.2876	-0.3643	-0.4482	0.2506	0.2526	-0.2164	0.1964	-0.1654	-0.1648	0.2679	0.4359	-0.3057	0.0516	-0.2294	0.5042	0.3459	0.0985	-0.0477	-0.2674
Mode 11 50 Percent Mass Fraction Burn Angle	*°ATDC*		0.1245	-0.6374	-0.5699	0.0063	-0.2952	-0.2331	0.0291	-0.2126	-0.1884	0.3399	0.3679	-0.3613	-0.5005	-0.3913	-0.1678	-0.2745	-0.3278	-0.2495	-0.1933

11.2 GENERAL ENGINE PRODUCTS (GEP) 6.5T ENGINE RESPONSE TO FUEL VARIABLES

11.2.1 GEP 6.5T Emissions, Peak Power, and Idle

Data from Table 12 are the weighted average regulated gaseous emission response, peak power produced, and idle combustion parameter relationships with fuel properties for the GEP 6.5T engine. The Table 12 highlighted values represent +/-0.80 or greater correlation coefficients. The weighted average emission values use the ESC weighting factors for the calculation. The emissions data for the GEP 6.5T engine indicate that all three regulated emission species, HC, CO, and NOx emissions responses are impacted significantly by the fuel properties. The HC emissions decrease for the GEP 6.5T engine with increasing values of the fuel properties BM, KVis, flashpoint, and the T10, T50, T90 distillation temperatures. The KVis and T10 have the greatest impact on the GEP 6.5T HC emissions. The CO emission response decreases as KVis increases, and the T10 and T50 temperatures increase, with KVis having the greatest impact. The NOx emission response increases as fuel density, BM, carbon content, and aromatics content increase. Increasing density and aromatics content have the greatest impact for increasing NOx emissions for the GEP engine. The GEP 6.5T weighted average NOx emission response decreases as NHofC increases, hydrogen content, H/C, and saturates contents increase. The NHofC and saturates have the greatest impact on lowering GEP 6.5T engine weighted average NOx emissions.

The GEP 6.5T engine Peak Power fuel property correlation data from Table 12 indicate density, BM, carbon content, aromatics, flashpoint, and T10 and T90 distillation temperatures all reveal peak power increases with fuel property value increases. Antagonistic fuel property effects on GEP 6.5T engine power are NHofC, hydrogen content, H/C, and saturates content. The GEP 6.5T engine has a mechanical fuel injection pump, in a Pump-Line-Nozzle (PLN) configuration. The fuel Bulk Modulus is a measure of fuel compressibility, and effects fuel injection dynamics. As the saturate content of a fuel increases, there are more highly branched molecule chains, the fuel is more compressible, and the bulk modulus would be lower. Fuel bulk modulus is anticipated to have the most impact on engines with PLN fuel injection systems, and for this fuel set it is the most significant fuel property effecting the peak power of the GEP 6.5T engine, followed by the fuel density.

Included in Table 12 are selected combustion parameters for the ESC idle mode for the GEP 6.5T engine. The combustion parameter peak pressure in units of bar, is indicative of the piston loadings at idle for the slate of test fuels. There exists fuel property correlations with BM, KVis, flashpoint, and T10, T50, T90 distillation temperatures for increasing the GEP 6.5T cylinder pressure at idle with increasing fuel property values. The Location of Peak Pressure (LPP) with respect to engine TDC has impacts on engine efficiency and idle roughness. Fuel property correlations do not exist for LPP timing at idle for the GEP 6.5T engine.

The parameter Maximum Heat Release Rate (MHRR) in Joules/° from Table 12 indicate the level of premixed combustion that has been associated with knock, piston shock loading, and increased NOx emissions. At an idle mode the combustion in the engine is barely overcoming friction to keep the engine running, the heat release rate effects are muted. At the GEP 6.5T engine idle mode there is not any correlation of fuel properties with MHRR. The combustion parameter 50 Percent Mass Fraction Burned Angle (50MFB) attempts to condense the engine heat release profile curve into a single quantitative value. It is the angle with respect to engine TDC at which 50-percent of the energy released by the combustion event has occurred. A slight correlations exists for an advancing of 50MFB timing towards TDC at idle with increasing values of the fuel properties KVis, T50, T90, and the T90-10 distillation range. Combustion closer to TDC should result in greater engine efficiency.

Table 12. Fuel Property effects on GEP 6.5T Weighted Average Emissions, Peak Power, and Mode 1 Combustion

			Weighted Average Emissions, Peak Power, and Idle Combustion - Fuel Property Correlation Coefficients for GEP 6.5LT Engine																		
	Units	***Engine Condition***	***Density***	***CN***	***DCN***	***BM***	***Kvis***	***NHofC***	***C***	***H***	***H/C***	***Aromatics***	***Olefins***	***Saturates***	***Sulfur***	***Nitrogen***	***Flash***	***T10***	***T50***	***T90***	***T90-10***
HC	***gr/hp-hr***	***13-Mode Weighted Average***	-0.7338	0.0717	0.0385	**-0.8175**	**-0.9073**	0.6364	-0.6791	0.6159	0.6265	-0.5357	-0.2987	0.5290	-0.6222	-0.0445	**-0.8259**	**-0.9018**	**-0.8973**	**-0.8670**	-0.7023
CO	***gr/hp-hr***		-0.5138	-0.1948	-0.1589	-0.6539	**-0.8591**	0.3776	-0.4463	0.3304	0.3445	-0.2830	-0.1352	0.2762	-0.6947	-0.1842	-0.7614	**-0.8261**	**-0.8507**	-0.7768	-0.6187
NOx	***gr/hp-hr***		**0.9551**	-0.7754	-0.7287	**0.8635**	0.5731	**-0.9497**	**0.8750**	**-0.9238**	**-0.9198**	**0.9681**	0.6141	**-0.9666**	0.3126	-0.2629	0.7431	0.6879	0.4757	0.4915	0.2960
Power	***BHP***	***Rated***	**0.9629**	-0.5300	-0.4534	**0.9715**	**0.8159**	**-0.9305**	**0.8833**	**-0.9167**	**-0.9176**	**0.8548**	0.5622	**-0.8563**	0.4629	-0.1615	**0.8481**	**0.8623**	0.7739	**0.8081**	0.6420
Mode 1 Peak Pressure	***bar***	***IDLE, 700-RPM***	0.7811	-0.2316	-0.2031	**0.8711**	**0.9541**	-0.6984	0.6947	-0.6688	-0.6745	0.6027	0.5046	-0.6194	0.4529	-0.1580	**0.8978**	**0.9260**	**0.9271**	**0.8954**	0.7283
Mode 1 Location of Peak Pressure	***°ATDC***		-0.2884	-0.0578	0.0316	-0.4412	-0.4961	0.2237	-0.3368	0.2314	0.2490	-0.0581	0.0716	0.0424	-0.3885	0.2240	-0.4708	-0.4590	-0.5502	-0.5613	-0.5269
Mode 1 Maximun Heat Release Rate	***J/°***		0.6415	-0.5280	-0.4821	0.6081	0.6105	-0.5697	0.5779	-0.5301	-0.5335	0.6057	0.7370	-0.6555	0.0348	-0.2532	0.7486	0.6667	0.4507	0.4139	0.1985
Mode 1 50 Percent Mass Fraction Burn Angle	***°ATDC***		-0.2774	-0.3103	-0.2720	-0.4949	**-0.8079**	0.1449	-0.2731	0.1618	0.1790	0.0469	-0.0008	-0.0405	-0.4660	0.2756	-0.5917	-0.6964	**-0.9060**	**-0.8869**	**-0.8222**

11.2.2 GEP 6.5T Engine ESC A-Speed Modal Response to Fuel Variables

The ESC includes an idle mode previously discussed, and four load conditions (100%, 75%, 50% 25%) at three engine speeds. The three engine speeds are calculated based on a formula that takes into consideration the power and the speed at the rated condition. For the GEP 6.5T engine the ESC A-Speed of 1928 rpm is close to the peak torque speed of 2100 rpm, as the torque curve in the 1900-2100 rpm speed range is fairly flat. Mode 2 is 100%, Mode 6 is 75%, Mode 5 is 50%, and Mode 7 is 25% loads respectively.

The A-Speed combustion correlations with fuel properties are shown in Table 13 for the GEP 6.5T engine. The Table 13 highlighted values represent +/-0.80 or greater correlation coefficients. Mode 2 peak cylinder pressure shows increasing cylinder pressure with increasing values of fuel density and BM. The peak pressure reveals a reduction with increases in NHofC, hydrogen content, and H/C. The fuel BM showed the most significant fuel property effect on peak pressure. The Mode 2 LPP advances towards TDC with increasing BM and increasing T90 distillation temperature. The GEP 6.5T engine has a PLN fuel injection system that is sensitive to BM effects, thus combustion advances as BM increases. There are not any fuel properties that show a significant relationship to either the MHRR or 50MFB angle for Mode 2 for the GEP 6.5T engine.

Mode 6 (75% load), Table 13, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density and bulk modulus. Peak cylinder pressures are reduced with increasing values of NHofC and hydrogen content for the GEP 6.5T engine. The fuel BM showed the most significant fuel property effect on peak cylinder pressure. There are not any fuel properties that show a significant relationship to either the LPP or the MHRR at Mode 6 for the GEP 6.5T engine. The location of the 50MFB advanced due to fuel density and BM increases, and retarded when NHofC increased for Mode 6.

Mode 5 (50% load), Table 13, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density and BM. Peak cylinder pressure at Mode 5 decreases with increasing values of NHofC, hydrogen content, H/C, and saturates content. The engine combustion response for the LPP, the MHRR, and the 50MFB angle with the GEP 6.5T engine do not reveal any significant fuel property correlations at Mode 5.

Mode 7 (25% load), Table 13, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, carbon content, and aromatics content. Peak cylinder pressure at Mode 5 decreases with increasing values of NHofC, hydrogen content, H/C, and saturates content. For Mode 7 the engine combustion response for LPP, the MHRR, and the 50MFB angle with the GEP 6.5T engine do not reveal any significant fuel property correlations.

For the ESC A-Speed with the GEP 6.5T engine, the combustion parameter peak pressure was impacted mostly by fuel density, BM, NHofC, and fuel structure at all A-Speed load conditions. The fuel bulk modulus was the single fuel property that had the greatest impact for the A-Speed combustion performance of the GEP 6.5T engine.

Table 13. GEP 6.5T European Stationary Cycle A-Speed fuel property effects on Modal Combustion Variables

	Units	Engine Condition	European Stationary Cycle A Speed (1928-RPM) Modal Combustion Fuel Property Correlation Coefficients for GEP 6.5LT Engine																		
			Density	CN	DCN	BM	Kvis	NHofC	C	H	H/C	Aromatics	Olefins	Saturates	Sulfur	Nitrogen	Flash	T10	T50	T90	T90-10
Mode 2 Peak Pressure	*bar*	*100% LOAD*	**0.8207**	-0.4634	-0.4384	**0.8989**	0.7468	**-0.8191**	0.7788	**-0.8200**	**-0.8223**	0.6505	0.4041	-0.6482	0.3581	-0.3384	0.7319	0.7388	0.7612	0.7944	0.6941
Mode 2 Location of Peak Pressure	*°ATDC*		-0.7390	0.2905	0.3219	**-0.8669**	-0.7642	0.6994	-0.6087	0.6634	0.6611	-0.5616	-0.2892	0.5511	-0.5119	0.2316	-0.7386	-0.7375	-0.7947	**-0.8022**	-0.7059
Mode 2 Maximun Heat Release Rate	*J/°*		0.5141	-0.5880	-0.5648	0.3877	0.2182	-0.5485	0.6731	-0.6154	-0.6289	0.5072	0.4145	-0.5197	-0.0782	-0.3390	0.4255	0.3346	0.1364	0.1244	-0.0180
Mode 2 50 Percent Mass Fraction Burn Angle	*°ATDC*		-0.6042	0.4919	0.6055	-0.6195	-0.4126	0.5728	-0.5753	0.5302	0.5346	-0.5983	-0.3263	0.5897	-0.2785	0.2795	-0.6075	-0.4918	-0.3326	-0.2993	-0.1380
Mode 6 Peak Pressure	*bar*	*75% LOAD*	**0.8201**	-0.5903	-0.6005	**0.8960**	0.6547	**-0.8436**	0.7223	**-0.8053**	-0.7998	0.7061	0.4633	-0.7073	0.2681	-0.3822	0.6669	0.6359	0.6479	0.6823	0.5953
Mode 6 Location of Peak Pressure	*°ATDC*		-0.5072	0.1753	0.2888	-0.6246	-0.5958	0.4423	-0.3419	0.3594	0.3558	-0.3656	-0.1891	0.3589	-0.4404	0.1587	-0.6424	-0.5584	-0.6031	-0.5370	-0.4351
Mode 6 Maximun Heat Release Rate	*J/°*		0.4931	-0.6796	-0.5990	0.3627	-0.0042	-0.6101	0.5208	-0.6701	-0.6611	0.5665	0.4487	-0.5784	-0.0764	-0.2869	0.1219	0.1051	-0.0511	0.0514	0.0118
Mode 6 50 Percent Mass Fraction Burn Angle	*°ATDC*		**-0.8165**	0.6401	0.6964	**-0.8355**	-0.5707	**0.8014**	-0.6893	0.7613	0.7549	-0.7669	-0.4737	0.7639	-0.3583	0.3771	-0.7413	-0.6367	-0.5232	-0.5184	-0.3636
Mode 5 Peak Pressure	*bar*	*50% LOAD*	**0.8656**	-0.6956	-0.6435	**0.8691**	0.6175	**-0.9017**	0.7382	**-0.8711**	**-0.8597**	0.7968	0.5988	**-0.8090**	0.2477	-0.3788	0.6617	0.6380	0.5872	0.6129	0.4961
Mode 5 Location of Peak Pressure	*°ATDC*		-0.5305	0.1550	0.2456	-0.5622	-0.6055	0.4203	-0.4601	0.3832	0.3922	-0.3639	-0.1858	0.3569	-0.5888	0.0954	-0.7592	-0.6873	-0.5469	-0.4062	-0.1759
Mode 5 Maximun Heat Release Rate	*J/°*		-0.0279	-0.1430	-0.1055	-0.0697	-0.4306	-0.0843	-0.0113	-0.0999	-0.0885	0.1163	-0.4526	-0.0404	0.0265	-0.0450	-0.4653	-0.4252	-0.2810	-0.1265	0.0674
Mode 5 50 Percent Mass Fraction Burn Angle	*°ATDC*		-0.7841	0.6721	0.6918	-0.7434	-0.5119	0.7721	-0.5974	0.7260	0.7121	-0.7613	-0.5820	0.7744	-0.3510	0.3667	-0.7035	-0.6017	-0.4399	-0.4102	-0.2310
Mode 7 Peak Pressure	*bar*	*25% LOAD*	**0.8900**	-0.6880	-0.6896	**0.8586**	0.6387	**-0.8693**	**0.8035**	**-0.8226**	**-0.8212**	**0.8391**	0.5817	**-0.8450**	0.3276	-0.3003	0.7871	0.7172	0.5419	0.5212	0.3209
Mode 7 Location of Peak Pressure	*°ATDC*		0.7291	-0.5762	-0.4399	0.5899	0.3928	-0.7493	0.7528	-0.7859	-0.7875	0.7460	0.5140	-0.7508	0.2074	-0.0391	0.5404	0.5173	0.3297	0.3570	0.2048
Mode 7 Maximun Heat Release Rate	*J/°*		0.6103	-0.7234	-0.5775	0.5192	0.2398	-0.6895	0.5001	-0.6718	-0.6530	0.7199	0.6620	-0.7483	-0.1365	-0.2810	0.2806	0.2675	0.1839	0.2871	0.2505
Mode 7 50 Percent Mass Fraction Burn Angle	*°ATDC*		0.0347	-0.2980	-0.1247	-0.0036	-0.2015	-0.1714	0.0302	-0.2009	-0.1840	0.1587	0.1760	-0.1693	-0.4558	-0.1747	-0.3531	-0.2772	-0.1371	0.0390	0.2155

11.2.3 GEP 6.5T Engine ESC B-Speed Modal Response to Fuel Variables

The ESC includes an idle mode previously discussed, and four load conditions (100%, 75%, 50% 25%) at three engine speeds. For the GEP 6.5T engine the ESC B-Speed of 2641 rpm represents an intermediate speed between peak torque and peak power. Mode 8 is 100%, Mode 4 is 75%, Mode 3 is 50%, and Mode 9 is 25% loads respectively.

The B-Speed combustion correlations with fuel properties are shown in Table 14 for the GEP 6.5T engine. The Table 14 highlighted values represent +/-0.80 or greater correlation coefficients. Mode 8 peak cylinder pressure shows increasing cylinder pressure with increases values of fuel density, BM, KVis, carbon content, aromatics, flashpoint, and T10, T50, and T90 distillation temperatures. The peak pressure reveals a reduction with increases in NHofC, hydrogen content, and H/C. The fuel BM showed the most significant fuel property effect on peak pressure, followed by fuel density. There were not any fuel properties that show a significant relationship to either the LPP, the MHRR, or the 50MFB angle for Mode 8 operation of the GEP 6.5T engine.

Mode 4 (75% load), Table 14, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, and aromatics content. Peak cylinder pressures are reduced with increasing values of NHofC, hydrogen content, and saturates content for the GEP 6.5T engine. The fuel density followed by the fuel BM showed the most significant fuel property effects on peak cylinder pressure. There are not any fuel properties that show a significant relationship to the LPP. The Mode 4 MHRR for the GEP 6.5T engine reveals an increase in MHRR with decreasing cetane number. The location of 50MFB advanced due to fuel density, BM, and aromatics content increases. The 50MFB angle retarded from TDC when NHofC, hydrogen content, H/C, and saturates content increased at Mode 4. The fuel density followed by aromatics content were the most significant fuel property effects on 50MFB angle.

Mode 3 (50% load), Table 14, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, bulk modulus, carbon content, and aromatics content. Peak cylinder pressure at Mode 3 decreases with increasing values of NHofC, hydrogen content, H/C, and saturates content. The engine combustion responses for LPP and the MHRR with the GEP 6.5T engine do not reveal any significant fuel property correlations at Mode 3. The location of 50MFB advanced due to fuel density, BM, aromatics content, and flashpoint increases. The 50MFB angle retarded from TDC when NHofC, hydrogen content, H/C, and saturates content increased at Mode 3. The fuel density, followed by NHofC, then BM, were the most significant fuel properties effecting the 50MFB angle at Mode 3.

Mode 9 (25% load), Table 14, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, and aromatics content. Peak cylinder pressure at Mode 9 decreases with increasing values of NHofC, hydrogen content, H/C, and saturates content. Fuel density was the most significant property effecting peak pressure. The Mode 9 combustion response for LPP with the GEP 6.5T engine do not reveal any significant fuel property correlations. The Mode 9 MHRR for the GEP 6.5T engine reveals an increase in MHRR when aromatics content increases or the saturates content decreases. The location of 50MFB advanced towards TDC due to flashpoint and T10 distillation temperature increases for Mode 9.

For the ESC B-Speed with the GEP 6.5T engine, the combustion parameter peak pressure was impacted mostly by fuel density, fuel BM, NHofC, and fuel structure at all B-Speed load conditions. The fuel density and fuel BM were the fuel properties that had the greatest impact on the B-Speed combustion performance for the GEP 6.5T engine.

Table 14. GEP 6.5T European Stationary Cycle B-Speed fuel property effects on Modal Combustion Variables

			European Stationary Cycle B Speed (2641-RPM) Modal Combustion - Fuel Property Correlation Coefficients for GEP 6.5LT Engine																		
	Units	*Engine Condition*	*Density*	*CN*	*DCN*	*BM*	*Kvis*	*NHofC*	*C*	*H*	*H/C*	*Aromatics*	*Olefins*	*Saturates*	*Sulfur*	*Nitrogen*	*Flash*	*T10*	*T50*	*T90*	*T90-10*
Mode 8 Peak Pressure	*bar*	*100% LOAD*	**0.9397**	-0.5232	-0.4516	**0.9740**	**0.8297**	**-0.9098**	**0.8316**	**-0.8834**	**-0.8812**	**0.8241**	0.5441	**-0.8259**	0.4262	-0.2133	**0.8419**	**0.8470**	**0.8074**	**0.8340**	0.6874
Mode 8 Location of Peak Pressure	*°ATDC*		0.6770	-0.6219	-0.4775	0.6211	0.4007	-0.6815	0.5760	-0.6804	-0.6702	0.7233	0.5448	-0.7345	0.1828	-0.2420	0.5188	0.4994	0.3474	0.3774	0.2439
Mode 8 Maximun Heat Release Rate	*J/°*		0.5755	-0.7209	-0.5815	0.4576	0.1237	-0.6740	0.5063	-0.6758	-0.6583	0.7095	0.5215	-0.7187	-0.1401	-0.2945	0.1729	0.1647	0.0991	0.2256	0.2232
Mode 8 50 Percent Mass Fraction Burn Angle	*°ATDC*		-0.5952	0.6580	0.6886	-0.4481	-0.1319	0.5885	-0.6092	0.5606	0.5638	-0.7276	-0.3893	0.7161	-0.1365	0.0558	-0.4557	-0.3014	0.0038	0.0103	0.1889
Mode 4 Peak Pressure	*bar*	*75% LOAD*	**0.9280**	-0.6561	-0.6424	**0.9237**	0.6804	**-0.9087**	0.7861	**-0.8561**	**-0.8492**	**0.8771**	0.5778	**-0.8788**	0.3731	-0.2389	0.7887	0.7319	0.6150	0.6323	0.4692
Mode 4 Location of Peak Pressure	*°ATDC*		0.7203	-0.6182	-0.5978	0.6529	0.4962	-0.6680	0.7374	-0.6633	-0.6719	0.7030	0.4101	-0.6968	0.1385	-0.3029	0.7250	0.6134	0.4004	0.3287	0.1092
Mode 4 Maximun Heat Release Rate	*J/°*		0.6426	**-0.8118**	-0.6736	0.5086	0.1509	-0.7357	0.5830	-0.7465	-0.7306	0.7639	0.5621	-0.7739	-0.1321	-0.3881	0.2435	0.2189	0.1112	0.2299	0.1979
Mode 4 50 Percent Mass Fraction Burn Angle	*°ATDC*		**-0.9056**	0.7231	0.7239	**-0.8599**	-0.5721	**0.8836**	-0.7935	**0.8445**	**0.8396**	**-0.8960**	-0.5737	**0.8954**	-0.3379	0.2406	-0.7804	-0.6766	-0.4815	-0.4857	-0.2942
Mode 3 Peak Pressure	*bar*	*50% LOAD*	**0.9352**	-0.7264	-0.6735	**0.9260**	0.6671	**-0.9460**	**0.8084**	**-0.9205**	**-0.9115**	**0.8716**	0.6478	**-0.8840**	0.2811	-0.3441	0.7589	0.7163	0.6130	0.6442	0.4951
Mode 3 Location of Peak Pressure	*°ATDC*		0.1431	-0.0815	-0.1013	0.1198	-0.0145	-0.1250	0.0877	-0.0914	-0.0892	0.1258	-0.2419	-0.0794	0.4094	-0.0967	0.0090	0.0504	0.0104	0.0350	0.0202
Mode 3 Maximun Heat Release Rate	*J/°*		0.6080	-0.7878	-0.6439	0.4944	0.1474	-0.7079	0.5291	-0.7120	-0.6937	0.7230	0.5847	-0.7400	-0.1720	-0.3844	0.2063	0.1892	0.1136	0.2504	0.2440
Mode 3 50 Percent Mass Fraction Burn Angle	*°ATDC*		**-0.9407**	0.6671	0.6138	**-0.9136**	-0.7032	**0.9300**	-0.7775	**0.9003**	**0.8897**	**-0.8886**	-0.7201	**0.9097**	-0.3999	0.2610	**-0.8057**	-0.7745	-0.6277	-0.6498	-0.4693
Mode 9 Peak Pressure	*bar*	*25% LOAD*	**0.8894**	-0.7384	-0.7050	**0.8575**	0.6367	**-0.8783**	0.7981	**-0.8457**	**-0.8417**	**0.8386**	0.6281	**-0.8512**	0.2075	-0.3912	0.7697	0.7015	0.5509	0.5523	0.3739
Mode 9 Location of Peak Pressure	*°ATDC*		-0.3603	-0.0749	0.0266	-0.4101	-0.5445	0.2344	-0.3657	0.2164	0.2346	-0.1597	-0.0407	0.1507	-0.5783	-0.0626	-0.6339	-0.6183	-0.4759	-0.3315	-0.1102
Mode 9 Maximun Heat Release Rate	*J/°*		0.7334	-0.7818	-0.6444	0.6415	0.3968	-0.7706	0.6318	-0.7541	-0.7407	**0.8005**	0.7148	**-0.8291**	-0.0736	-0.3519	0.4933	0.4532	0.3135	0.3739	0.2657
Mode 9 50 Percent Mass Fraction Burn Angle	*°ATDC*		-0.7501	0.3813	0.4210	-0.7564	-0.7308	0.6540	-0.6766	0.6238	0.6314	-0.6023	-0.4736	0.6145	-0.5028	0.1724	**-0.8787**	**-0.8268**	-0.6188	-0.5368	-0.2795

11.2.4 GEP 6.5T Engine ESC C-Speed Modal Response to Fuel Variables

The ESC includes an idle mode previously discussed, and four load conditions (100%, 75%, 50% 25%) at three engine speeds. For the GEP 6.5T engine the ESC C-Speed of 2995 rpm is close to the rated power speed of 3100 rpm. Mode 10, Mode 12, Mode 13, and Mode 11 are the 100%, 75%, 50%, and 25% loads respectively.

The C-Speed combustion correlations with fuel properties are shown in Table 15 for the GEP 6.5T engine. The Table 15 highlighted values represent +/-0.80 or greater correlation coefficients. Mode 10 peak cylinder pressure shows increasing cylinder pressure with increases values of fuel density, BM, and T90 distillation temperature. The peak pressure reveals a reduction with increases in NHofC, hydrogen content, and H/C. The fuel BM showed the most significant fuel property effect on peak pressure. There are not any fuel properties that show a significant relationship to either the LPP or the MHRR for Mode 10 with the GEP 6.5T engine. The 50MFB angle advances towards TDC with fuel density and aromatics content increases, The 50MFB retards from TDC with increases in NHofC and saturates content.

Mode 12 (75% load), Table 15, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, carbon content, and aromatics content. Peak cylinder pressures are reduced with increasing values of NHofC, hydrogen content, H/C, and saturates content for the GEP 6.5T engine. The NHofC and fuel density showed the most significant fuel property effects on peak cylinder pressure. The Mode 12 LPP advances towards TDC with increasing flashpoint. The MHRR at Mode 12 increases with an aromatics content increase, and also increases with decreasing CN and decreasing saturates content for the GEP 6.5T engine. The location of 50MFB advances towards TDC due to fuel density, BM, carbon content, aromatics content, and flashpoint increases. The 50MFB angle retards away from TDC when NHofC, hydrogen content, H/C, and saturate contents increase for Mode 12. Fuel density had the most impact on the 50MFB angle.

Mode 13 (75% load), Table 15, peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, carbon content, and aromatics content. Peak cylinder pressures are reduced with increasing values of NHofC, hydrogen content, H/C, and saturates content for the GEP 6.5T engine. The NHofC and fuel density showed the most significant fuel property effects on peak cylinder pressure. There are not any fuel properties that show a significant relationship to the LPP. The MHRR at Mode 13 increases with an aromatics content increase. The MHRR also increases with decreasing CN and decreasing saturates content for the GEP 6.5T engine. The location of 50MFB advances towards TDC due to fuel density, BM, carbon content, aromatics content, and flashpoint increases. The 50MFB angle retards away from TDC when NHofC, hydrogen content, H/C, and saturate contents increase for Mode 13. Fuel density had the most impact on the 50MFB angle.

Mode 11 (25% load), Table 15 peak cylinder pressure shows increasing cylinder pressure with increases in values of fuel density, BM, aromatics content, and flashpoint. Peak cylinder pressure at Mode 11 decreases with increasing values of NHofC, hydrogen content, H/C, and saturates content. Fuel density was the most significant property effecting peak pressure. The Mode 11 combustion response for LPP with the GEP 6.5T engine do not reveal any significant fuel property correlations. The Mode 11 MHRR for the GEP 6.5T engine reveals an increase in MHRR when aromatics content increases. Decreases in CN, NHofC, hydrogen content, and saturates content also increase the MHRR. The location of 50MFB advanced towards TDC due to flashpoint and T10 distillation temperature increases for Mode 11.

For the ESC C-Speed with the GEP 6.5T engine, the combustion parameter peak pressure was impacted mostly by fuel density, fuel BM, NHofC, and fuel structure at all C-Speed load conditions. The fuel density, NHofC, BM were the fuel properties that had the greatest impact on the C-Speed combustion performance for the GEP 6.5T engine. The cetane number did impact combustion performance at the intermediate to light loads

Table 15. GEP 6.5T European Stationary Cycle C-Speed fuel property effects on Modal Combustion Variables

	Units	Engine Condition	European Stationary Cycle C Speed (2995-RPM) Modal Combustion - Fuel Property Correlation Coefficients for GEP 6.5LT Engine																		
			Density	CN	DCN	BM	Kvis	NHofC	C	H	H/C	Aromatics	Olefins	Saturates	Sulfur	Nitrogen	Flash	T10	T50	T90	T90-10
Mode 10 Peak Pressure	bar	100% LOAD	**0.8858**	-0.5809	-0.4991	**0.9221**	0.7275	**-0.9034**	0.7825	**-0.8954**	**-0.8885**	0.7724	0.5460	-0.7793	0.2970	-0.3554	0.7019	0.7197	0.7357	**0.8081**	0.7245
Mode 10 Location of Peak Pressure	°ATDC		-0.2775	0.3033	0.1646	-0.2408	-0.3019	0.3057	-0.2275	0.3071	0.2983	-0.3258	-0.6600	0.3905	0.3766	0.1577	-0.2203	-0.2346	-0.2424	-0.3124	-0.3053
Mode 10 Maximun Heat Release Rate	J/°		0.6518	-0.7372	-0.5865	0.5521	0.2906	-0.7207	0.5266	-0.7106	-0.6909	0.7497	0.7044	-0.7814	-0.1175	-0.3171	0.3357	0.3275	0.2289	0.3242	0.2682
Mode 10 50 Percent Mass Fraction Burn Angle	°ATDC		**-0.8590**	0.6691	0.6333	-0.7974	-0.5839	**0.8167**	-0.7262	0.7744	0.7679	**-0.8847**	-0.6372	**0.8943**	-0.3231	0.1924	-0.7721	-0.7007	-0.4664	-0.4446	-0.2223
Mode 12 Peak Pressure	bar	75% LOAD	**0.9236**	-0.7290	-0.6711	**0.9001**	0.6580	**-0.9365**	**0.8069**	**-0.9077**	**-0.8990**	**0.8909**	0.6617	**-0.9035**	0.2547	-0.4100	0.7160	0.6977	0.6041	0.6625	0.5316
Mode 12 Location of Peak Pressure	°ATDC		-0.6535	0.2567	0.3273	-0.6795	-0.6589	0.5458	-0.6368	0.5163	0.5307	-0.4986	-0.1601	0.4754	-0.5912	0.1643	**-0.8066**	-0.7500	-0.6057	-0.4994	-0.2711
Mode 12 Maximun Heat Release Rate	J/°		0.7318	**-0.8007**	-0.6737	0.6304	0.3186	-0.7890	0.6320	-0.7711	-0.7559	**0.8307**	0.6548	**-0.8478**	-0.0466	-0.3422	0.4102	0.3773	0.2522	0.3467	0.2712
Mode 12 50 Percent Mass Fraction Burn Angle	°ATDC		**-0.9310**	0.6665	0.6605	**-0.9026**	-0.6933	**0.9090**	**-0.8366**	**0.8896**	**0.8869**	**-0.8708**	-0.5965	**0.8758**	-0.4007	0.3989	**-0.8121**	-0.7737	-0.6262	-0.6487	-0.4682
Mode 13 Peak Pressure	bar	50% LOAD	**0.9398**	-0.7493	-0.6813	**0.9035**	0.6501	**-0.9556**	**0.8522**	**-0.9395**	**-0.9332**	**0.9002**	0.6294	**-0.9072**	0.2383	-0.3958	0.7354	0.7006	0.6043	0.6501	0.5124
Mode 13 Location of Peak Pressure	°ATDC		-0.4027	0.0396	0.1523	-0.4487	-0.5485	0.2796	-0.4247	0.2620	0.2820	-0.2013	-0.0719	0.1930	-0.5372	0.1119	-0.6811	-0.6240	-0.4854	-0.3667	-0.1567
Mode 13 Maximun Heat Release Rate	J/°		0.7122	**-0.8033**	-0.6616	0.6056	0.2933	-0.7771	0.6289	-0.7711	-0.7562	**0.8125**	0.6356	**-0.8286**	-0.1020	-0.3440	0.3869	0.3507	0.2370	0.3266	0.2581
Mode 13 50 Percent Mass Fraction Burn Angle	°ATDC		**-0.9307**	0.6542	0.5958	**-0.9084**	-0.7349	**0.9155**	**-0.8256**	**0.8929**	**0.8879**	**-0.8844**	-0.6615	**0.8975**	-0.3066	0.3223	**-0.8164**	-0.7850	-0.6764	-0.6907	-0.5209
Mode 11 Peak Pressure	bar	25% LOAD	**0.9387**	-0.7312	-0.6822	**0.9125**	0.6955	**-0.9219**	**0.8338**	**-0.8932**	**-0.8883**	**0.9033**	0.6646	**-0.9151**	0.2536	-0.3840	**0.8115**	0.7576	0.6206	0.6415	0.4673
Mode 11 Location of Peak Pressure	°ATDC		-0.3161	-0.0449	0.1120	-0.3777	-0.4848	0.1876	-0.3344	0.1652	0.1848	-0.1408	0.0164	0.1253	-0.5300	0.0744	-0.6170	-0.5537	-0.4286	-0.2960	-0.0976
Mode 11 Maximun Heat Release Rate	J/°		0.7750	**-0.8392**	-0.7143	0.6659	0.3777	**-0.8124**	0.6947	**-0.8044**	-0.7929	**0.8529**	0.6850	**-0.8723**	-0.0677	-0.3881	0.5155	0.4558	0.2948	0.3560	0.2390
Mode 11 50 Percent Mass Fraction Burn Angle	°ATDC		-0.7977	0.4531	0.4966	-0.7884	-0.7395	0.7151	-0.7361	0.6944	0.7011	-0.6719	-0.4583	0.6755	-0.4721	0.3135	**-0.8915**	**-0.8316**	-0.6553	-0.5735	-0.3285

11.3 ENGINE COMPARISONS

At the European Stationary Cycle A-Speed the GEP 6.5T engine displayed more significant impacts from fuel properties on combustion performance than the CAT C7. The fuel properties density, BM, net heat of combustion, and fuel H/C atom ratio all effected peak cylinder pressures, at all loads, with the GEP 6.5T engine. Combustion phasing was not impacted by fuel properties for the GEP 6.5T engine. Peak cylinder pressures for the CAT C7 were effected at high loads by density, BM, viscosity, and fuel distillation. The cetane number showed combustion phasing impacts at light loads only for the CAT C7 engine.

For the European Stationary Cycle B-Speed the GEP 6.5T engine there were more significant impacts from fuel properties on combustion performance than with the CAT C7. The fuel properties density, BM, KVis, net heat of combustion, fuel H/C, and fuel structure all effected peak cylinder pressures, at all loads, with the GEP 6.5T engine. Combustion phasing at intermediate loads were impacted by the same fuel properties for the GEP 6.5T engine. Peak cylinder pressures for the CAT C7 were effected at 75% load by viscosity, and fuel distillation. The cetane number showed combustion phasing impacts at light loads only for the CAT C7 engine. In general the GEP 6.5T was more sensitive to fuel density and BM and the CAT C7 was more sensitive to CN at the B-Speed.

At the European Stationary Cycle C-Speed the GEP 6.5T engine also displayed more significant impacts from fuel properties on combustion performance than the CAT C7. The fuel properties density, BM, net heat of combustion, and fuel H/C atom ratio all effected peak cylinder pressures, at all loads, with the GEP 6.5T engine. Combustion phasing at intermediate loads were affected by the same fuel properties for the GEP 6.5T engine. The combustion rate for the GEP 6.5T engine was sensitive to cetane number, heating value, and fuel structure at intermediate and light loads. Peak cylinder pressures for the CAT C7 were not affected by fuel properties for any load. Bulk modulus and viscosity effects were evident at the peak load condition for the CAT C7. Combustion phasing for the CAT C7 was affected by fuel density, heating value, and fuel structure at most loads. The fuel cetane number showed combustion phasing impacts at light load only for the CAT C7 engine.

12.0 OTHER OBSERVATIONS

12.1 BULK MODULUS – GEP 6.5T ISSUES

In accordance with historical trends for a pump-line-nozzle injection system, as the bulk modulus increases, the delay between pressure rise in the injection pump and the needle lift event decreases. On the GEP 6.5T engine this has the effect of pushing the timing more negative and away from TDC. Figure 31 shows only the measured needle lift timing for the first lift event.

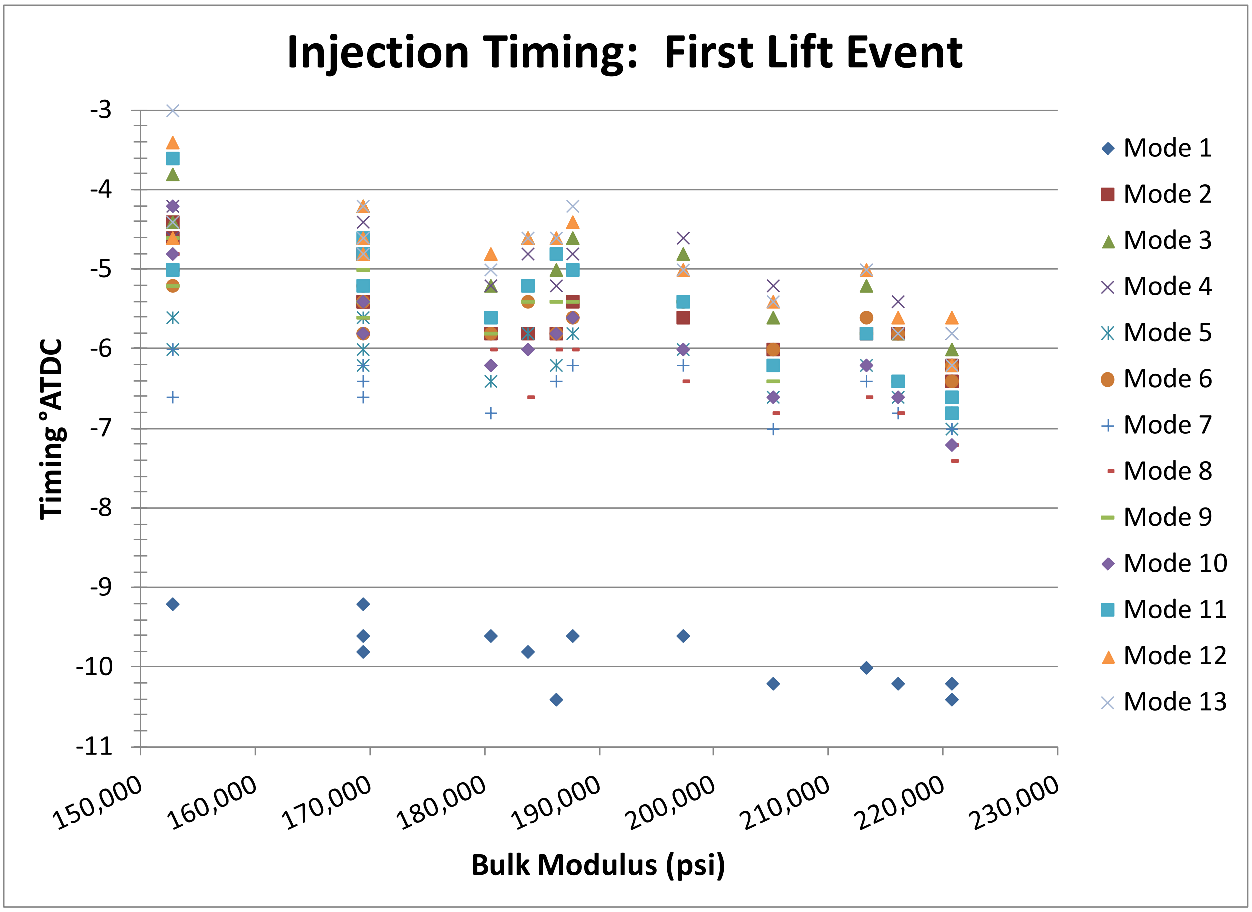

Figure 31. GEP 6.5T Injection Timing vs. Bulk Modulus

The result of increasing bulk modulus on the GEP 6.5T engine would be to move the fuel burn curve (which has a nominal CA50 timing that occurs after top dead center) closer to TDC. This should increase engine efficiency by providing a longer effective expansion stroke. Unfortunately, for the purposes of this study, bulk modulus was not able to be decoupled from energy density as seen in Figure 32, so the effect of bulk modulus scales directly with energy density in the results presented.

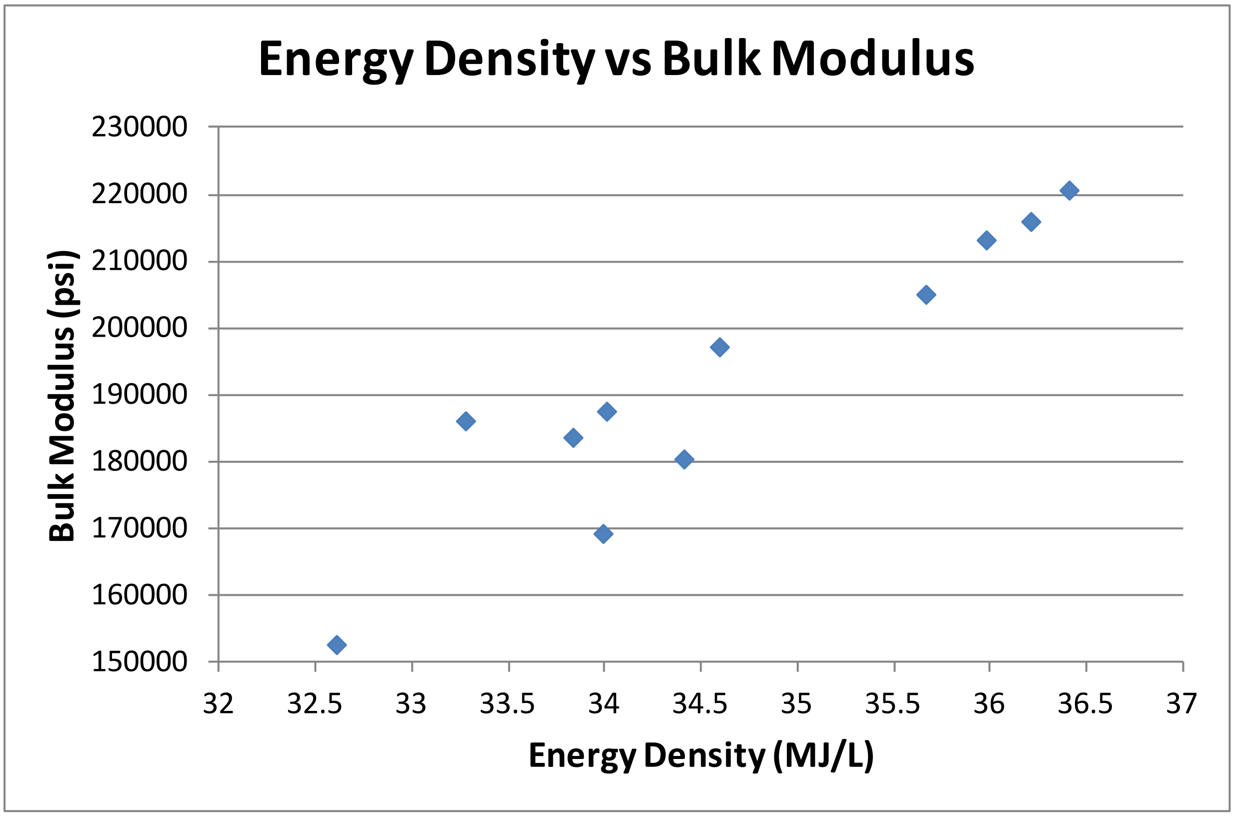

Figure 32. Fuel Bulk Modulus vs. Energy Density

Using the injection line pressure transducer TFLRF staff were able to observe the differences in ringing frequency (as seen in Figure 33) between the two most disparate fuels which was caused by the inherent differences in bulk modulus. At engine idle conditions (Mode 1) fuel 2 showed a 6700 Hz frequency, and fuel 5 a 5800 Hz ringing frequency. The difference between the fuels is a 31% lower bulk modulus and a 13.5% lower ringing frequency.

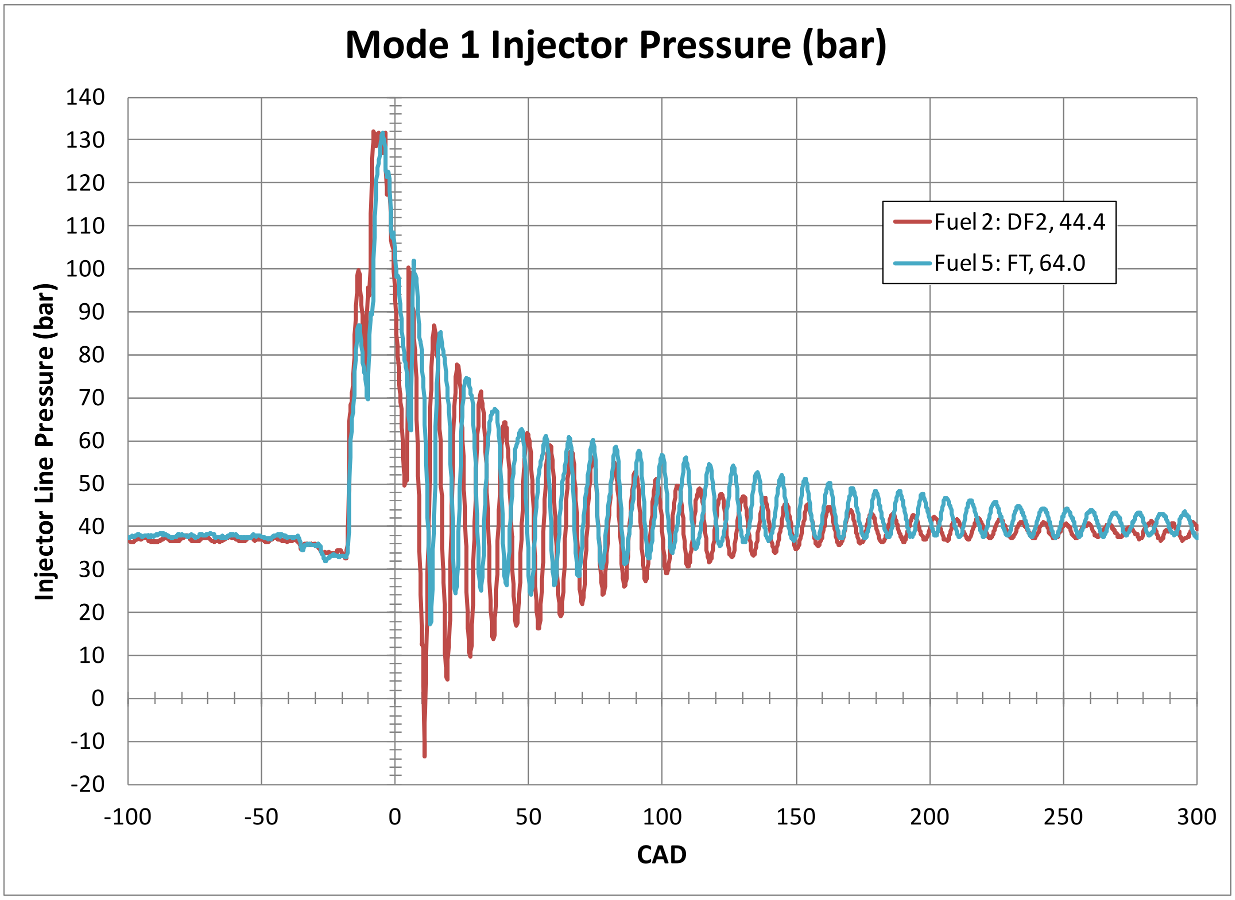

Figure 33. GEP 6.5T ESC Mode 1 Injection Line Ringing Frequency

12.2 GEP 6.5T IDLE QUALITY ISSUES

The idle quality was severely affected by low bulk modulus fuel and high cetane fuel. In the pre-chamber pressure trace as much as 70% of the mass was burned before TDC for the highest cetane number fuel. The main chamber pressure trace showed only slightly less MFB before TDC. The worst offender can be seen in Figure 34 by following the plotted line for Fuel 15 (cetane number 74).

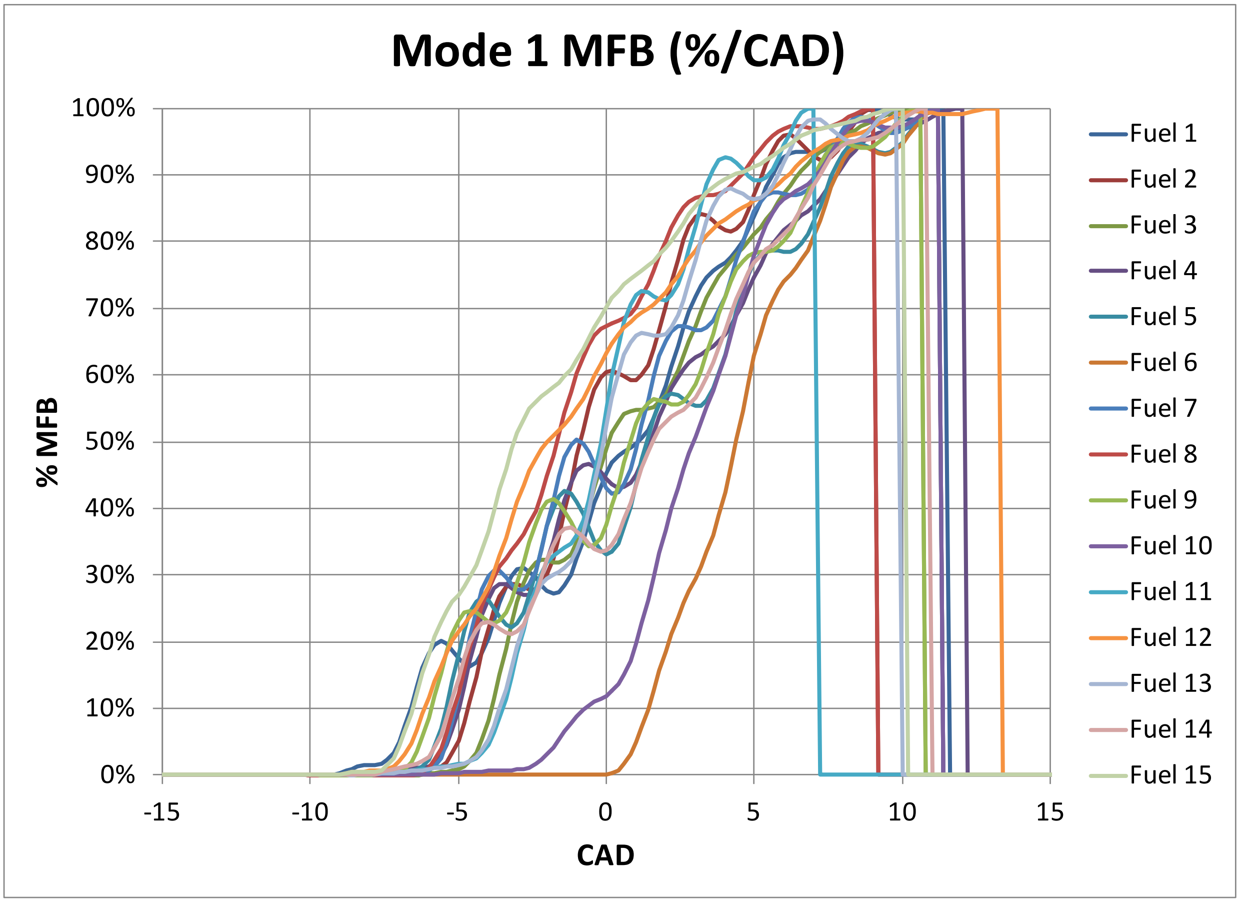

Figure 34. GEP 6.5T ESC Mode 1 MFB

It was also observed that fuel 6 (cetane improved FT-SPK) performed worse than fuel 10 (28 cetane number). The cause of this poor performance can be seen in Figure 35.

Following the trace of fuel 6, the needle does not appear to actuate with the same general timing as all the other fuels. While fourteen of the fifteen fuels exhibit needle lift events around minus 10° ATDC, fuel 6 skips the first lift event and only opens at around minus 3° ATDC. This causes the entire burn curve to occur after TDC. It is assumed that the low bulk modulus of the fuel is the cause of this phenomenon.

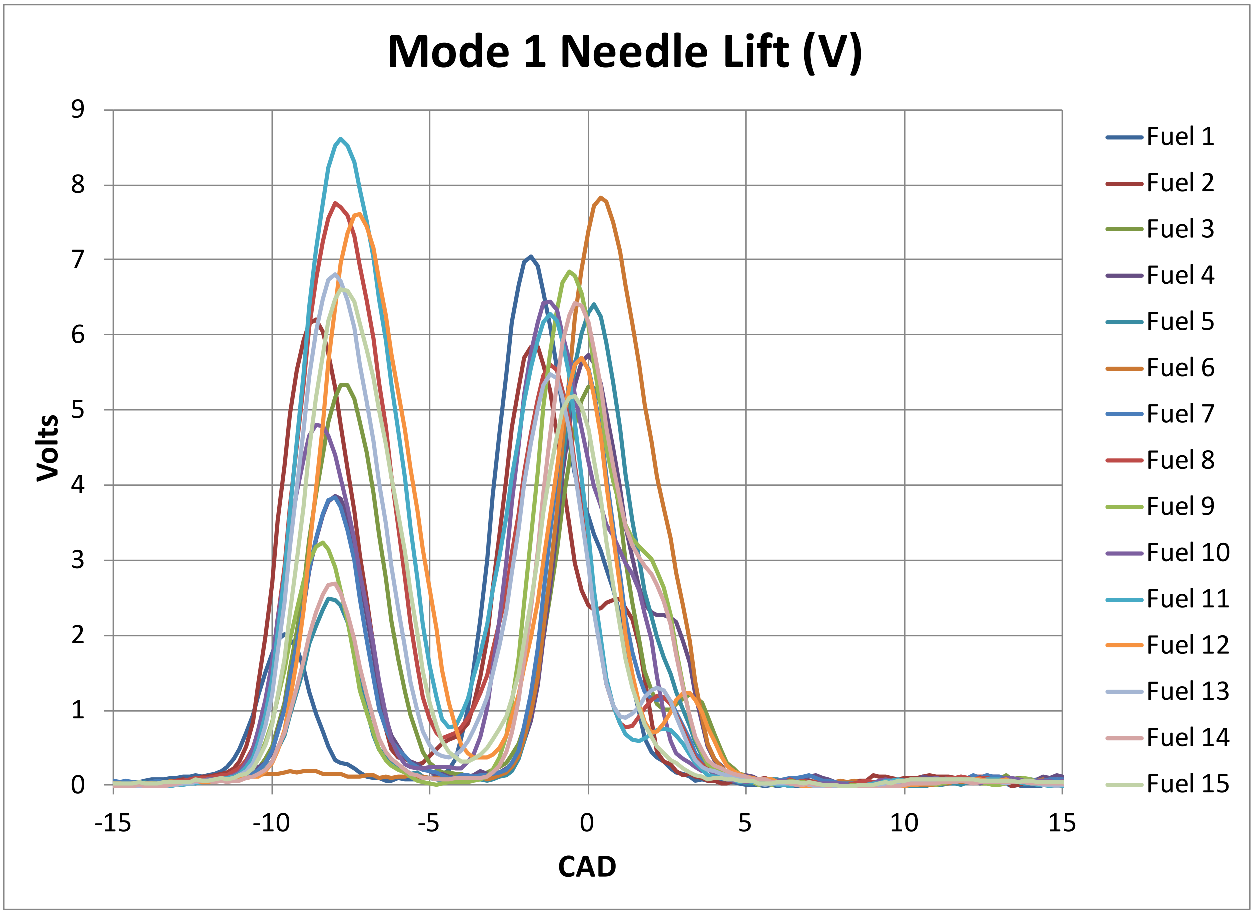

Figure 35. GEP 6.5T ESC Mode 1 Needle Lift

12.3 EFFECT OF FUEL TYPE ON C7 ECM CONTROL

During operation of the ESC on the CAT C7 engine, it was observed that the ECM did not maintain same injection mode strategy for a few given speed/load points across all fuels. During the medium load points (50% & 75%), some of the fuels showed different injection modes. They alternated between a pre-injection with a split main and a pre-injection with single main. TFLRF investigated to see if the CAT C7 ECM was adapting the injection timing based on fuel, or if other factors were involved.

To investigate this effect, the CAT C7 fuel lines were modified with 3-way valves at the point where the fuel line enters and exits the head. This allowed the fuel source to be switched instantaneously. The new fuel would be delivered to the injectors (specifically injector #1 which was first in the fuel pathway) within a few revolutions of the crankshaft.

The invented procedure was then to record high-speed data, while simultaneously throwing the fuel valves. It was hoped that the ECM would react fast enough to observe a change in injection timing during the data acquisition event.

Overall the tests were successful as seen in Figure 36 through Figure 39. The injection timing shifts were within roughly 25 cycles of the new fuel source. At one operating point, after about 400 cycles which constituted a new steady state, the ECM changed injection modes. It was observed that the CAT C7 ECM adapts its fueling strategy based on the fuel type, through a model-based closed loop control.

TLFRF identified fuels that caused the injection mode changes. The fuels causing injection mode changes were characterized by having both a high cetane number (>50) and a narrow T90-T10 distillation range (<50°C).

The two test fuels that demonstrated this timing shift and mode change were:

Fuel 3, Jet A	Fuel 9, JP8/S8 +0.3%
42.8 CN	60.5 CN
30.3°C (T90-T10)	48.4°C (T90-T10)
0.7946 g/ml	0.7809 g/mL

Figure 36 and Figure 37, demonstrate the ECM adjustment after hot swapping fuels during Mode 6 of the ESC. First, a shift in the crank angle location, at which the MFB is at 10%, occurs due to the new fuel entering the engine. This event is shortly followed in time by a shift in the same direction of the injector current timings. The injector timing data shown comes from the current transducer (please refer to Figure 10). For this ESC mode there were three distinct current pulses. Injector timing #1 has been omitted from all to show increased detail in the MFB shift.

In Figures 36 through 39, the x-axis is labeled 'cycles' and represents the progression of time by incrementally counting revolutions of the crankshaft. The y-axis is labeled 'degrees ATDC' and represents the crank angle at which each measured or calculated event occurs.

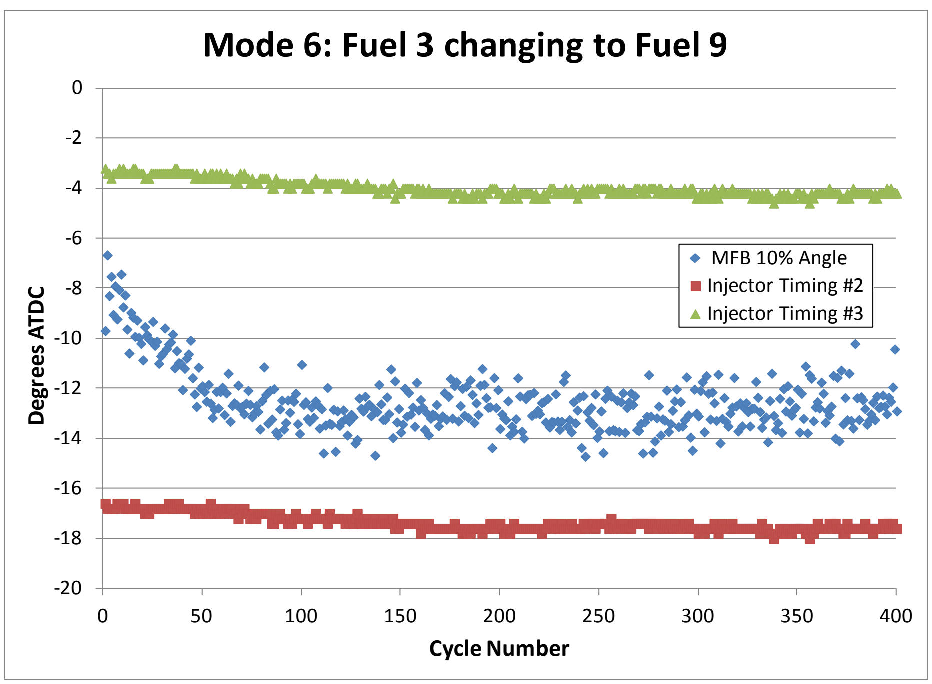

Figure 36. CAT C7 ESC Mode 6 Fuel Hot Swap Forward

Swapping fuels in the reverse order, a similar shift occurred and the injection timing reverted to the original values.

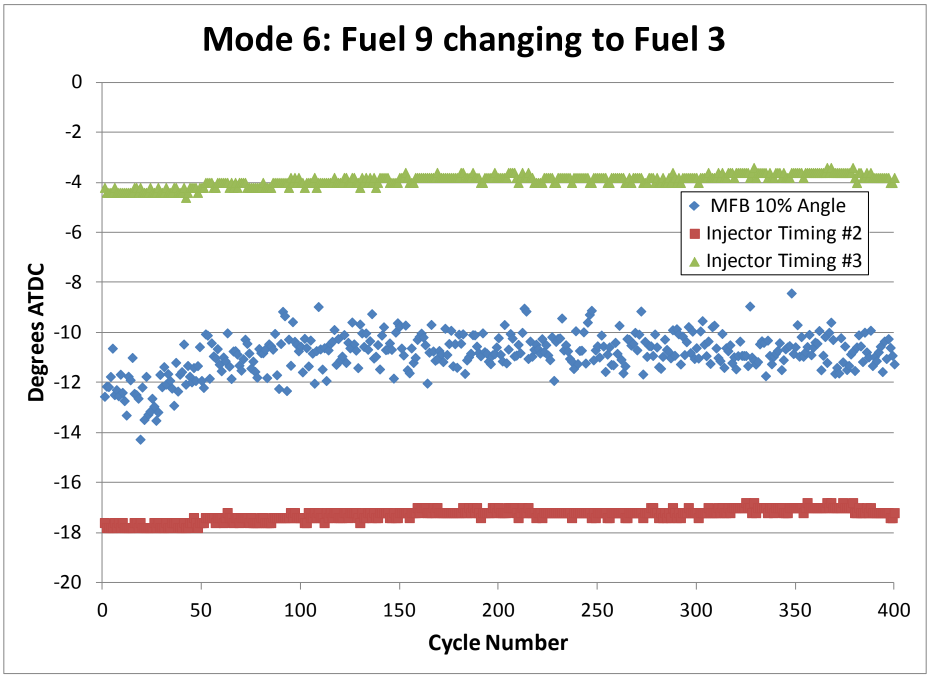

Figure 37. CAT C7 ESC Mode 6 Fuel Hot Swap Reverse

Figure 38 and Figure 39 demonstrate the ECM adjustment after hot swapping fuels during Mode 12 of the ESC. First, a shift in the crank angle location, at which the MFB is at 10%, occurs due to the new fuel entering the engine. This event is shortly followed in time by a shift in the same direction of the injector current timings. Then after about 400 cycles at the new steady state condition, the injection timing experiences an abrupt mode change.

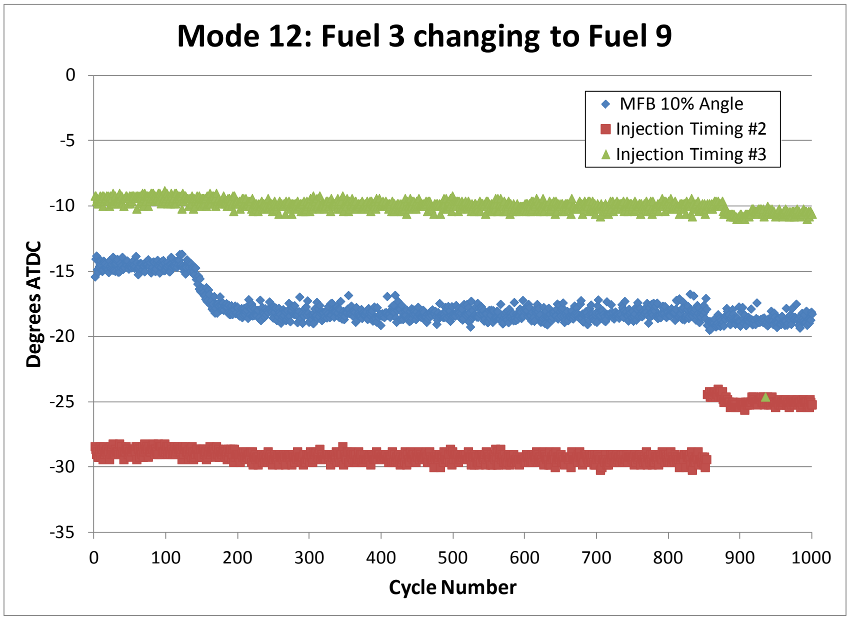

Figure 38. CAT C7 ESC Mode 12 Fuel Hot Swap Forward

When swapping fuels in the reverse order, the mode change did not occur during the 1000 measured cycles (only the first 400 are shown for clarity).

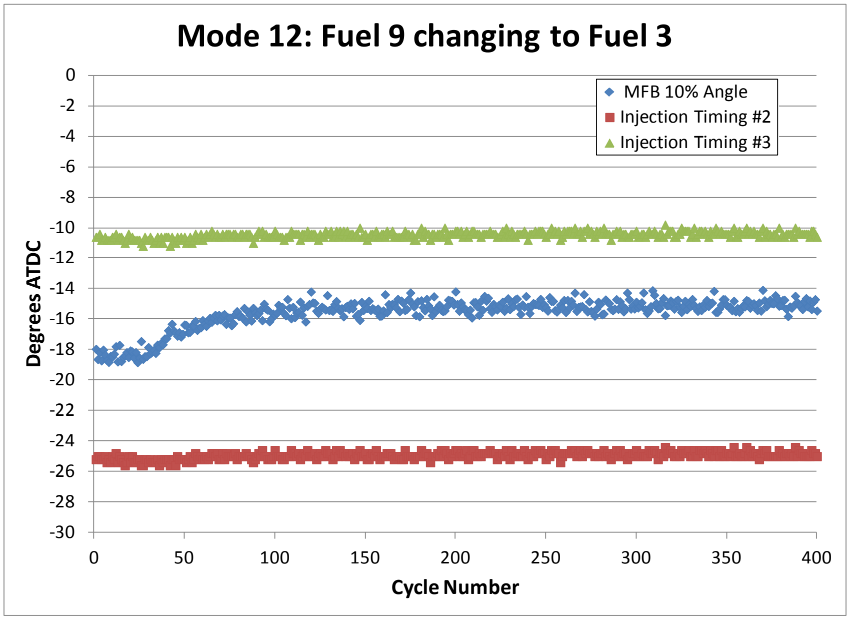

Figure 39. CAT C7 ESC Mode 12 Fuel Hot Swap Reverse

This investigation demonstrated that the C7 ECM injection mode strategy was influenced by different fuel types, through a model-based closed loop control.

13.0 SUMMARY

TFLRF staff were able to observe that fuels with low cetane number may be detrimental to IDI engines at high loads due to excessive HRR (1.5 to 2 times higher). This excessive combustion noise may, in the long run, damage engine internal components. And speaking generally, low cetane number fuel will provide a hard-to-start condition when the engine and environment are cold.

TFLRF staff were also able to observe that high cetane fuel can be detrimental to peak power on engines with adaptive ECM controls. Traditionally high cetane fuels operating on engines with static timing promotes NOx formation. This phenomenon was seen on the GEP 6.5T engine. High cetane number can also cause rough engine operation at light load conditions due to higher MFB before TDC.

It is recommended that the cetane number for ground vehicles stay between 40 and 60. It is also recommend that bulk modulus stay above 180,000 psi for engines with pump-line-nozzle type fuel injection systems. Finally it is recommend that a fuel's distillation characteristics exhibit a T90-T10 temperature that is greater than 50°C.

When engine power output is the primary design goal for a fuel, density is the primary property of interest; the higher the better.

APPENDIX A

FUEL PROPERTIES

The following fuels were used on both engines with one exception. Fuel 9 was a cetane improved fuel that was used up prior to t esting on the GEP 6.5T engine, so a new drum had to be blended. The updated properties for the fuel 9 that was used on the GEP 6. 5T engine follow the main tables.

Test Fuel Number			1	2	3	4	5	6	7	8
Properties	Units	Test Method	HRJ8	2007 DF2	JetA	Ft. Bliss JP8/S8	Shell FT	Shell FT + 0.4%	Generator Sets JetA/HRJ8	2007 DF2 + 0.3%
Density @ 15°C	g/mL	D4052	0.7628	0.8551	0.7946	0.7809	0.7360	0.7360	0.7798	0.8551
Kinematic Viscosity @ 40°C	cSt	D445	1.538	2.510	1.130	1.120	0.900	0.900	1.310	2.510
Net Heat of Combustion	MJ/kg	D240	43.622	42.577	43.303	43.525	44.300	44.300	43.504	42.577
Hydrocarbon Content										
Carbon	wt%	D5291	84.37	86.75	85.78	85.6	83.94	83.94	85.38	86.75
Hydrogen			15.17	12.95	13.94	14.5	16.46	16.46	14.62	12.95
Hydrocarbon Composition										
Aromatics	vol %	D1319	0.7	29.9	17.0	10.5	0.4	0.2	8.4	35.4
Olefins			0.2	1.4	0.7	1.0	0.5	0.3	1.0	1.8
Saturates			99.1	68.7	82.3	88.5	99.1	99.5	90.6	62.8
Sulfur Content	mg/kg	D5453	0.45	30.3	0.2	<1	3	3	1.8	30.3
Nitrogen Content	mg/kg	D4629	1.3	7	1	2	1	426	1	284
Flash Point	°C	D56	44.5	69.4	52.7	51	43.9	42	46	70
Distillation										
10%	°C	D 86	165.0	215.4	176.5	171.0	161.5	161.6	171.1	213.5
50%			228.0	259.3	187.1	187.0	168.8	168.7	197.2	258.8
90%			273.0	311.1	206.8	223.0	186.0	184.0	266.2	309.4
T90-T10		Calculated	108.0	95.7	30.3	52.0	24.5	22.4	95.1	95.9
Cetane Number		D613	60.4	44.4	42.8	49.9	64.0	71.7	51.7	54.3
IQT		D6890	58.7	42.6	45.0	49.7	59.1	85.5	53.5	52.0
HFRR	mm	D6079	0.670	0.580	0.690	0.631	0.810	0.840	0.670	0.580
Bulk Modulus @ 30°C	psi	by S.O.S.	186209	220720	180500	169359	152749	152749	187645	220720

Test Fuel Number			9	10	11	12	13	14	15
Properties	Units	Test Method	Ft. Bliss + 0.3%	Special Diesel #1 6CPDST06	Special Diesel #2 6CPDST10	FT Diesel Blend 21/79 + 0.3%	50/50 Special D. Blend	Ft. Bliss + 0.1%	Navy FT Diesel #1
Density @ 15°C	g/mL	D4052	0.7809	0.841	0.8492	0.7963	0.8453	0.7809	0.7722
Kinematic Viscosity @ 40°C	cSt	D445	1.120	1.460	3.050	2.550	2.050	1.120	2.410
Net Heat of Combustion	MJ/kg	D240	43.525	42.407	42.639	43.442	42.562	43.525	43.813
Hydrocarbon Content									
Carbon	wt%	D5291	85.6	85.99	86.47	85.35	87.06	85.6	84.78
Hydrogen			14.5	12.46	12.98	14.54	12.79	14.5	15.21
Hydrocarbon Composition									
Aromatics	vol %	D1319	9.4	38.0	29.2	9.3	36.4	8.8	0.4
Olefins			0.7	5.0	8.7	1.0	1.7	0.6	0.7
Saturates			89.9	57.0	62.1	89.7	61.9	90.6	98.9
Sulfur Content	mg/kg	D5453	<1	1	0.0	33.7	1.8	<1	0.4
Nitrogen Content	mg/kg	D4629	288	1	3	322	6	89	1
Flash Point	°C	D56	45	50	77	60	61	42	55
Distillation									
10%	°C	D 86	169.4	178.6	226.0	208.9	195.1	169.0	193.5
50%			183.5	205.4	266.4	273.3	240.7	183.7	272.3
90%			217.8	272.3	311.4	329.1	303.2	217.5	338.2
T90-T10		Calculated	48.4	93.7	85.4	120.2	108.1	48.5	144.7
Cetane Number		D613	60.5	28.0	38.5	78.2	36.3	55.9	74.2
IQT		D6890	66.6	30.4	40.2	95.2	37.5	61.0	85.4
HFRR	mm	D6079	0.631	0.640	0.510	0.590	0.600	0.631	0.570
Bulk Modulus @ 30°C	psi	by S.O.S.	169359	205132	216027	197281	213265	169359	183737

Number			9 (C7)	9a (6.5T)
Properties	Units	Test Method	JP8/S8 + 0.3%	JP8/S8 + 0.3%
Density @ 15°C	g/mL	D4052	0.7809	
Kinematic Viscosity @ 40°C	cSt	D445	1.120	
Net Heat of Combustion	MJ/kg	D240	43.525	
Hydrocarbon Content				
Carbon	wt%	D5291	85.6	
Hydrogen			14.5	
Hydrocarbon Composition				
Aromatics	vol %	D1319	9.4	
Olefins			0.7	
Saturates			89.9	
Sulfur Content	mg/kg	D5453	<1	
Nitrogen Content	mg/kg	D4629	288	341
Flash Point	°C	D56	45	43
Distillation				
10%	°C	D 86	169.4	169.2
50%			183.5	185.2
90%			217.8	220.5
T90-T10		Calculated	48.4	51.3
Cetane Number		D613	60.5	64.4
IQT		D6890	66.6	62.5
HFRR	mm	D6079	0.631	
Bulk Modulus @ 30°C	psi	by S.O.S.	169359	171894