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ADA

IMPACT OF FIRE RESISTANT FUEL BLENDS ON COMPRESSION IGNITION ENGINE PERFORMANCE

INTERIM REPORT
TFLRF No. 412

by

Adam C. Brandt
Edwin A. Frame

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

byLuis A. Villahermosa
Joel Schmitigal

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. DAAE-07-99-C-L053 (WD38)
Contract No. W56HZV-09-C-0100 (WD003)

Approved for public release: distribution unlimited

July 2011

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14. ABSTRACT

From testing completed, it was found that FRF blends can be successfully used in typical compression ignition engines with an associated power loss depending on FRF blend proportions. Typical engine output losses vary from 3 to 9% in peak power and torque depending on injection system configuration and FRF blend chemistry.

15. SUBJECT TERMS

Fire Resistant Fuel (FRF), Diesel, JP-8, Mist Control Additive (MCA), Compression Ignition, Caterpillar C7, General Engine Products 6.5L(T), Engine, Performance

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EXECUTIVE SUMMARY

During an Army research program in the mid-1980's, Southwest Research Institute (SwRI) developed a fire-resistant diesel fuel that would self extinguish when ignited by an explosive projectile. This fire resistant fuel (FRF) was composed of a stable mixture of diesel fuel, 10% water, and an emulsifier. The research program ended in 1987 without the FRF blend being fielded due to several reasons, including some technical problems. Recently, due to the war in Iraq and Afghanistan, there has been a renewed interest in FRF development. The Army research program was restarted to continue development of FRF, with a redefined scope to include the development of FRF using JP-8 to comply with the Army's Single Fuel Forward strategy.

Various FRF blends have been developed with varying quantities of water, emulsifier, mist control additive, and base fuels. Ballistics testing has been used to determine the needed quantities of each FRF constituent to produce a successful FRF blend. Samples of each FRF blend were collected and analyzed to determine critical physical properties in an effort to determine FRF impact on overall engine function and performance.

Due to the FRF blends containing up to 10% water, there was a desire to determine engine performance changes due to FRF blends. Two high density compression ignition engines were chosen from current Army tactical vehicles to represent legacy and current diesel engine technology for FRF compatibility testing. The first engine was the Caterpillar (CAT) C7, a 330hp 7.2L direct injected turbocharged intercooled inline six cylinder diesel engine commonly used many military vehicles including the Family of Medium Tactical Vehicles (FMTV), IAV Stryker, and many Mine Resistant Ambush Protected (MRAP) variants. The second engine chosen was the General Engine Products (GEP) 6.5L(T), a 190-hp pre-chamber injection turbocharged V8 diesel engine as used in the High Mobility Multipurpose Wheeled Vehicle (HMMWV).

Throughout testing, it was found that both engines experienced approximately a 3 to 9% loss in peak power and torque output depending on the injection system configuration and FRF blend chemistry. No mechanical issues were experienced from FRF use in the engines throughout the duration of testing. There was a indication of reduction of nitrogen oxide (NOx) production with the use of FRF blends, but due to various technical problems with emissions equipment, full emissions characterizations of each fuel were not collected.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI®), San Antonio, Texas, performed this work during the period of January 2008 through July 2011 under Contract No. DAAE-07-99-C-L053, and Contract No. W56HZV-09-C-0100. The U.S. Army Tank-Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Luis Villahermosa (AMSTA-RBFF) served as the TARDEC contracting officer's technical representative. Mr. Joel Schmitigal of TARDEC served as the project technical monitor.

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

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ACRONYMS AND ABBREVIATIONS

ATPD – Automotive Tank Purchase Description
avg – average
BHP or bhp – brake horsepower
BSFC – brake specific fuel consumption
BSOM – Beyond Scope of Method
CAT – Caterpillar
FMTV – Family of Medium Tactical Vehicles
FRF – fire resistant fuel
ft-lb – foot-pound
GEP – General Engine Products
HC – hydrocarbon
HEUI – Hydraulically Actuated Electronically Controlled Unit Injection
HMMWV – High Mobility Multipurpose Wheeled Vehicle
HP or hp – horsepower
IED – improvised explosive device
lbf – pound force
lbm – pound mass
M-ATV – MRAP All Terrain Vehicle
MCA – mist control additive
MRAP – Mine Resistant Ambush Protected
NOx – oxides of nitrogen
ppm – parts per million
RPM or rpm – revolutions per minute
SwRI - Southwest Research Institute
TARDEC – Tank-Automotive RD&E Center
TFLRF – U.S. Army TARDEC Fuels and Lubricants Research Facility

1.0 INTRODUCTION AND BACKGROUND

During an Army research program in the mid-1980's, Southwest Research Institute (SwRI) developed a fire-resistant diesel fuel that would self extinguish when ignited by an explosive projectile. This fire resistant fuel (FRF) was composed of a stable mixture of diesel fuel, 10% water, and an emulsifier. During an event of an explosion, such as that from a ballistic round, pool fire burning of an FRF would quickly self extinguish. This ability to self extinguish is due to the formation of water vapor that concentrates above the surface of the fuel as it is heated, effectively limiting oxygen available to combust with the fuel.

The research program ended in 1987 without the FRF blend being fielded. This was due to several reasons, including some technical problems. Recently, due to the war in Iraq and Afghanistan, there has been a renewed interest in FRF development. The Army research program was restarted to continue development of FRF, with a redefined scope to include the development of FRF using JP-8 to comply with the Army's Single Fuel Forward strategy.

2.0 OBJECTIVE

One main aspect of the Army FRF research program is the compatibility of FRF with legacy and expected future ground vehicle equipment. With the addition of water and emulsifier in the FRF blends, there is an expected proportional engine output power loss to the volume of water utilized in the fuel. It was desired to quantify the engine output losses due to various FRF blends using compression ignition engines commonly found in military tactical vehicles.

A survey of current Army tactical vehicles yielded two high density compression ignition engines that were found to be a good representation of past and present compression ignition engine technology. This included the Caterpillar (CAT) C7 and the General Engine Products (GEP) 6.5L(T) engine. The CAT C7 engine is commonly used in the Family of Medium Tactical Vehicles (FMTV), the IAV Stryker, some Mine Resistant Ambush Protected (MRAP) variants, and the MRAP All Terrain Vehicle (M-ATV). The C7 engine is representative of current diesel engine technology by utilizing direct injection at high injection pressures for engine fueling. The GEP 6.5L(T) engine is commonly used in the many High Mobility Multipurpose Wheeled

Vehicle (HMMWV) variants. The GEP 6.5L(T) engine utilizes an older style pre-chamber injection, pump line nozzle configuration representative of many legacy equipment engines.

3.0 EFFECTS ON ENGINE PERFORMANCE

FRF blends were tested in the CAT C7 and GEP 6.5L(T) engines to determine the effects of FRF on engine performance. All base fuel and FRF blends underwent chemical analysis to determine critical properties in an effort to understand engine output changes associated with each blend. Engine performance data was collected for each blend and analyzed to determine maximum power and torque output changes, as well as statistical significance between changes.

3.1 FUEL PROPERTIES

All FRF blends consist of a base fuel, surfactant, and water typically blended in a ratio of 84%vol fuel, 6%vol surfactant, and 10%vol H_2O (some work has also been completed using 3%vol surfactant and 5% H_2O). Some FRF blends also contain 125 or 250ppm of a mist control additive (MCA) to help reduce fuel mist in the event of a fuel tank rupture aiding in the FRF's ability to self extinguish. Table 1 below outlines all variations of FRF blends that have undergone engine testing by TFLRF staff to date, and what components they are composed of. Diesel based fuels tested include: DF2, DF2-FRF, and DF2-FRF plus MCA. JP8 based fuels tested include JP8, JP8-FRF, and JP8-FRF plus MCA blended from commercially available JP8 (Age Refining) and JP8 blended onsite from Jet-A.

Table 1 - FRF Blends for Chem. Lab Property Testing

	FRF Blends using Haltermans Cert. Diesel			
Base Fuel No	DF2	DF2-FRF	DF2-FRF MCA	**DF2:**
	Surfactant ->	+ 6% vol Surfactant	+ 6% vol Surfactant	Haltermann Cert Diesel
	Deionized Water ->	+ 10% vol Water	+ 10% vol Water	AL-28125F
		Mist Control Additive ->	+ 125 ppm MCA	
				JP8:
	FRF Blends using Blended JP8 (From Jet-A)			Blended From Jet-A
Base Fuel No.	JP8 (Blended)	JP8-FRF	JP8-FRF MCA	AL-27860F
	Surfactant ->	+ 6% vol Surfactant	+ 6% vol Surfactant	
	Deionized Water ->	+ 10% vol Water	+ 10% vol Water	**JP8:**
		Mist Control Additive ->	+ 125 ppm MCA	Age Refining
				AL-27810F
	FRF Blends using Age Refining JP8			
Base Fuel No	JP8 (Age)	JP8-FRF	JP8-FRF MCA	**Surfactant:**
	Surfactant ->	+ 6% vol Surfactant	+ 6% vol Surfactant	Lubrizol Schercomid ODA
	Deionized Water ->	+ 10% vol Water	+ 10% vol Water	AL-28115X
		Mist Control Additive ->	+ 250 ppm MCA	
				Mist Control Additive:
	JP8 (Age)	JP8-FRF	JP8-FRF MCA	Baker Petrolite FLO XS
	Surfactant ->	+ 3% vol Surfactant	+ 3% vol Surfactant	AL-27797X
	Deionized Water ->	+ 5% vol Water	+ 5% vol Water	
		Mist Control Additive ->	+ 250 ppm MCA	

To determine varying properties between each individual blend, and to help understand changes in engine performance as a function of fuel, samples were taken for chemical analysis after the completion of the blending process for each fuel. Table 2 below lists the following ASTM tests that were completed on each of the samples.

Table 2 - ASTM Fuel Property Tests

KVIS @ 40°C	D445	**Bulk modulus**	D6793
Heat of Combustion	D3388	**Hydrogen**	D3701
Gravity, API @15°C	D1298	**BOCLE**	D5001
Flash point	D93	**HFRR**	D6078
Distillation	D86	**SLBOCLE**	D6079
Aromatics	D1319	**IQT**	D6890-04
Olefins	D1319	**Nitrogen**	D3228
Sulfur	D2622		

Final results for the chemical analysis are shown below in Table 3 (As noted in the table, some standard ASTM tests were unable to be run on fuel samples containing water. This is denoted by the notation of beyond scope of method (BSOM) in the results. In addition, the distillation of the JP-8 plus 6%vol surfactant yielded abnormal results. Subsequently, all other distillations of samples containing just fuel and surfactant were considered to be beyond the scope of method).

Table 3 - Base, FRF, and FRF+MCA Fuel Analysis Results

Property	Test Method	Haltermann Certified Diesel	+ 6% Vol Surfactant	+10% Vol Water	+125 ppm Mist Control Additive	JP-8 (Blended from Jet A)	+ 6% vol Surfactant	+ 10% vol Water	+ 125 ppm Mist Control Additive	JP-8 (Age Refinery)	+ 6% vol Surfactant	+ 10% Vol Water	+ 125 ppm Mist Control Additive	+ 250 ppm Mist Control Additive
Hydrocarbons by FIA	D1319													
Aromatic *(vol%)*		30.9	26.1	BSOM†	BSOM†	16.9	17.2	BSOM†	BSOM†	16.9	17.6	BSOM†	BSOM†	BSOM†
Olefin *(vol%)*		2.0	4.0	BSOM†	BSOM†	2.7	4.0	BSOM†	BSOM†	1.0	1.1	BSOM†	BSOM†	BSOM†
Saturates *(vol%)*		67.1	69.9	BSOM†	BSOM†	80.4	78.8	BSOM†	BSOM†	82.1	81.3	BSOM†	BSOM†	BSOM†
Heat of Combustion	D240													
GROSS *(BTU/lb)*		19725.1	19270.3	17548.6	17669.2	19706.7	19369.7	17181.7	17124.6	19915.3	19533.0	17266.4	17275.6	17573.4
NET *(BTU/lb)*		18436.0	18068.8	16482.1	16544.3	18470.5	18160.9	15984.8	15928.6	18639.0	18281.3	16053.0	16061.3	16357.3
Sulfur *(wt%)*	D2622	10ppm	<0.001	<0.001	<0.001	0.0027	0.0024	0.0018	0.002	0.007	0.007	0.005	0.005	0.005
Nitrogen *(ppm)*	D4629	1.4	3138.0	2812.3	2799.8	1.0	3167.7	3281.4	3227.3	1.2	3667.0	3100.0	3980.0	2853
Flash Point *(°F)*	D93	166	165	321‡	321‡	134	141	142	138	107.1	100.4	104	96.8	97.7
(°C)		74.4	73.9	160.6‡	160.6‡	56.7	60.6	61.1	58.9	41.7	38	40	36	36.5
Kinematic Viscosity, 40C (cSt)	D445	2.63	3.65	4.19	4.32	1.29	1.84	2.15	2.34	1.1	1.74	2.15	2.68	4.97
Density, 15C (g/mL)	D4052	0.8484	0.8566	0.8698	0.8690	0.8144	0.8258	0.8435	0.8426	0.7912	0.8033	0.8249	0.8255	0.8223
SLBOCLE (g)	D6078	4400	5400	5150	5000	3550	4900	4200	3900	3200	4400	3000	5600	4400
BOCLE (mm)	D5001	0.46	0.45	0.54	0.55	0.46	0.47	0.53	0.57	0.49	0.5	0.55	0.6	0.56
HFRR (µm)	D6079	584	239	229	237	702	245	245	278	537	263	0.216	0.256	0.285
IQT	D6890-04	42.49	40.01	37.85	37.56	38.79	38.24	32.71	32.50	43.41	43.17	37.06	37.44	38.52
Bulk Modulus (average)	D6793	240055	244522	251427	254287*	220041	232098	232212	231897*	211141	215625	233180	206067*	184949*
Hydrogen *(mass%)*	D5291	14.1	13.17	12.27	12.78	13.66	13.26	13.12	12.65	13.96	13.72	13.3	13.31	13.33
Distillation	D86													
IBP		184.3	177.3			171.4				136.2				
10		210.7	209.8			184.9				157.8				
20		224.4	225.1	BSOM†	BSOM†	189	Abnormal	BSOM†	BSOM†	164.1	BSOM†	BSOM†	BSOM†	BSOM†
50		261.9	263			199.9	Run			184.9				
90		315.5	310.7			225.8				236.7				
FBP		340.7	310.6			247.3				259.9				

†BSOM - Beyond scope of method with water present, ‡Abnormal result believed to be a product of water content

*Operator noted difficulty in removing entrained air with AMA samples in Bulk Modulus testing. Air bubbles present in the fluid will effect measured Bulk Modulus.

Property	Age JP8 + 3% vol Surfactant	+ 5% Vol Water	+ 250 ppm Mist Control Additive
Hydrocarbons by FIA			
Aromatic *(vol%)*	17.8	BSOM†	BSOM†
Olefin *(vol%)*	0.9	BSOM†	BSOM†
Saturates *(vol%)*	81.3	BSOM†	BSOM†
Heat of Combustion			
GROSS *(BTU/lb)*	19770.5	17948.5	18572
NET *(BTU/lb)*	18514.2	16713.2	17326.7
Sulfur *(wt%)*	0.007	0.006	0.006
Nitrogen *(ppm)*	1600.0	2167.0	1862
Flash Point *(°F)*	104	109.4	94.1
(°C)	40	43	34.5
Kinematic Viscosity, 40C (cSt)	1.38	1.67	1.69
Density, 15C (g/mL)	0.7965	0.8152	0.8075
SLBOCLE (g)	3700	4800	5100
BOCLE (mm)	0.47	0.59	0.55
HFRR (µm)	0.247	0.207	0.285
IQT	44.30	39.31	41.12
Bulk Modulus (average)	211278	215176	178594*
Hydrogen *(mass%)*	13.77	13.54	13.65
Distillation			
IBP			
10			
20	BSOM†	BSOM†	BSOM†
50			
90			
FBP			

Critical fuel properties that have the most impact on the engine performance are: density, viscosity, and heat of combustion. The relationship of these properties, coupled with the design of the fuel injection system, greatly impact the power output of a given engine. As discussed further in the report, the density and viscosity of the fuel used has a significant impact on efficiency of the Stanadyne rotary injection pump used in the GEP 6.5L(T) engine, thus largely effecting its power output when varying fuels. In contrast, the hydraulically actuated electronically controlled unit injector (HEUI) injection system used on the CAT C7 engine does not show a large sensitivity to these properties, and is less affected by varying fuels.

3.2 ENGINE PERFORMANC EVALUATIONS

Powercurves were used to quantify changes in engine power and torque output as a function of the fuel used. Powercurves consist of running the engines at full rack from idle to engine governed speed in 200-rpm increments. Data was logged continuously throughout the run to monitor the state of the engine and its overall performance. To mitigate any possible transient effects, data was logged at each interval for two minutes after reaching steady state conditions at a constant engine speed. Reported data is comprised of the average value of the final two minutes of each step of the powercurve. Engine speed is controlled by an energy absorbing dynamometer while engine control and data acquisition is handled by a SwRI developed PRISM data acquisition system. Three powercurves were run for each individual fuel with the resulting data averaged to minimize any bias due to ambient conditions or test stand variation.

3.2.1 Engine Specifications

The CAT C7 engine is a 7.2L direct injected turbocharged intercooled diesel engine. It uses a hydraulically actuated, electronically controlled unit injection (HEUI) fuel system, producing approximately 330hp* and 860ft-lbs* of torque. Detailed engine specifications can be seen below in Table 4 (*when operating on diesel fuel).

Table 4 - CAT C7 Engine Specifications

Bore	4.33 inch ~ 110 mm
Stroke	5.00 inch ~ 127 mm
Displacement	441 in^3 ~ 7227 cc
Injection	HEUI
Rated Power	330 HP ~ 246 kW @ 2400 rpm
Rated Load	860 ft·lbf ~ 1166 N·m @ 1440 rpm

The GEP 6.5L(T) engine is a 6.5L pre-chamber injection turbocharged diesel engine. It uses a mechanically controlled rotary fuel injection system (pump line nozzle configuration) producing approximately 190hp* and 385ft-lbs* of torque. Detailed engine specifications can be seen below in Table 5 (*when operating on diesel fuel).

Table 5 – GEP 6.5L(T) Engine Specifications

Bore	4.06 inch ~ 103 mm
Stroke	3.82 inch ~ 97.03 mm
Displacement	394.7 in^3 ~ 6468 cc
Injection	Mechanical Injection
Rated Power	190 hp ~ 141 kW @ 3400 rpm
Rated Load	385 ft-lb ~ 522 N·m @ 1800 rpm

3.2.2 Test Cell Installations

Each engine is installed into a test cell with systems to monitor and control the engine functions. Figure 1 and Figure 2 below respectively shows the CAT C7 and GEP 6.5L(T) test cell installations.

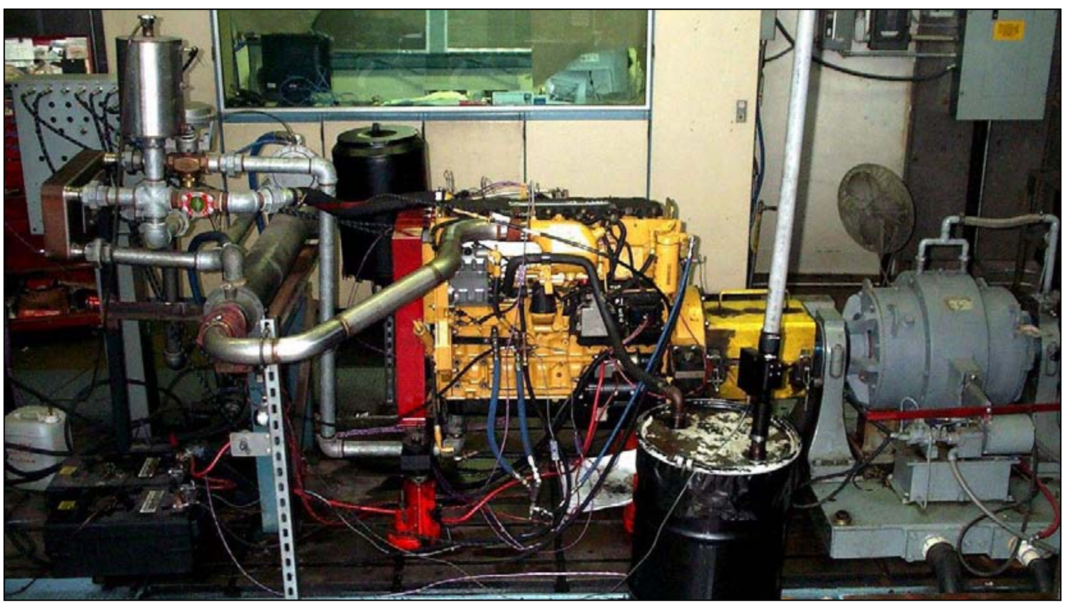

Figure 1 - CAT C7 Test Cell Installation

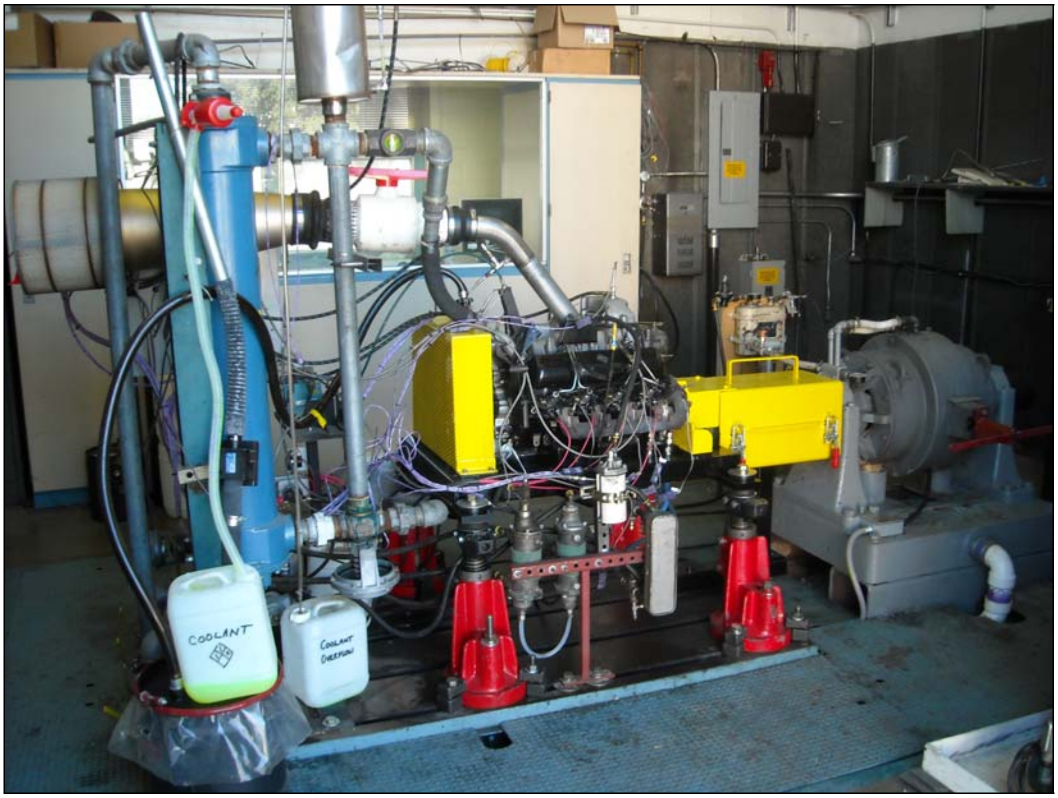

Figure 2 - GEP 6.5L(T) Test Cell Installation

- Each engine is instrumented to monitor various engine parameters, temperatures, and pressures. An SwRI developed PRISM data acquisition and controls system is used to display and log real time engine data during testing.
- Engine speed is controlled by an energy absorbing dynamometer. Engine load is controlled using a PRISM controller to simulate operator pedal input.
- Coolant and fuel temperature are controlled by PRISM using the building supplied process water and appropriately sized heat exchangers.
- The GEP 6.5L(T) oil temperature is independently controlled by PRISM using an external oil to water heat exchanger. The CAT C7 relies on an internal engine coolant to oil heat exchanger for oil temperature control.
- Engines are supplied with fuel by using a “day tank” at ambient pressure that allows the engine to feed and return fuel as needed. Fuel in the day tank is kept at a constant level by a secondary fuel pump that replenishes the tank supply as necessary. The make-up

fuels flow rate into the day tank is the resulting fuel used by the engine, and is measured by a Micromotion mass flowrate system and logged with PRISM.

- Inlet air is drawn in from the building ventilation system at ambient conditions.
- Engine exhaust is drawn from the engine by the building exhaust handling system and discharged outside to the atmosphere. Butterfly valves are used to regulate engine exhaust backpressure.
- Emissions are sampled from an exhaust probe installed between the engine and exhaust system butterfly valve.
- Crankcase blowby is ducted through a drum to capture any entrained oil. Gases are then vented to the ambient air from the drum through a hot-wire flow meter to measure the blowby rate.
- Engines are lubricated with Army Reference Oil, MIL-PRF-2104G, SAE grade 15W40.

3.2.3 Caterpillar Performance Plots

Final powercurves for the CAT C7 engine are broken down to specific base fuels and their appropriate FRF blends. Base fuels include Haltermann Certified Diesel, JP-8 blended from Jet-A, and Age Refining JP-8. All powercurve plots for each base fuel and respective FRF blend can be seen below. Discussion of C7 powercurve data and relative power output changes for each fuel can be seen in the “Changes in Engine Performance” section of the report.

Figure 4 and Figure 4 below shows the maximum output power and torque change between DF2, DF2-FRF, and DF2-FRF MCA (125ppm). As expected, DF2 produced the most power and torque while DF2-FRF MCA produced the least. (Note - with the addition of water in the FRF, the shape of the torque curve near the standard C7 1400rpm peak torque point is skewed. This effect is exaggerated with the use of MCA fuels as shown in the plots, with the peak torque point actually shifting later in the engine speed range to 1600rpm. Due to this “flattening” of the torque curve in the C7 engine with the change in fuel composition, all torque data for the C7 will be compared at both the standard 1400rpm point as well as 1600rpm to allow for a thorough comparison.)

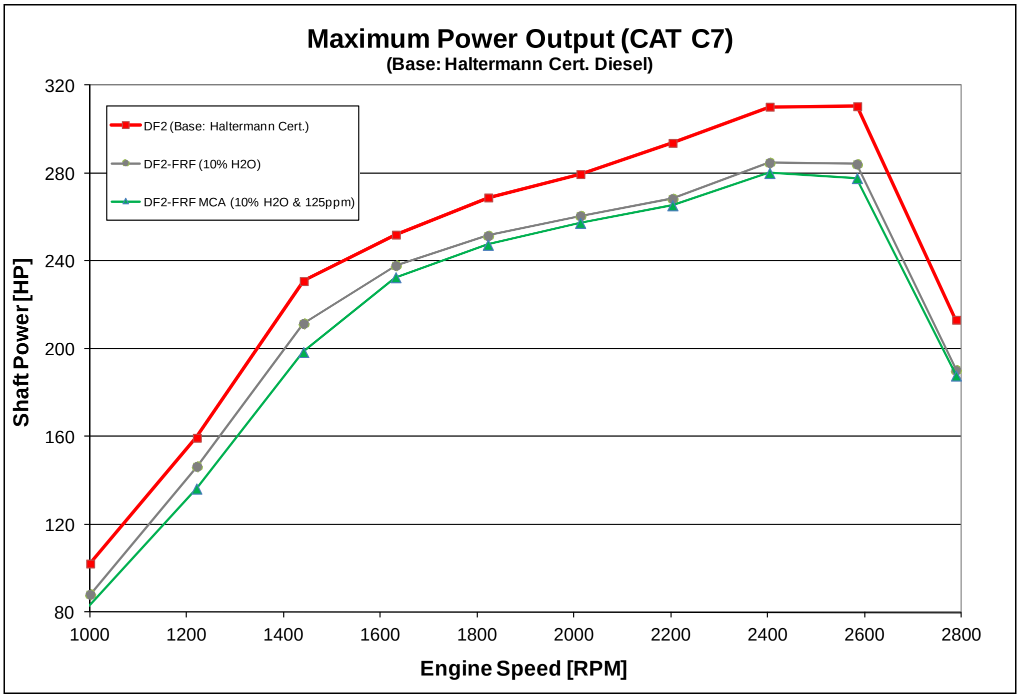

Figure 3 - CAT C7 Maximum FRF Power Output (Base: Haltermann Cert.)

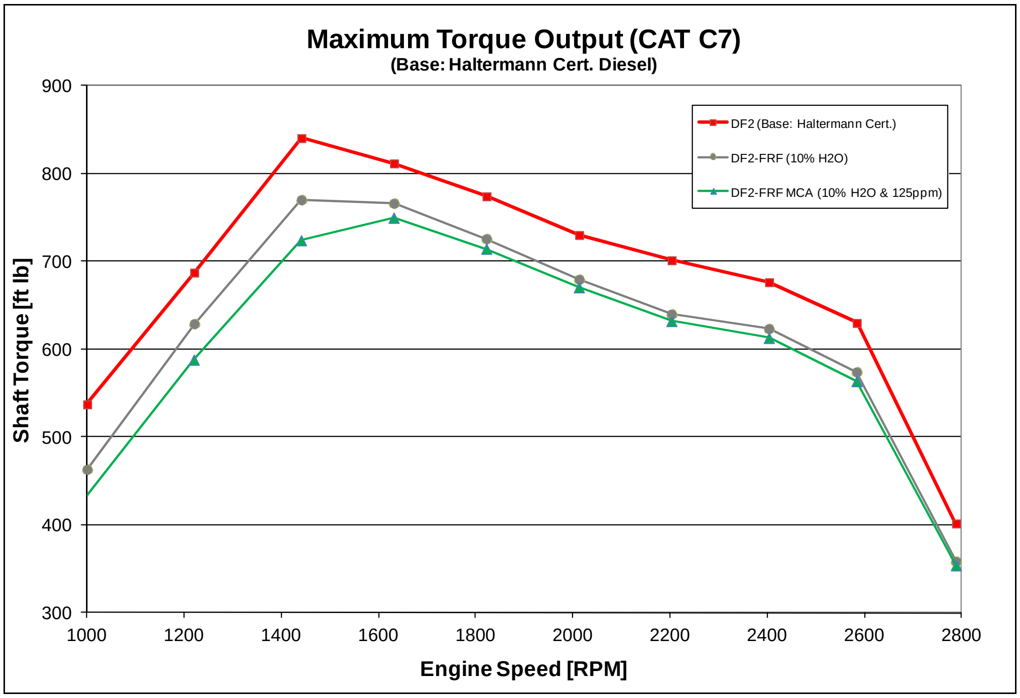

Figure 4 - CAT C7 Maximum FRF Torque Output (Base: Haltermann Cert.)

Figure 5 below shows the brake specific fuel consumption (BSFC) for the CAT C7 using DF2 and FRF blends.

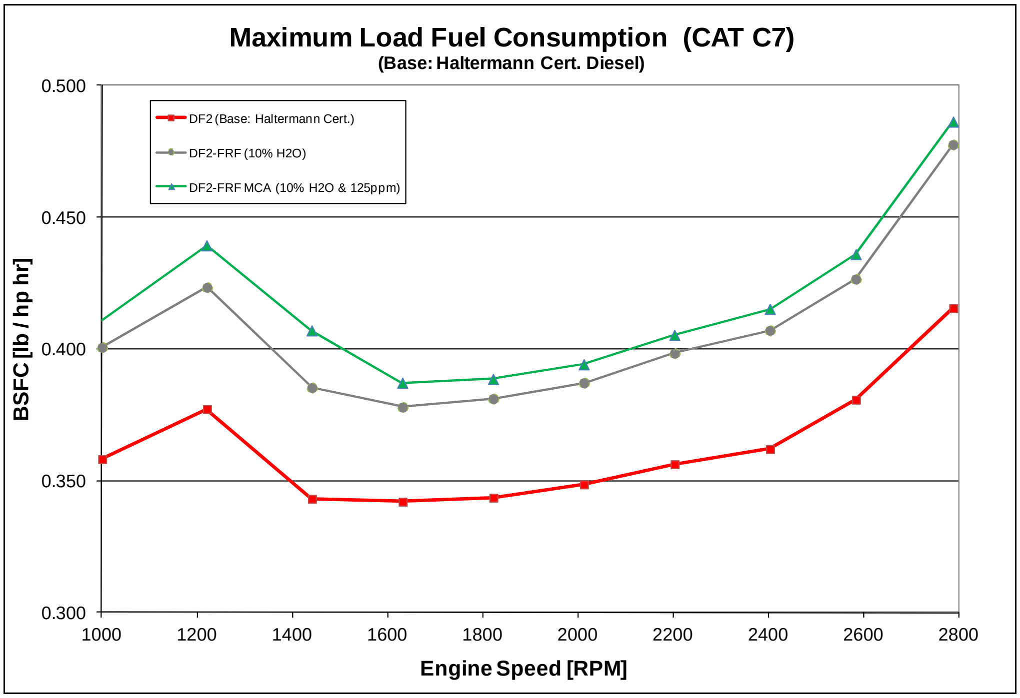

Figure 5 - CAT C7 FRF Brake Specific Fuel Consumption (Base: Haltermann Cert.)

Figure 6 and Figure 7 below shows the maximum output power and torque change between blended JP-8, JP-8-FRF, and JP-8-FRF MCA (125ppm). As expected, JP-8 produced the most power and torque, and JP-8-FRF MCA produced the least.

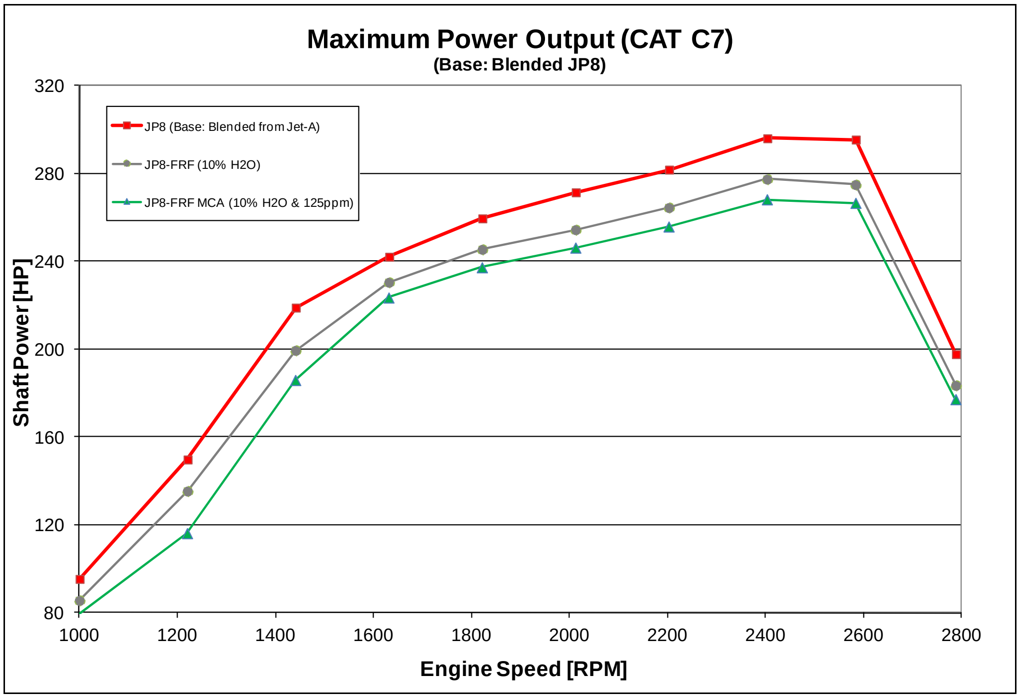

Figure 6 - CAT C7 Maximum FRF Power Output (Base: Blended JP-8)

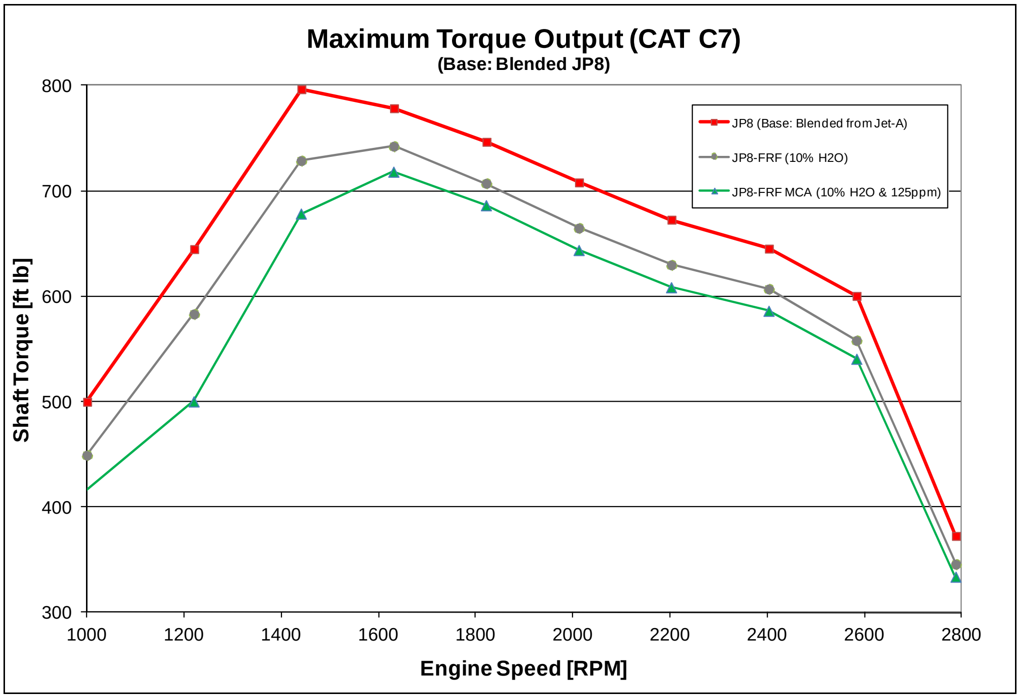

Figure 7 - CAT C7 Maximum FRF Torque Output (Base: Blended JP-8)

Figure 8 below shows the brake specific fuel consumption (BSFC) for the Cat C7 using blended JP8 and FRF blends.

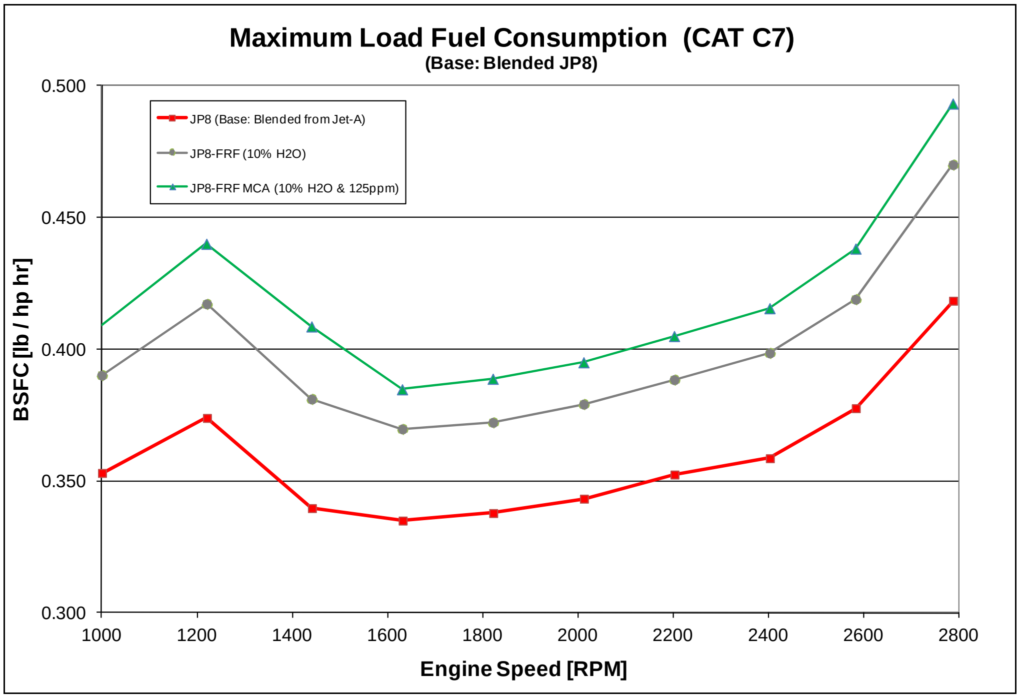

Figure 8 - CAT C7 FRF Brake Specific Fuel Consumption (Base: Blended JP-8)

Figure 9 and Figure 10 below shows the maximum output power and torque change between Age Refining JP-8, JP-8-FRF, and JP-8-FRF MCA (250ppm). As expected, JP-8 produced the most power and torque. In addition, the FRF blend with only 5%vol of water made more power and torque than both FRF blends with 10%vol water.

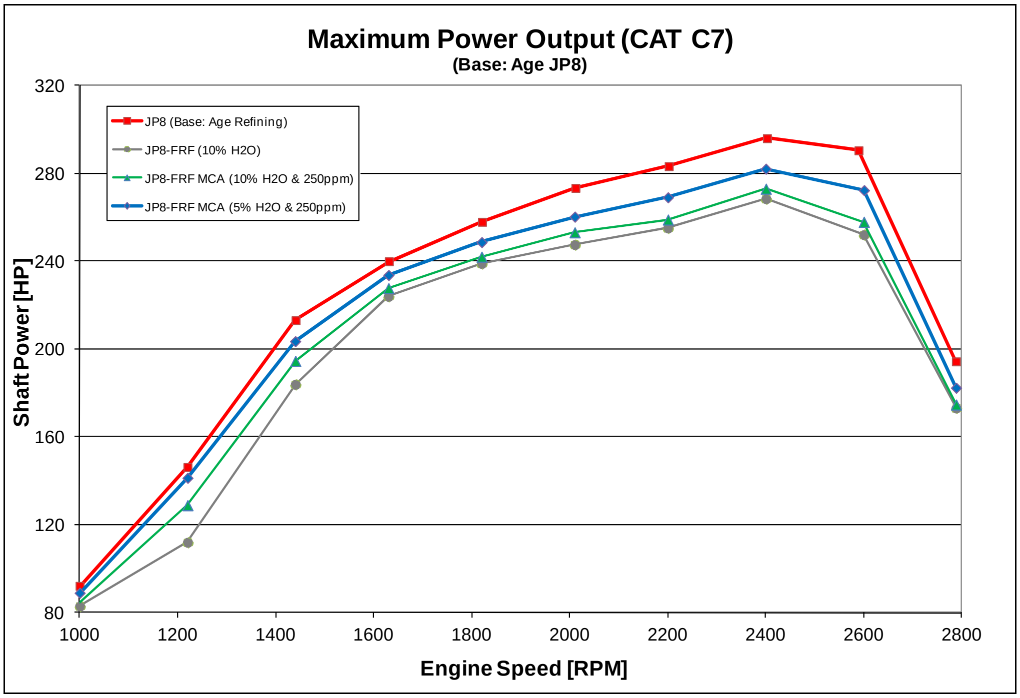

Figure 9 - CAT C7 Maximum FRF Power Output (Base: Age JP-8)

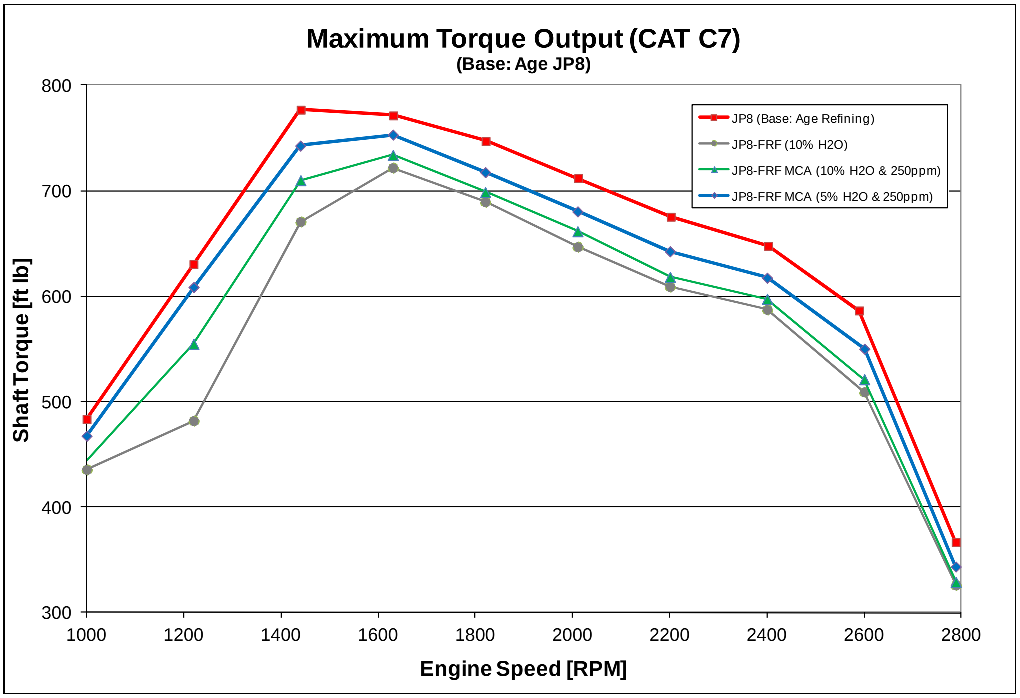

Figure 10 - CAT C7 Maximum FRF Torque Output (Base: Age JP-8)

Figure 11 below shows the brake specific fuel consumption (BSFC) for the CAT C7 using Age Refining JP-8 and FRF blends.

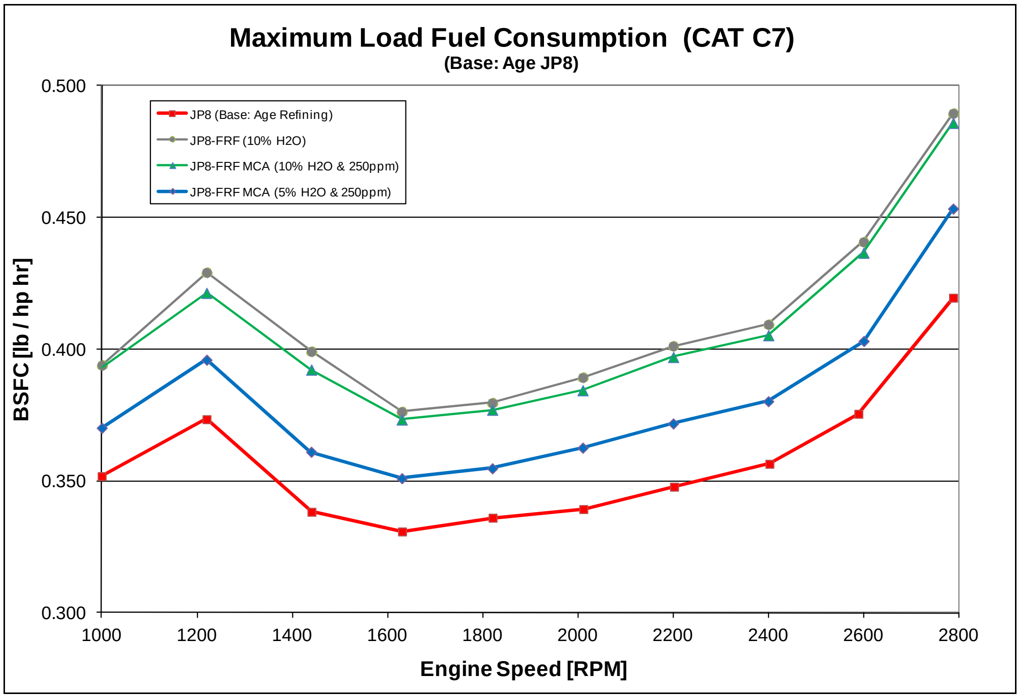

Figure 11 - CAT C7 FRF Brake Specific Fuel Consumption (Base: Age JP-8)

3.2.4 General Engine Products Performance Plots

Final powercurves for the GEP 6.5L(T) engine are broken down to specific base fuels and their appropriate FRF blends. Base fuels include Haltermann Certified Diesel, JP-8 blended from Jet-A, and Age Refining JP-8. All powercurve plots for each base fuel and respective FRF blend can be seen below. Discussion of GEP 6.5L(T) powercurve data and relative power output changes for each fuel can be seen in the "Changes in Engine Performance" section of the report.

Figure 12 and Figure 13 below shows the maximum output power and torque change between DF2, DF2-FRF, and DF2-FRF MCA (125ppm). As expected, DF2 produced the most power and torque while DF2-FRF MCA produced the least.

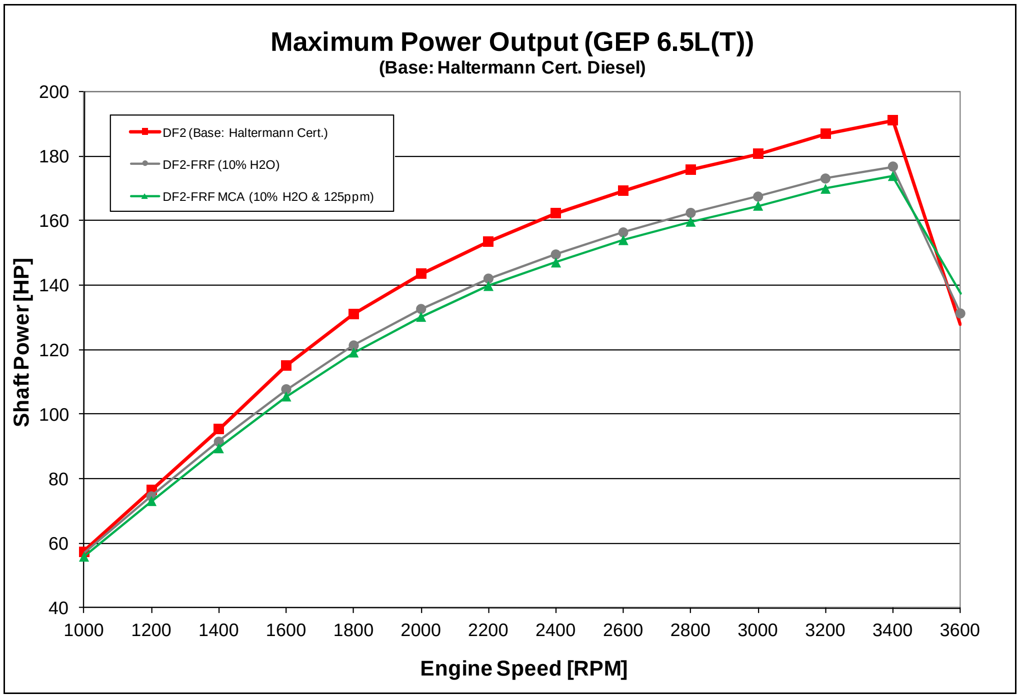

Figure 12 – GEP 6.5L(T) Maximum FRF Power Output (Base: Haltermann Cert.)

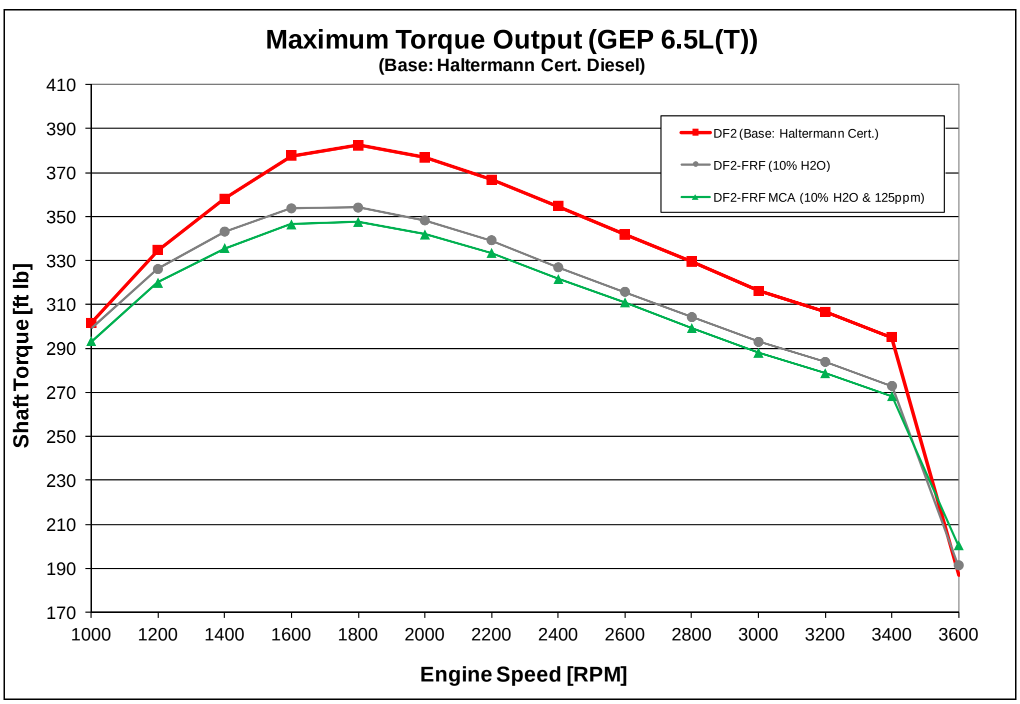

Figure 13 – GEP 6.5L(T) Maximum FRF Torque Output (Base: Haltermann Cert.)

Figure 14 below shows the brake specific fuel consumption (BSFC) for the GEP 6.5L(T) using DF2 and FRF blends.

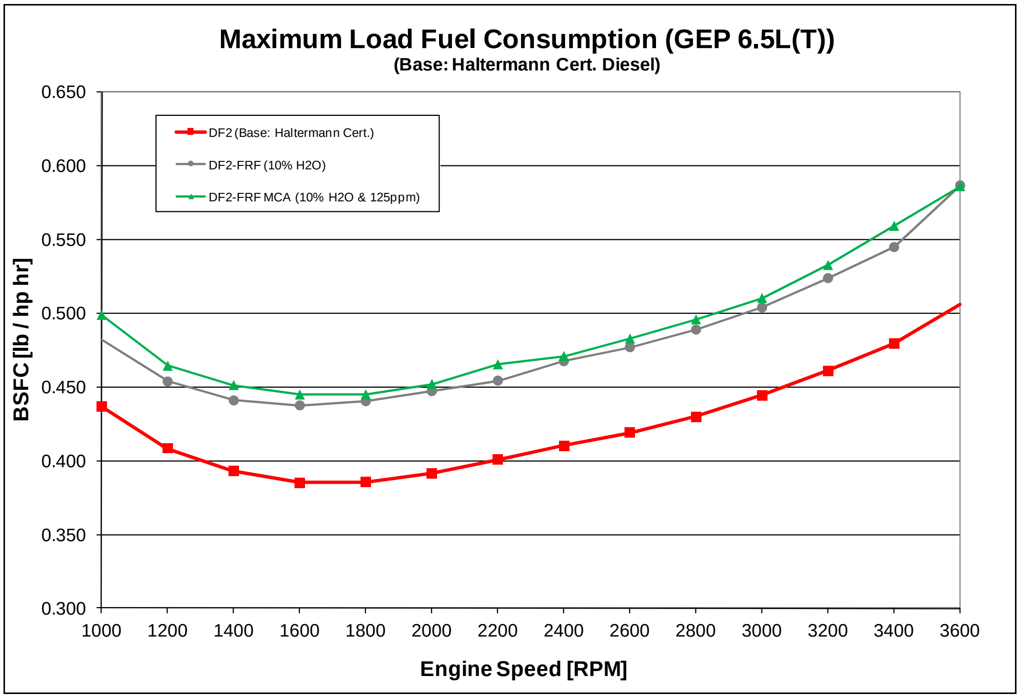

Figure 14 – GEP 6.5L(T) FRF Brake Specific Fuel Consumption (Base: Haltermann Cert.)

Figure 15 and Figure 16 below shows the maximum output power and torque change between blended JP-8, JP-8-FRF, and JP-8-FRF MCA (125ppm). As expected, JP-8 produced the most power and torque, and JP-8-FRF MCA produced the least. (Note, for all JP-8 based FRF blends, output power and torque for engines speeds below 1400rpm are the same or better than its respective base fuel. This is due to the sensitivity of the Stanadyne rotary injection pump to the fuels density and viscosity. The resulting increase in the FRF's density and viscosity due to the surfactant and water outweighs the reduction in heat of combustion due to the water content, yielding greater engine output. The FRF blends effectively increase the efficiency of the injection pump improving engine performance).

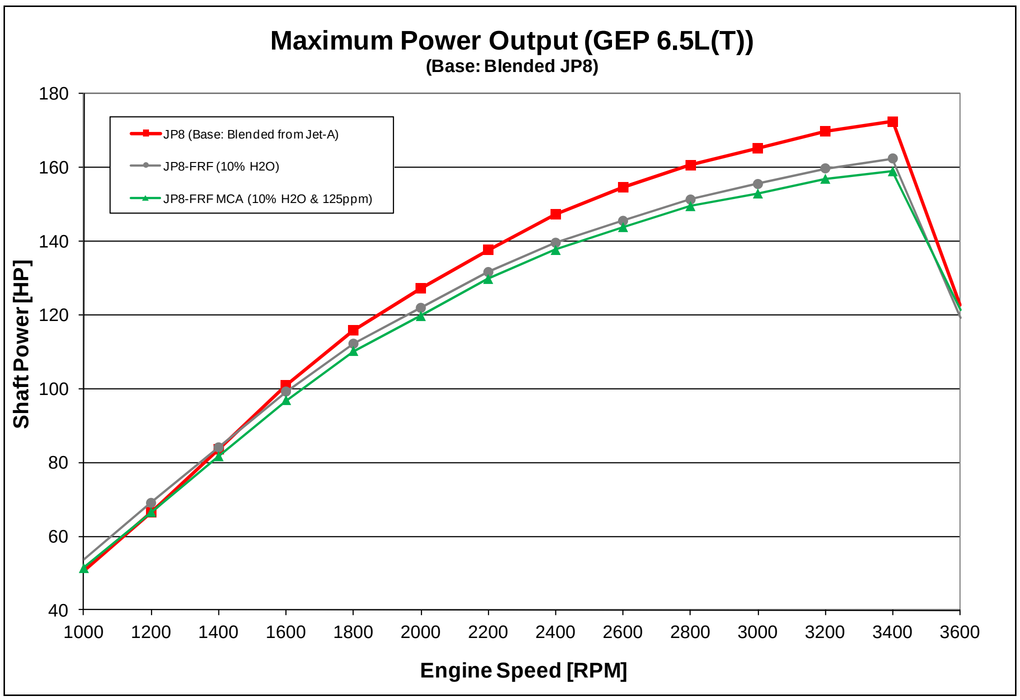

Figure 15 – GEP 6.5L(T) Maximum FRF Power Output (Base: Blended JP-8)

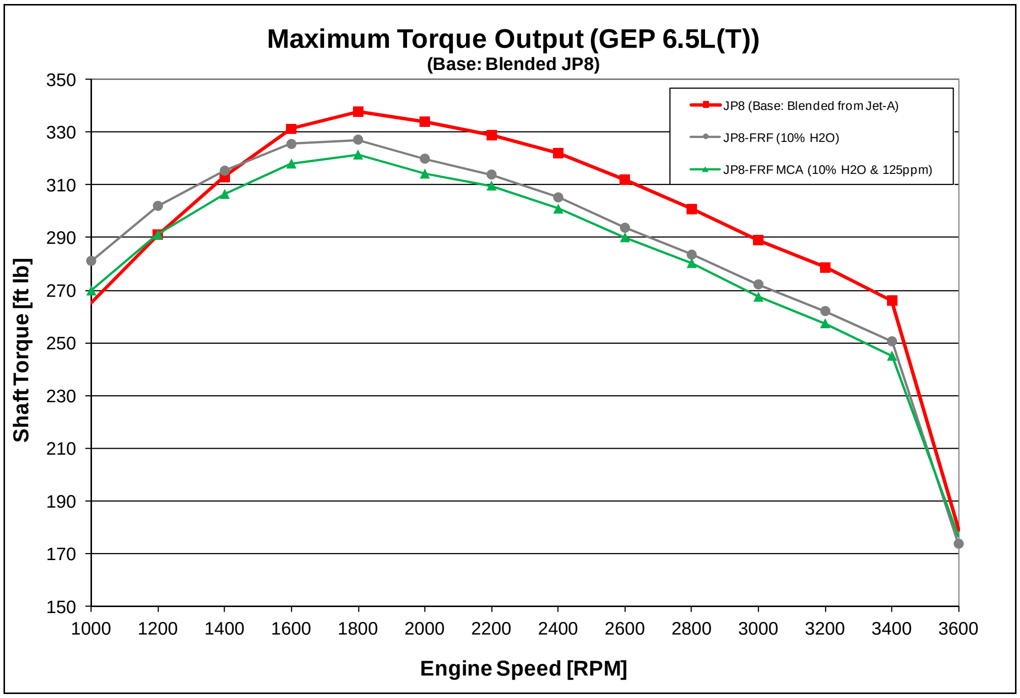

Figure 16 – GEP 6.5L(T) Maximum FRF Torque Output (Base: Blended JP-8)

Figure 17 below shows the brake specific fuel consumption (BSFC) for the GEP 6.5L(T) using blended JP-8 and FRF blends.

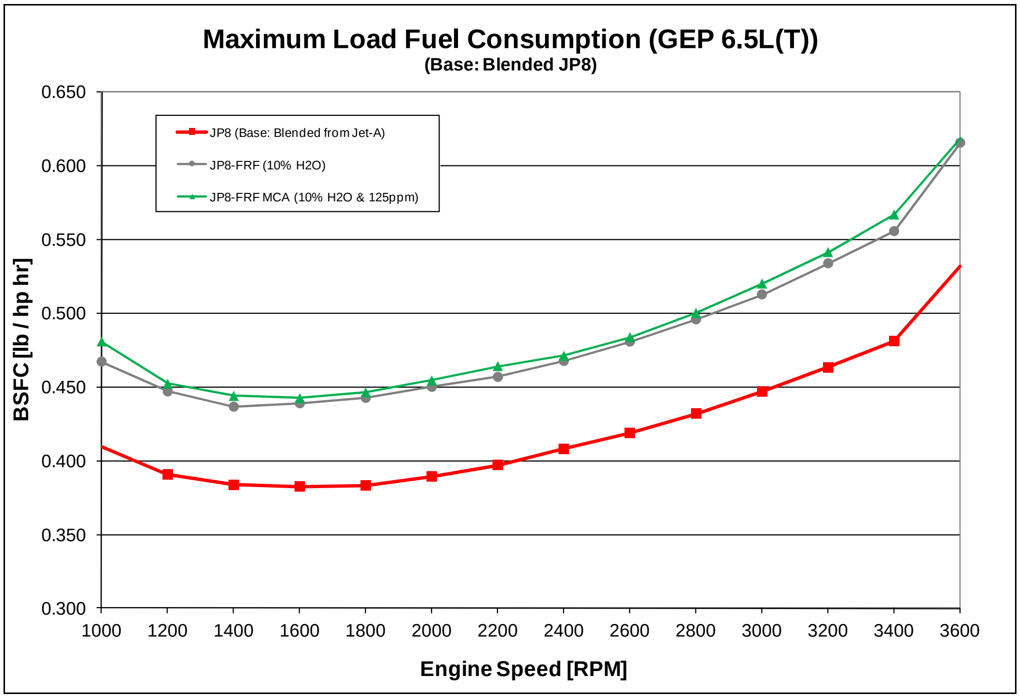

Figure 17 – GEP 6.5L(T) FRF Brake Specific Fuel Consumption (Base: Blended JP-8)

Figure 18 and Figure 19 below shows the maximum output power and torque change between Age Refining JP-8, JP-8-FRF, and JP-8-FRF MCA (250ppm). As expected, JP-8 produced the most power and torque. Interestingly, all other FRF blends made similar power and torque despite the varying concentrations of water and MCA. When comparing this phenomenon to fuel property analysis, it is noted that despite the decreased water content present in the 5% water FRF blend which should yield increased heat of combustion, the viscosity and density do not receive the benefit from the increased levels of water and surfactant in the fuel. As previously noted, the Stanadyne rotary injection pump is sensitive to these properties, thus power output of the GEP 6.5L(T) engine is heavily dependent on them.

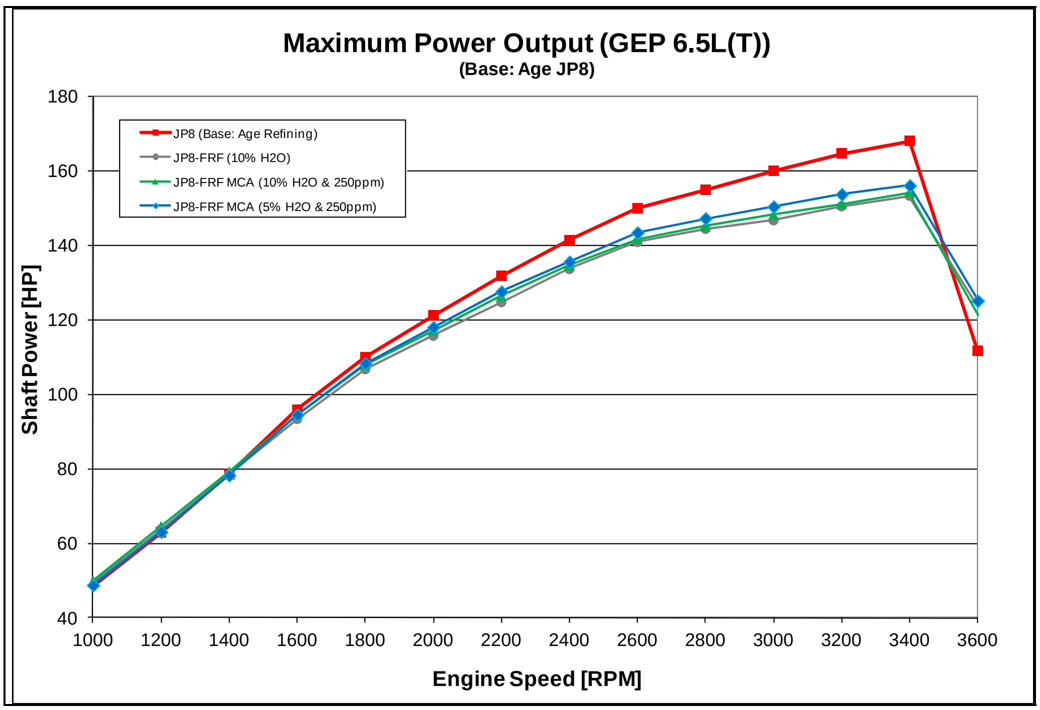

Figure 18 – GEP 6.5L(T) Maximum FRF Power Output (Base: Age JP-8)

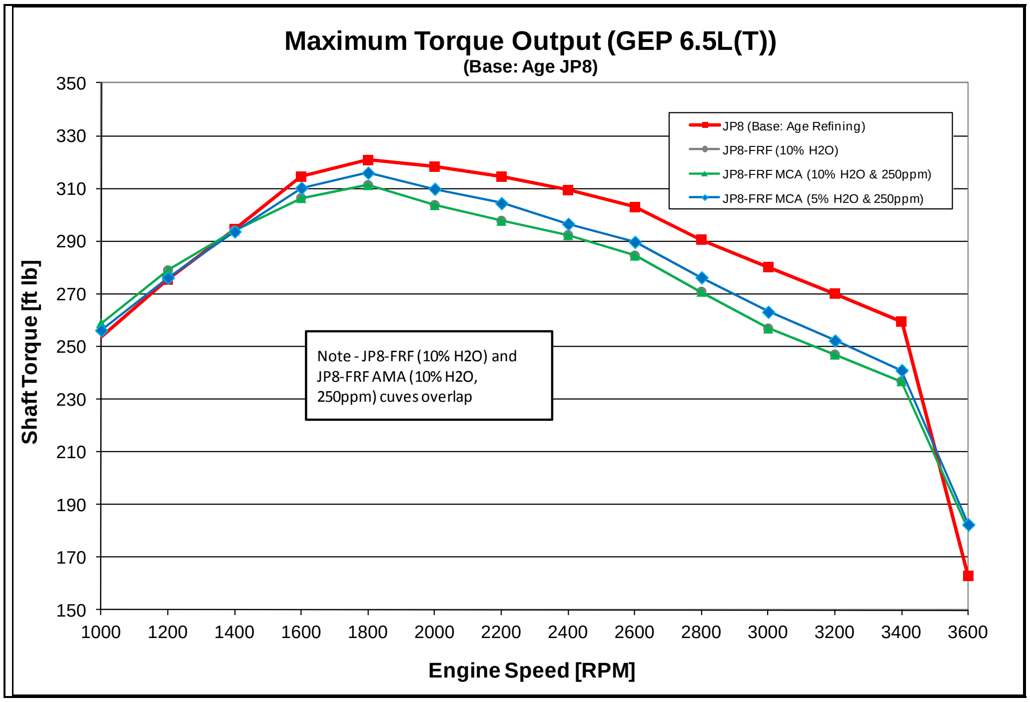

Figure 19 – GEP 6.5L(T) Maximum FRF Torque Output (Base: Age JP-8)

Figure 20 below shows the brake specific fuel consumption (BSFC) for the CAT C7 using Age Refining JP-8 and FRF blends.

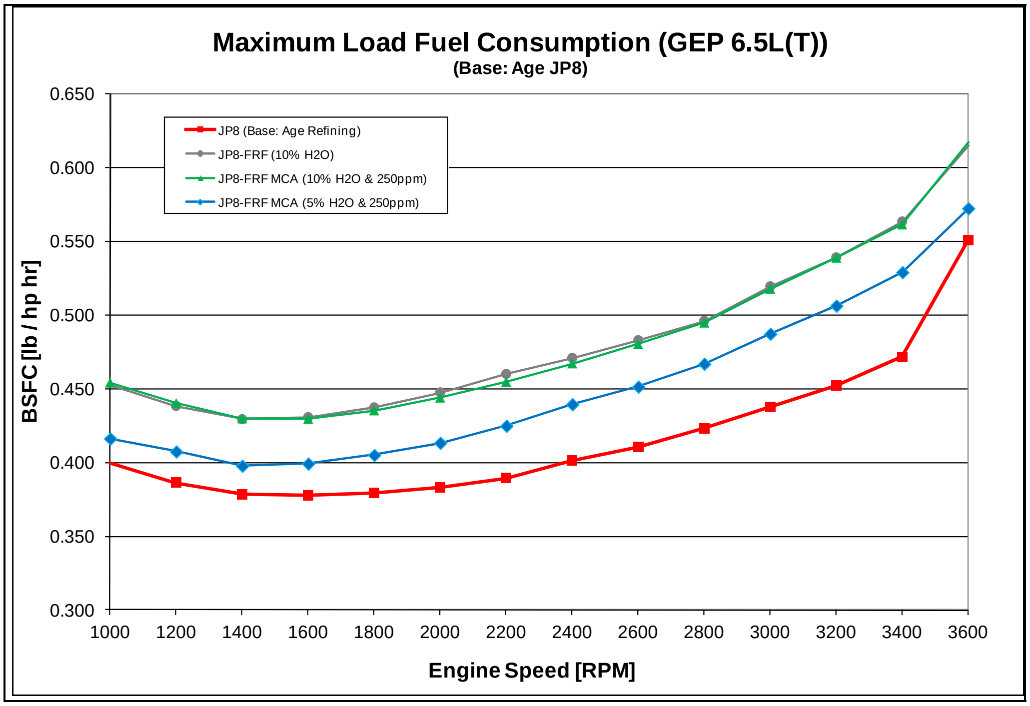

Figure 20 – GEP 6.5L(T) FRF Brake Specific Fuel Consumption (Base: Age JP-8)

3.2.5 Change In Engine Performance and Statistical Analysis

To determine overall test stand repeatability, and verify actual performance losses versus test stand deviation, statistical analysis was completed for C7 and 6.5L(T) engines. The analysis consisted of running 5 additional powercurves using DF2 to determine the significance of the calculated losses between base, FRF, and FRF+MCA fuel blends. Using the Student's T-test analysis approach, all engine output power and torque losses were compared between each base, FRF, and FRF+MCA fuel blend to determine whether the change was significant based on the 95% and 99% confidence interval. Table 6 and Table 7 on the next pages show in detail the statistical analysis results for the CAT C7 and the GEP 6.5L(T) engine respectively.

Table 6 - CAT C7 Statistical Analysis Comparison - All Fuels

	DF2 (Haltermann Cert.)			DF2 - FRF (Haltermann Cert.)			DF2-FRF MCA (Haltermann Cert., 125ppm)			JP8 (Blended)			JP8-FRF (Blended)			JP8-FRF MCA (Blended, 125ppm)		
	8 Total Runs			3 Total Runs			3 Total Runs			3 Total Runs			3 Total Runs			3 Total Runs		
	Power 2400rpm [hp]	Torque 1400rpm [ft lbs]	Torque 1600rpm [ft lbs]	Power 2400rpm [hp]	Torque 1400rpm [ft lbs]	Torque 1600rpm [ft lbs]	Power 2400rpm [hp]	Torque 1400rpm [ft lbs]	Torque 1600rpm [ft lbs]	Power 2400rpm [hp]	Torque 1400rpm [ft lbs]	Torque 1600rpm [ft lbs]	Power 2400rpm [hp]	Torque 1400rpm [ft lbs]	Torque 1600rpm [ft lbs]	Power 2400rpm [hp]	Torque 1400rpm [ft lbs]	Torque 1600rpm [ft lbs]
Average	308.71	831.43	807.52	284.80	770.17	766.19	280.15	724.00	749.67	296.10	796.39	778.33	277.31	728.81	743.06	268.27	678.42	718.08
St. Dev.	2.40	14.78	8.59	2.07	26.35	6.52	1.18	1.42	2.54	3.31	6.99	5.17	1.83	5.26	9.09	3.28	26.54	6.50
95% CI (+/-)	1.66	10.24	5.95	1.43	18.26	4.52	0.82	0.98	1.76	2.30	4.85	3.58	1.27	3.65	6.30	2.27	18.39	4.51
Upper Limit	310.37	841.67	813.47	286.23	788.42	770.71	280.97	724.98	751.43	298.39	801.23	781.92	278.58	732.45	749.35	270.54	696.81	722.59
Lower Limit	307.04	821.19	801.57	283.37	751.91	761.68	279.33	723.02	747.90	293.80	791.54	774.75	276.04	725.16	736.76	266.00	660.02	713.58
% Change - Base and FRF				**-7.7%**	**-7.4%**	**-5.1%**							**-6.3%**	**-8.5%**	**-4.5%**			
Statistically Significant w/ 95% CI				YES	YES	YES							YES	YES	YES			
Statistically Significant w/ 99% CI				YES	YES	YES							YES	YES	YES			
% Change - Base and FRF+MCA							**-9.3%**	**-12.9%**	**-7.2%**							**-9.4%**	**-14.8%**	**-7.7%**
Statistically Significant w/ 95% CI							YES	YES	YES							YES	YES	YES
Statistically Significant w/ 99% CI							YES	YES	YES							YES	YES	YES
% Change - FRF and FRF+MCA							**-1.6%**	-6.0%	**-2.2%**							**-3.3%**	**-6.9%**	**-3.4%**
Statistically Significant w/ 95% CI							YES	NO	YES							YES	YES	YES
Statistically Significant w/ 99% CI							NO	NO	NO							NO	NO	NO

% Change in bold represents a statistically significant change with respect to 95% Confidence Interval --- All FRF blends considered to have 10%vol H2O unless otherwise stated.

	JP8 (Age)			JP8-FRF (Age)			JP8-FRF MCA (Age, 250ppm)			JP8-FRF MCA (Age, 5% H2O, 250ppm)		
	3 Total Runs			3 Total Runs			3 Total Runs			3 Total Runs		
	Power 2400rpm [hp]	Torque 1400rpm [ft lbs]	Torque 1600rpm [ft lbs]	Power 2400rpm [hp]	Torque 1400rpm [ft lbs]	Torque 1600rpm [ft lbs]	Power 2400rpm [hp]	Torque 1400rpm [ft lbs]	Torque 1600rpm [ft lbs]	Power 2400rpm [hp]	Torque 1400rpm [ft lbs]	Torque 1600rpm [ft lbs]
Average	296.10	776.83	771.36	268.48	670.80	721.89	273.04	709.94	733.95	282.16	742.75	753.17
St. Dev.	1.84	4.01	1.09	0.94	9.20	0.78	4.63	16.47	11.05	1.21	6.19	2.11
95% CI (+/-)	1.28	2.78	0.75	0.65	6.38	0.54	3.20	11.42	7.66	0.84	4.29	1.46
Upper Limit	297.38	779.61	772.11	269.13	677.18	722.43	276.24	721.36	741.60	283.00	747.04	754.63
Lower Limit	294.83	774.06	770.61	267.83	664.43	721.35	269.83	698.53	726.29	281.32	738.46	751.70
% Change - Base and FRF				**-9.3%**	**-13.6%**	**-6.4%**						
Statistically Significant w/ 95% CI				YES	YES	YES						
Statistically Significant w/ 99% CI				YES	YES	YES						
% Change - Base and FRF+MCA							**-7.8%**	**-8.6%**	**-4.9%**	**-4.7%**	**-4.4%**	**-2.4%**
Statistically Significant w/ 95% CI							YES	YES	YES	YES	YES	YES
Statistically Significant w/ 99% CI							YES	YES	NO	YES	YES	YES
% Change - FRF and FRF+MCA							1.7%	**5.8%**	1.7%			
Statistically Significant w/ 95% CI							NO	YES	NO			
Statistically Significant w/ 99% CI							NO	NO	NO			

Table 7 - GEP 6.5L(T) Statistical Analysis Comparison - All Fuels

	DF2 (Haltermann Cert.)		DF2 - FRF (Haltermann Cert.)		DF2-FRF MCA (Haltermann Cert.,		JP8 (Blended)		JP8-FRF (Blended)		JP8-FRF MCA (Blended, 125ppm)	
	8 Total Runs		3 Total Runs		3 Total Runs		3 Total Runs		3 Total Runs		3 Total Runs	
	Power 3400rpm [hp]	Torque 1800rpm [ft lbs]	Power 3400rpm [hp]	Torque 1800rpm [ft lbs]	Power 3400rpm [hp]	Torque 1800rpm [ft lbs]	Power 3400rpm [hp]	Torque 1800rpm [ft lbs]	Power 3400rpm [hp]	Torque 1800rpm [ft lbs]	Power 3400rpm [hp]	Torque 1800rpm [ft lbs]
Average	190.85	382.72	176.71	354.08	173.76	347.56	172.27	337.69	162.29	327.11	158.85	321.47
St. Dev.	1.94	4.19	2.16	4.91	0.27	0.19	1.89	5.83	1.76	3.07	0.81	1.36
95% CI (+/-)	1.34	2.91	1.50	3.40	0.19	0.13	1.31	4.04	1.22	2.13	0.56	0.94
Upper Limit	192.20	385.63	178.21	357.48	173.95	347.69	173.58	341.74	163.51	329.24	159.41	322.41
Lower Limit	189.51	379.81	175.21	350.68	173.58	347.42	170.96	333.65	161.08	324.98	158.29	320.53
% Change - Base and FRF			**-7.4%**	**-7.5%**					**-5.8%**	**-3.1%**		
Statistically Significant w/ 95% CI			YES	YES					YES	YES		
Statistically Significant w/ 99% CI			YES	YES					YES	NO		
% Change - Base and FRF+MCA					**-9.0%**	**-9.2%**					**-7.8%**	**-4.8%**
Statistically Significant w/ 95% CI					YES	YES					YES	YES
Statistically Significant w/ 99% CI					YES	YES					YES	YES
% Change - FRF and FRF+MCA					-1.7%	-1.8%					**-2.1%**	**-1.7%**
Statistically Significant w/ 95% CI					NO	NO					YES	YES
Statistically Significant w/ 99% CI					NO	NO					NO	NO
% Change in bold represents a statistically significant change with respect to 95% Confidence Interval												

	JP8		JP8-FRF		JP8-FRF AMA		JP8-FRF AMA	
	3 Total Runs		3 Total Runs		3 Total Runs		3 Total Runs	
	Power 3400rpm [hp]	Torque 1800rpm [ft lbs]	Power 3400rpm [hp]	Torque 1800rpm [ft lbs]	Power 3400rpm [hp]	Torque 1800rpm [ft lbs]	Power 3400rpm [hp]	Torque 1800rpm [ft lbs]
Average	167.96	320.72	152.34	311.28	154.15	314.91	155.17	315.97
St. Dev.	0.16	2.06	1.99	1.72	1.90	1.91	0.45	1.42
95% CI (+/-)	0.11	1.43	1.38	1.19	1.32	1.32	0.31	0.98
Upper Limit	168.06	322.15	153.72	312.47	155.47	316.24	155.48	316.95
Lower Limit	167.85	319.29	150.96	310.08	152.83	313.59	154.86	314.99
% Change - Base and FRF			**-9.3%**	**-2.9%**				
Statistically Significant w/ 95% CI			YES	YES				
Statistically Significant w/ 99% CI			YES	YES				
% Change - Base and FRF+MCA					**-8.2%**	**-1.8%**	**-7.6%**	**-1.5%**
Statistically Significant w/ 95% CI					YES	YES	YES	YES
Statistically Significant w/ 99% CI					YES	NO	YES	NO
% Change - FRF and FRF+MCA					1.2%	1.2%		
Statistically Significant w/ 95% CI					NO	NO		
Statistically Significant w/ 99% CI					NO	NO		
All FRF blends considered to have 10%vol H2O unless otherwise stated.								

From Table 6 we can see that for the CAT C7 we show an approximate loss of 8% in peak power and 7.5% in peak torque from base diesel to DF2-FRF, and an additional 1-2% loss in peak power and observed peak torque with addition of MCA. Similarly, with blended JP-8, we see a 6% loss in peak power and 4.5% loss in observed peak torque from base JP-8 to JP-8-FRF, and an additional 3% loss in peak power and observed peak torque with the addition of MCA. Finally, we see a 9% loss in peak power and 6.5% loss in observed peak torque from Age JP-8 to JP-8-FRF, and no statistically significant change with the addition of MCA. The overall losses experienced with the use of FRF blends in the CAT C7 tend to show a larger shift in output power then compared to the approximate loss of 4% output that is experienced from using JP-8 fuels over DF2.

From Table 7 we can see that the GEP 6.5L(T) engine experiences an approximate loss of 7.5% in peak power and torque from base diesel to DF2-FRF blend, and no statistically significant change in engine output with the addition of MCA. For blended JP-8, the 6.5L(T) engine shows a loss of 6% in peak power and 3% in peak torque with the JP-8-FRF blend, and an additional 2% in peak power and torque loss with the MCA. Lastly, the Age JP-8 blend showed a loss of 9% in peak power and 3% in peak torque with the JP-8-FRF blend, and no statistically significant change with the addition of MCA. Unlike the CAT C7, the overall losses experienced with the use of FRF blends in the GEP 6.5L(T) tend to show a smaller shift in output power then compared to the approximate 10-12% output loss that is experienced from using JP-8 fuels over DF2. As previously discussed, the FRF fuels in the GEP 6.5L(T) engine see benefit from the addition of surfactant and water which results in an increase in fuel viscosity. This translates into an increase in efficiency of the Stanadyne rotary injection pump which helps compensate for some of the losses.

For FRF blends containing only 5% H_2O, the CAT C7 saw a corresponding increase in output power and torque with the reduction in water content, yielding a 5% loss in peak power and 2.5% loss in observed peak torque over the 8% and 5% loss in peak power and observed peak torque with the 10% water FRF blend. For the GEP 6.5L(T) engine using 5% DI H_2O FRF blends, there was a much smaller increase in power output over the FRF blend with 10% water. This is due again to the sensitivity of the Stanadyne rotary injection pump to the fuels viscosity and density. Despite the higher total energy content of the 5% H_2O blend compared to the 10% H_2O blend, the 5% water blend suffers from a viscosity that is over 60% less than the viscosity of the 10% H_2O FRF blend effectively reducing the efficiency of the injection pump resulting in lower engine output.

3.3 SPECIAL CONSIDERATIONS

Throughout the course of engine compatibility testing, some FRF related engine impact issues where further investigated to help determine total vehicle impact related to FRF use. This includes a micro vs. macro emulsion study on FRF blends and their impact on engine function, and HMMWV performance modeling based on JP-8-FRF data. These issues and their results are discussed below.

3.3.1 Micro vs. Macro Emulsions

Throughout testing, FRF were constantly blended to meet fuel needs for engine performance testing. FRF developed by SwRI are based on a micro emulsion where water particles are suspended in the fuel on the sub-micron level, leaving the fuel nearly clear and the presence of water virtually undistinguishable to the naked eye. During one batch of DF2-FRF blending, the water did not emulsify properly into the fuel resulting in a fuel that was milky in appearance. This is termed a macro emulsion when the water present in the fuel is easily distinguished to the naked eye. The macro emulsion contained the same percent volume of water and surfactant as the micro emulsion FRF blend, but the water was not suspended properly in the fuel. Since both the micro and macro emulsion have the same chemical makeup, it was expected that the fuels would perform similarly in the engine. Upon completion of the blend, it was decided to run the macro emulsion in the engine to determine if blend quality had any appreciable effect on engine performance and fuel system functionality. Figure 21 and Figure 22 below, show the resulting powercurves on the CAT C7 when using the macro emulsion DF2-FRF blend.

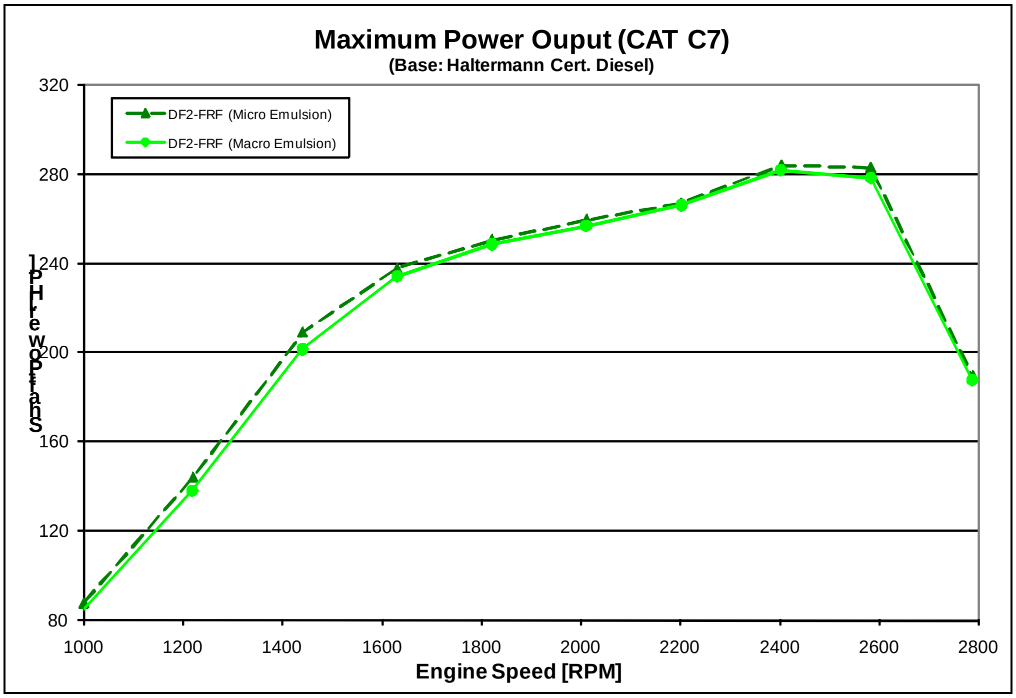

Figure 21 - CAT C7 Emulsion Study, Maximum Power Output

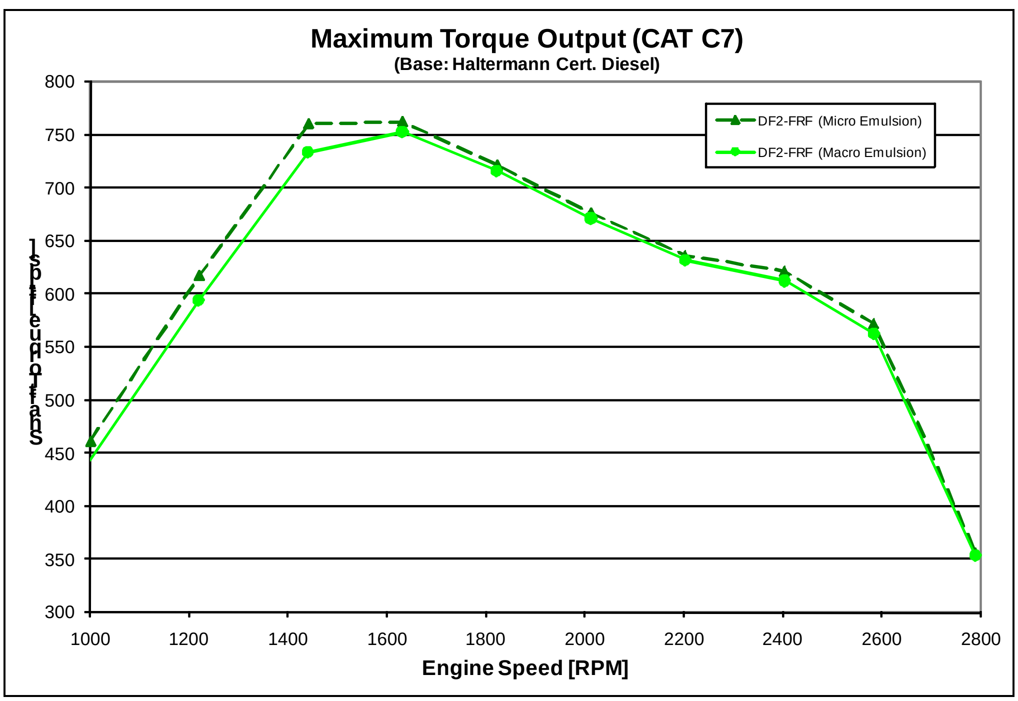

Figure 22 - CAT C7 Emulsion Study, Maximum Torque Output

From the curves, it can be seen that the macro emulsion had no appreciable effect on produced engine power. Peak torque output did experience a loss of 5% from standard DF2-FRF runs at standard 1400rpm peak torque speed, and 2% loss in peak torque at the shifted 1600rpm. Due to the single point macro emulsion data, a complete statistical analysis could not be completed, so it is unknown whether this is statistically significant, or attributable to random test stand variation. This data does however give an indication that a poorly emulsified FRF blend doesn't yield any appreciable engine performance changes over a properly emulsified fuel. Table 8 below summarizes the power and torque variations in the CAT C7.

Table 8 - CAT C7 Emulsion Study, Power and Torque Variations

	Peak Power @ 2400 RPM			Peak Torque @ 1400 RPM			Peak Torque @ 11600 RPM		
	Emulsion	Power, [hp]	Delta	Emulsion	Torque, [ft lbs]	Delta	Emulsion	Torque, [ft lbs]	Delta
DF2-FRF	*Micro*	284.80		*Micro*	770.17		*Micro*	766.19	
DF2-FRF	*Macro*	281.58	-1%	*Macro*	734.00	-5%	*Macro*	752.83	-2%

After testing, fuel samples of the macro emulsion were taken and stored at room temperature to determine the emulsion quality on blend stability. Within a week, the fuel and water had completely separated and would be unusable in equipment without further blending. It was determined from this test that if a macro emulsion can be used immediately upon blending, it appears to pose no mechanical risk to engine function, but is not capable of any reasonable amount of storage time.

3.3.2 Performance Modeling using JP-8 FRF

Upon completion of performance testing using FRF, data was sent to TARDEC to model vehicle performance impact when using JP-8-FRF in the HMMWV and LMTV. Referencing the ATPD 2099C and ATPD 2131 specifications, the modeled values were compared to determine the associated performance loss between JP-8 and JP-8-FRF MCA in each vehicle type. Results can be seen below in Table 9 and Table 10.

Table 9 - HMMWV Performance Modeling using JP-8 and JP-8-FRF MCA

Specification Requirement:	*ATPD 2099C Specification*	JP8 (Blended JP8)	JP8 FRF MCA (Blended JP8, 125ppm)	% change
0-30 mph (s)	9.4	8.95	9.97	11.4
0-50 mph (s)	26.1	23.54	27.12	15.2
Top Speed (mph)	60	71	68	4.4
Speed on Grade				
5% grade (mph)	24	46	40	15.0
20% grade (mph)		18	14	28.6
40% grade (mph)		11	11	0.0
60% grade (mph)		8	7	14.3

Table 10 - LMTV Performance Modeling using JP-8 and JP-8-FRF MCA

Specification Requirement:	*ATPD 2131G Specification*	JP8 (Blended JP8)	JP8 FRF MCA (blended JP8, 125 ppm)	% change
0-30 mph (s)		8.73	9.86	0.1
0-50 mph (s)		24.36	28.44	0.2
Top Speed (mph)		60.22	59.43	0.0
Speed on Grade				
2% grade (mph)	55	57.48	54.84	4.6
3% grade (mph)	45	54.07	49.61	8.3
5% grade (mph)		45.44	40.75	10.3
20% grade (mph)		14.8	10.43	29.5
40% grade (mph)		8.12	7.04	13.3
60% grade (mph)		5.79	5.39	6.9

3.4 ENGINE EMISSION CHANGES

Exhaust samples were taken from the engines during the powercurve tests and analyzed for gaseous emissions. The sampling process uses a vacuum pump to extract gases from the exhaust system and place them into an emissions sample bag. This process is completed while the engine is held at a constant speed before advancing to the next step of the powercurve. The exhaust is sampled for approximately 2.5 minutes to reduce the possibility of anomalies in the collected data. After sampling was completed, the bag was removed from the vacuum pump and its contents were analyzed.

3.4.1 Caterpillar Emission Results

The most notable change in engine emissions with the use of FRF blends comes in the form of oxides of nitrogen, or NOx, reductions. This is due primarily to the reduced combustion temperatures with the presence of water in the fuel. Figure 23 below shows the changes in NOx emissions for each fuel in the CAT C7 engine (Note – Consistent emissions data could not be gathered at low engine speeds due to engine variation found during C7 performance testing at low speeds. Therefore, emissions data presented for the CAT C7 focuses at engine speeds near peak power).

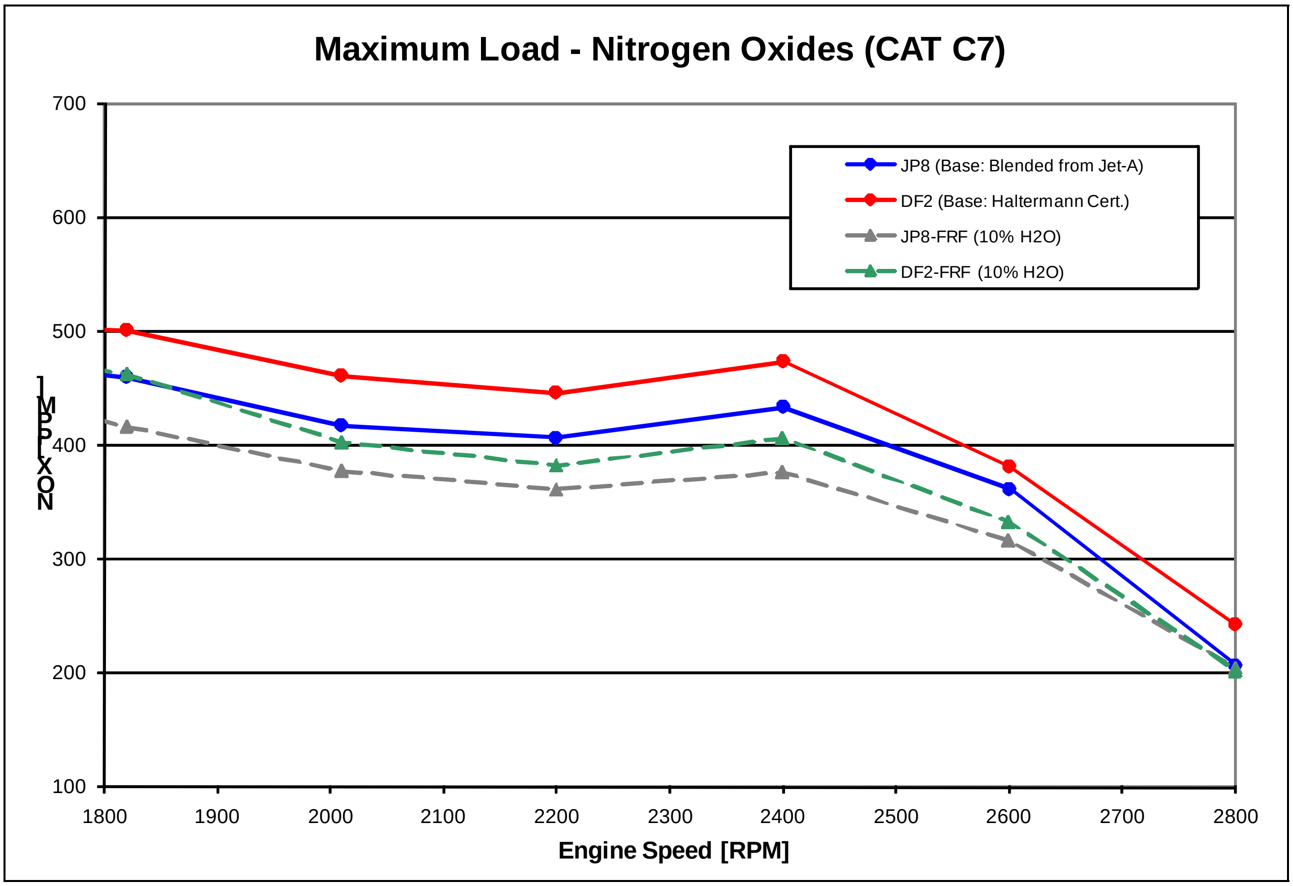

Figure 23 - CAT C7 Maximum Load NOx Emissions

As expected, FRF blends were found to have a significant impact on engine NOx emissions. Table 11 below summarizes the percent NOx reduction found at peak power between each base fuel and FRF blend.

Table 11 - CAT C7 NOx Emissions Reduction at Peak Power

C7 Peak Power - 2400rpm Maximum Load - NOx (ppm)		
DF2	405.0	
DF2 FRF	338.5	-16.4%
JP8	381.8	
JP8 FRF	350.1	-8.3%

3.4.2 General Engine Products Emissions Results

Due to undetermined emissions bench and test stand problems, no reliable emissions data was able to be collected for the 6.5L(T) engine. It is expected that the 6.5L(T) engine would see similar reductions in NOx emissions due to the water present in the fuel, but emissions data for the GEP 6.5L(T) engine cannot be quantified at this time.

4.0 CONCLUSIONS

From testing completed, it was found that FRF blends can be successfully used in typical compression ignition engines with an associated power loss depending on FRF blend proportions. Typical engine output losses vary from 3 to 9% in peak power and torque depending on injection system configuration and FRF blend chemistry. During testing no mechanical issues were noted with the use of FRF blends due to water, emulsifier, and MCA content present in fuels. In addition, it was noted that FRF emulsion quality didn’t have any significant impact on engine function, but did drastically limit overall shelf life of poorly emulsified blends. It is also expected that FRF use in most compression ignition engines would decrease the production of nitrogen-oxides, but due to various emissions equipment problems, full engine emissions characterizations could not be attained.