ADA

EVALUATION OF HYDROPROCESSED RENEWABLE DIESEL (HRD) FUEL IN A CATERPILLAR ENGINE USING THE 210 HOUR TWV CYCLE

INTERIM REPORT
TFLRF No. 440

By
Douglas M. Yost

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

For
Eric Sattler
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD17-Task 1)

May 2014

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
21 MAY 2014	**Technical Report**	**01-06-2011 to 01-05-2014**

4. TITLE AND SUBTITLE
EVALUATION OF HYDROPROCESSED RENEWABLE DIESEL (HRD) FUEL IN A CATERPILLAR ENGINE USING THE 210 HOUR TWV CYCLE

5a. CONTRACT NUMBER
W56HZV-09-C-0100

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Douglas Yost

5d. PROJECT NUMBER
SwRI 08.14734.17.102

5e. TASK NUMBER
WD 17 (Task 1)

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI),Southwest Research Institute,P.O. Drawer 28510,San Antonio,TX,78228-0510

8. PERFORMING ORGANIZATION REPORT NUMBER
TFLRF No. 440

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC/U.S. Army TARDEC, Force Projection Technologies, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000

10. SPONSOR/MONITOR’S ACRONYM(S)
TARDEC

11. SPONSOR/MONITOR’S REPORT NUMBER(S)
#25130

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This task evaluated engine performance using a Hydroprocessed Renewable Diesel (HRD) fuel that meets ASTM D975 No. 2 diesel specification, over both ambient-temperature and desert-temperature endurance cycles, to performance and engine emissions observed under similar conditions using a petroleum-based Reference Diesel Fuel (RDF). The use of Hydroprocessed Renewable Diesel fuel in the Caterpillar C7 engine provides adequate performance without any significant negative impact on engine durability, emissions, performance, fuel consumption, lubricant degradation, or cleanliness. The use of the Hydroprocessed Renewable Diesel fuel for the C7 engine is sufficient for both the ambient operating condition and the desert operating condition.

15. SUBJECT TERMS
Hydroprocessed Renewable Diesel, Reference Diesel Fuel, C7, emissions, power, performance, deposition, ambient, desert, synthetic fuel injector, piston, combustion chamber

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Public Release**	**70**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Disclaimers

Contracted Author

DTIC Availability Notice

Disposition Instructions

EVALUATION OF HYDROPROCESSED RENEWABLE DIESEL (HRD) FUEL IN A CATERPILLAR ENGINE USING THE 210 HOUR TWV CYCLE

INTERIM REPORT
TFLRF No. 440

By
Douglas M. Yost

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

For
Eric Sattler
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD17-Task 1)
SwRI® Project No.: 08.14734.17.102

May 2014

Approved by:

Gary Bessee

Gary B. Bessee, Director
U.S. Army TARDEC Fuels and Lubricants
Research Facility (SwRI®)

REPORT DOCUMENTATION PAGE					*Form Approved* *OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**					
1. REPORT DATE *(DD-MM-YYYY)* 05/21/2014		**2. REPORT TYPE** Interim Report			**3. DATES COVERED** *(From - To)* June 2011 – May 2014
4. TITLE AND SUBTITLE EVALUATION OF HYDROPROCESSED RENEWABLE DIESEL (HRD) FUEL IN A CATERPILLAR ENGINE USING THE 210 HOUR TWV CYCLE					**5a. CONTRACT NUMBER** W56HZV-09-C-0100
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Yost, Douglas					**5d. PROJECT NUMBER** SwRI 08.14734.17.102
					5e. TASK NUMBER WD 17 (Task 1)
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI®) Southwest Research Institute® P.O. Drawer 28510 San Antonio, TX 78228-0510					**8. PERFORMING ORGANIZATION REPORT NUMBER** TFLRF No. 440
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army RDECOM U.S. Army TARDEC Force Projection Technologies Warren, MI 48397-5000					**10. SPONSOR/MONITOR'S ACRONYM(S)**
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION / AVAILABILITY STATEMENT UNCLASSIFIED: Dist A Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This task evaluated engine performance using a Hydroprocessed Renewable Diesel (HRD) fuel that meets ASTM D975 No. 2 diesel specification, over both ambient-temperature and desert-temperature endurance cycles, to performance and engine emissions observed under similar conditions using a petroleum-based Reference Diesel Fuel (RDF). The use of Hydroprocessed Renewable Diesel fuel in the Caterpillar C7 engine provides adequate performance without any significant negative impact on engine durability, emissions, performance, fuel consumption, lubricant degradation, or cleanliness. The use of the Hydroprocessed Renewable Diesel fuel for the C7 engine is sufficient for both the ambient operating condition and the desert operating condition.					
15. SUBJECT TERMS Hydroprocessed Renewable Diesel, Reference Diesel Fuel, C7, emissions, power, performance, deposition, ambient, desert, synthetic fuel injector, piston, combustion chamber					
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	Unclassified	70	19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

EXECUTIVE SUMMARY

This project evaluated engine performance using a Hydroprocessed Renewable Diesel (HRD) fuel that meets ASTM D975 No. 2 diesel specification, over both ambient-temperature and desert-temperature endurance cycles, to performance and engine emissions observed under similar conditions using a petroleum-based Reference Diesel Fuel (RDF).

A Caterpillar C7 engine operating on Hydroprocessed Renewable Diesel fuel appeared to operate satisfactorily for 840 hours, simulating 80,000 miles of proving ground operation, without significant power, emissions, lubricant, or fuel injector degradation. In addition internal engine component deposition was relatively light at the ambient operating conditions.

Despite the elevated air, coolant and fuel temperatures, a C7 engine also completed the 840 hour desert condition test cycle without significant degradation of any engine performance parameter while utilizing Hydroprocessed Renewable Diesel fuel. Component conditions and cleanliness for the desert conditions were very similar to the component conditions seen at the ambient operating conditions.

The use of Hydroprocessed Renewable Diesel fuel in the Caterpillar C7 engine provides adequate performance without any significant negative impact on engine durability, emissions, performance, fuel consumption, lubricant degradation, or cleanliness. The use of the Hydroprocessed Renewable Diesel fuel for the C7 engine is sufficient for both the ambient operating condition and the desert operating condition.

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 June 2011 through May 2014 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. Luis Villahermosa (AMSRD-TAR-D/MS110) served as the TARDEC contracting officer's technical representative. Mr. Eric Sattler of TARDEC served as project technical monitor.

The authors would like to acknowledge the contribution of the TFLRF technical and administrative support staff.

TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

Tables **Page**

ACRONYMS AND ABBREVIATIONS

° C	degrees Centigrade
° F	degrees Fahrenheit
ASTM	ASTM International
bhp	brake horsepower
BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
CI	corrosion inhibitor
cm	Centimeter
CO	carbon monoxide
CRC	Coordinating Research Council
cSt	Centistokes
FMTV	Family of Medium Tactical Vehicles
ft	Foot
HC	hydrocarbon(s)
HP *or* hp	Horsepower
hr	Hour
HRD	Hydroprocessed Renewable Diesel
in	Inch
in^3	cubic inch
kW	Kilowatt
L	Liter
lb	Pound
lb_f	pound (force)
lb_m	pound (mass)
m	Meter
mg	Milligram
mm	Millimeter
NO_X	oxides of nitrogen
OEM	original equipment manufacturer
ppm	parts per million
psi	pounds per square inch
psiA	pounds per square inch, absolute
psiG	pounds per square inch, gauge
RDF	Reference Diesel Fuel
RPM	rotation(s) per minute
SwRI®	Southwest Research Institute®
TACOM	Tank Automotive and Armaments Command
TARDEC	Tank Automotive RD&E Center
TFLRF	TARDEC Fuel and Lubricants Research Facility
TWV	tactical wheeled vehicle
WD	work directive

1.0 INTRODUCTION AND BACKGROUND

Since the mid-1990s, the world's major energy companies have begun developing updated synthetic fuel processes that are less expensive to build and operate than traditional Fischer-Tropsch processes. The goal is to produce a sulfur-free product that helps meet air quality requirements from the conversion of various non-petroleum resources such as natural gas, coal, biomass, fats and oils, or other carbonaceous sources. Synthetic fuel chemistry can differ significantly from that of petroleum fuels since modern, low-temperature reaction synthetic fuels are free of aromatic and sulfur compounds. These differences may impact performance of equipment, such as: (1) fuel volumetric energy density and resultant power produced; (2) fuel cetane rating and the resultant ignition and combustion behavior; (3) fuel lubricity and adequate lubrication of some engine fuel systems and other equipment; and (4) fuel solvency and impacts on some elastomers in maintaining enough seal swell to avoid leakage when fuel systems are switched between petroleum and synthetic fuels. Some of these possible performance aspects are investigated in this project.

This project evaluated engine performance using a Hydroprocessed Renewable Diesel (HRD) fuel that meets ASTM D975 No. 2 diesel specification, over both ambient-temperature and desert-temperature endurance cycles, to performance and engine condition observed under similar conditions using petroleum-based fuels.

2.0 EVALUATION DETAILS

2.1 TEST CONFIGURATION

Testing was conducted with two Caterpillar C7 engines, in the configuration used in the Family of Medium Tactical Vehicles (FMTV) variants. Prior to testing, each engine’s fuel injectors and cylinder head were removed and the injectors, piston crowns, and fire deck were documented for deposition. Engine specifications are presented in Table 1. The engines were installed in TFLRF building 99, cell 4, with systems to monitor and control the test. Figure 1 shows a Caterpillar C7 engine installed in the test cell:

Table 1. Engine Specifications

Bore	4.33 inch ~ 110 mm
Stroke	5.00 inch ~ 127 mm
Displacement	441 in³ ~ 7.2 L
Rated Power	275 HP ~ 205 kW @ 2400 rpm
Rated Load	800 ft·lb_f ~ 1084 N·m @ 1440 rpm

Figure 1. Caterpillar C7 Engine Installed for Testing

- The engine was instrumented to measure a range of engine operating parameters, temperature and pressures. A SwRI-proprietary PRISM system controlled the engine and associated test equipment and acquired and logged test data.
- An absorbing dynamometer system limited engine speed. The factory engine controller regulated engine load, in response to a signal produced by the cell controller to simulate the OEM accelerator pedal output.

- Laboratory heat exchangers were installed to regulate coolant and manifold air temperature in place of the engine radiator and intercooler. Oil temperature was controlled indirectly by the coolant, via an oil-to-coolant heat exchanger integral to the engine.

- An OEM-style air filter and housing and appropriate ducting, including a Laminar Flow Element (LFE) for air flow measurement, was installed on the engine. Inlet air was drawn from inside the cell through the building ventilation system at ambient conditions then passed through dual radiator cores utilized for intake air temperature control.

- Ambient condition intake air temperature was obtained by plumbing chilled coolant from a three-ton refrigerated chiller through one of the air intake system radiator cores. Temperature control was by a three-way valve that controlled the flow of chilled coolant through the core.

- Desert condition elevated intake air temperature was obtained by plumbing hot coolant from the engine through the second of the air intake system radiator cores. Temperature control was by a three-way valve that controlled the flow of hot coolant through the core.

- Engine exhaust was drawn from the engine by a large fan and discharged above the building. A butterfly valve to control back-pressure and probes to sample smoke and gaseous emissions were installed in the exhaust stream.

- Crankcase blowby fumes were ducted into a drum where most of the entrained oil was captured, and then the gases were vented to the cell air through a flow meter to measure the blowby rate.

- Fuel was supplied to the engine at ambient pressure from a tank, which also received fuel recirculated from the engine. Fuel was supplied to the tank as necessary to maintain a constant level. The incoming fuel flow rate was measured by a Micro-Motion mass flow rate system. A heat exchanger was installed and controlled to prevent the fuel inlet from exceeding a set temperature. A new OEM fuel filter was installed before each test.

- Piping was installed to enable periodic oil sampling. A tube was mounted on the front engine case for oil additions.

- Engine coolant was a 60/40 blend of ethylene glycol antifreeze and de-ionized water.

- The engine was lubricated with Army Reference Oil, MIL-PRF-2104H, SAE grade 15W40. A new OEM oil filter was installed with each oil change.

2.2 TEST FUELS

Dynamic Fuels LLC was the supplier of the quantity of HRD fuel required to perform testing. Due to onsite tankage constraints, the HRD fuel was purchased in two allotments. At the start of the project the Dynamic Fuels production run had been HRD76 and HRJ5 for U.S. Navy use. Dynamic Fuels had previously produced and stored a -9 °C cloud point D 975 HRD no. 2 diesel fuel. Dynamic Fuels had been distributing their D 975 HRD product to the market through the Colonial pipeline. The Certificate of Analysis (COA) for the first purchased 12,000-gallon batch of HRD is included as Table 2 for fuel AF-8219.

The Certificate of Analysis (COA) for the second 10,000-gallon purchased batch of HRD is included as Table 3 for fuel AF-8295. Noted in the COA is that lubricity improver was not present in the fuel. Dynamic Fuels LLC does not treat the fuel at the refinery; it is usually treated at the distribution site. It was confirmed that fuel AF-8295 was not treated with lubricity additive at the rack when loaded on the truck. A sufficient quantity of Innospec OLI-9070.x lubricity improver additive was sent to TFLRF by Dynamic Fuels to treat the shipment of fuel AF-8295 to 275-ppm CI/LI additive concentration.

Dynamic Fuels LLC was queried to determine which fuel additives, and their approximate concentrations, that might be used in their HRD fuel processing. The response was as follow:

1. 1.1% Petroleum Diesel, for tax crediting purposes
2. 0.5 ppm Stadis 450 (Innospec), conductivity additive
3. 5 ppm Tolad 249 (Baker Petrolite), corrosion improver additive
4. 275 ppm OLI.9070.x (Innospec), commercial diesel lubricity improver additive, put in at the rack by the fuel distributor.

Table 2. Certificate of Analysis for Fuel AF-8219 Supplied by Dynamic Fuels LLC

Intertek

Vessel / Tank:	S/T 6020	Job. Ref. No.:	US200-0022855
Customer:	Dynamic Fuels	Lab Reference:	2012-GONZ-000863
Port/Terminal:	Dynamic Fuels	Date Submitted:	3/27/2012
Product:	Renewable Diesel		
Drawn By:	Intertek Caleb Brett Gonzales, La.		
Representing:	UML Composite		

Test Description	Method	Result	Units	Min.	Max
Appearance	Visual	C,B,F		Clear, Bright, Free	
Water Content	ASTM D2709	0.005	vol.%		0.05
Flash Point	ASTM D93A	138	deg.F	130	
Sulfur Content	ASTM D5453	<1.0	mg/kg		15
Viscosity at 40 deg.C	ASTM D445	2.559	mm2/s	1.9	4.1
Ash Content	ASTM D482	<0.001	wt.%		0.01
Ramsbottom Carbon Residue (10% Bottoms	ASTM D524	0.05	wt.%		0.35
Cetane Number	ASTM D613	71.9		40	
Cetane Index	ASTM D976	76.2		40	
Pour Point	ASTM 97	5.0	deg F		0
Cloud Point	ASTM D2500	10.4	deg.F		15
Copper Strip Corrosion	ASTM D130	1a			3
90% Recovered	ASTM D86	559.3	deg.F		650
Final Boiling Point	ASTM D86	578.6	deg.F		700
Distillation - % Recovery	ASTM D86	97.6	Vol.%	97.5	
Electrical Conductivity	ASTM D2624	93	pS/M	25	

Release by: Michael Catalano, Jr.

Table 3. Certificate of Analysis for Fuel AF-8295 Supplied by Dynamic Fuels LLC

DynamicFuels

Renewable Diesel Fuel

PO Box 599
36187 Highway 30
Geismar, LA 70734

July 18, 2012

Tank 6020

Description	Specification	Units	Test Method	Result
Appearance	Clear and free of visible suspended material		Visual	Clear, bright and Free
Water and Sediment	≤0.05	Vol%	ASTM D2709	0.05
Density	Report	g/ml	ASTM D4052	0.7791
API Gravity	report		ASTM D4052	50.05
Distillation – 90% Recovered	282-338	°C	ASTM D86	293.1
Flash Point	≥52	°C	ASTM D93A	61.1
Total Sulfur	≤15	ppm	ASTM D5453	<1.0
Kinematic Viscosity@ 40°C (104°F)	1.9-4.1	mm^2/s	ASTM D445	2.60
Aromatics [1]	≤35	Vol%	ASTM D1319	<5
Ash	≤0.01	Wt%	ASTM D482	<0.001
Carbon Residue on 10% Distillation residue	≤0.35	Wt%	ASTM D524	0.04
Cetane Index	≥40		ASTM D976	76.6
Cloud Point		°C	ASTM D5771	-13
Copper Corrosion@ 50°C(122°F)	≤3		ASTM D130	1a
Color, ASTM	≤2.5		ASTM D1500	<0.5
Conductivity	≥25	pS/m	ASTM D2624	38
Lubricity	≤520	micron	ASTM D6079	Note 2

Notes:
1 – ASTM D1319 test detection limits for Aromatics is 5-99 vol%.
2 – Without Lubricity additive added, lubricity will not meet D975 specifications

Carolina Golden
QA/QC Manager

The TFLRF analyses of each test fuel batch for conformance to the ASTM D975 no. 2 diesel fuel specification are shown in Table 4. Both batches of the HRD fuel met the specification requirements for D975 no. 2 diesel fuel. Additional descriptive fuel property measurements were performed on both batches of the HRD fuels and are shown in Table 5. Both batches of the HRD fuels look quite similar property wise, with the exception of the Isothermal Bulk Modulus measurement. Bulk modulus variations effect pump-line-nozzle fuel injection system engines, by altering injection timing. The HEUI fuel injection system of the C7 would not expected to be sensitive to fuel bulk modulus variations.

The COA for ULSD grade no. 2 Reference Diesel Fuel (RDF) utilized for engine break-in and performance and emission comparisons is included as Table 6.

Table 4. Hydroprocessed Renewable Diesel Fuel Properties for ASTM D975 Conformance

Property	Units	ASTM Test Method	Specification min	Specification max	HRD2 Batch 1 CL12-3725 AF-8219	HRD2 Batch 2 CL12-4110 AF-8295
Flash Point	°C	D93	52		55.5	55.5
Water & Sediment	%vol	D2709		0.05	0.05	< 0.005
Distillation	°C	D86				
		IBP			164.9	168
		5% Rec			204.8	207.1
		10% rec			223.8	225.5
		15% rec			236.7	238.1
		20% rec			248.9	248.1
		30% rec			265.1	263.8
		40% rec			274.7	273.6
		50% rec			280.1	279.7
		60% rec			289.9	283.7
		70% rec			287.1	287.2
		80% rec			290.2	290.4
		90% rec	282	338	294.1	294.1
		95% rec			297.9	297.4
		FBP			310.5	307.5
Kinematic Viscosity, 40°C	cSt	D445	1.9	4.1	2.56	2.57
Kinematic Viscosity, 20°C						4.05
Kinematic Viscosity, 0°C					6.61	
Ash	%mass	D482		0.01	<0.001	<0.001
Sulfur	ppm	D5453		15	2.5	1.2
Copper Strip Corrosion		D130		No. 3	1A	1A
Cetane Number		D613	40		72.9	74.2
Cetane Index		D976-80	40		76.4	76.7
Aromaticity	%vol	D1319		35	1.6	0.9
Olefins					1.6	1.7
Saturates					96.8	97.4
Cloud Point	°C	D2500			-14	-12
CFPP	°C	D6371			-15	-12
Ramsbottom, 10% residue	%mass	D524		0.35	0.04	0.03
Conductivity	pS/m	D2624	25		128	40
Lubricity HFRR	micron	D6079		520	330	422

Table 5. Hydroprocessed Renewable Diesel Fuel Additional Analysis

Property	Units	ASTM Test Method	Specification min	Specification max	HRD2 Batch 1 CL12-3725 AF-8219	HRD2 Batch 2 CL12-4110 AF-8295
Lubricty BOCLE	micron	D5001			540	540
Isentropic Bulk Modulus, 30°C	psi				159302	188550
Net Heat of Combustion	BTU/lb	D4809			18749.4	18832.3
Derived Cetane Number		D6890			75.97	74.08
Density, 15°C	g/mL	D4052			0.7800	0.7792
Density, 30°C	g/mL	D4052			0.7696	0.7688
Acidity, TAN	mg KOH/g	D3242			0.01	0.006
Hydrocarbon Structure	%vol	D2425M				
	Paraffin				93.8	95.7
	Mono Cyclic Paraffin				4.4	2.9
	Di-Cyclic Paraffin				1.1	1.1
	Tri-Cyclic Paraffin				0	0
	Napthene				5.5	4
	Saturate				99.3	99.7
	AKBenz				0.1	0
Carbon	%mass	D5291			84.91	84.73
Hydrogen	%mass	D5291			15.08	15.04
Nitrogen & Water	mg/kg	D6304			40	98
Elemental	ppb/ppm	D7111				
		Al			326ppb	404ppb
		Ba			<100ppb	<100ppb
		Ca			<100ppb	<100ppb
		Cr			<100ppb	<100ppb
		Cu			<100ppb	<100ppb
		Fe			<100ppb	<100ppb
		Li			<100ppb	<100ppb
		Pb			<100ppb	<100ppb
		Mg			<100ppb	<100ppb
		Mn			<100ppb	<100ppb
		Mo			<100ppb	<100ppb
		Ni			<100ppb	<100ppb
		K			<1ppm	<1ppm
		Na			<1ppm	<1ppm
		Si			629ppb	<100ppb
		Ag			<100ppb	<100ppb
		Ti			<100ppb	<100ppb
		V			<100ppb	<100ppb
		Zn			<100ppb	<100ppb

Table 6. Certificate of Analysis for ULSD Reference Diesel Fuel

CERTIFICATE OF ANALYSIS

VALERO

Valero Three Rivers Refinery

Product Name: **Texas LED Diesel** Tank No: **303** Date: **5/19/2006**

Certification Number: 1

ASTM METHOD	Results	Specification
Aromatic Content, mass%	5.19	10 max
D93 Flash Pt., F	172	125 min
D1500 ASTM Color	<0.5	2.5 max
D86 Distillation, F		
IBP, F	391	Report
10% Recovery Pt.	428	Report
50% Recovery Pt.	487	Report
90% Recovery Pt.	570	540-640
FBP, F	619	690 max
D524 Carbon Residue	0.003	0.35 max
D445 Viscosity, cSt@40C	2.41	1.9-4.1
D4737 Cetane Index	55.4	48 min.
CPC Scale Haze Rating	1	2 max
Blotter Rating	1	7 max
D130 Corrosion, Copper Strip	1A	1b max
D6428 Sulfur, ppm	1.130	15 max
D2500 Cloud Pt, F	-3.0	20 max
D97 Pour Pt., F	-20	10 max
D1796 BS&W, vol%	0	0.05 max
D4052 API Gravity @ 60 F	41.16	30 min
D6079 Lubricity,HFRR	335	520 max.

We hereby certify that this product complies to manufacturing and performance specifications

Gregg Goebel
Authorized Signature

2.3 Test Operation

2.3.1 Pre-Test Measurements, Ratings, and Photographs

Prior to the start of all testing, and the engine run-in, the engine was disassembled to determine injector nozzle tip deposits, and the piston crowns and engine combustion chamber deposits. Pre-test deposition was from the engine proof run at the factory.

2.3.2 Engine Run-In

Before beginning the test cycle, each new engine underwent a break-in procedure lasting approximately five hours, during which the engine repeatedly cycled through a variety of operating conditions, including engine speeds from idle to 2400 rpm (rated speed), and engine loads from idle (no load) to peak torque. The break-in procedure was performed utilizing the ULSD grade no. 2 Reference Diesel Fuel.

2.3.3 Pretest Engine Performance Checks

Each engine’s performance was measured prior to endurance testing. The engine was set to run at full power at each of ten engine speeds, including the peak torque speed, 1440 rpm; the rated speed, 2400 rpm; and the governed speed, 2800 rpm. The engine operated at each speed until conditions stabilized, after which the full range of data available was recorded, including gaseous emissions. At the completion of this testing, the engine oil was drained and replaced with a carefully-weighed quantity of new oil. A new oil filter was installed.

2.2.3 Test Cycle

The test cycle was based on the Army and Coordinating Research Council (CRC) 210-hour Tactical Wheeled Vehicle (TWV) procedure that simulates 20,000 miles of proving ground operation [1]. The cycle as defined includes 15 days of operation, each comprising five two-hour periods of rated power operation, alternated with four one-hour periods of idle operation, for a total of 14 hours per test day. The remaining 10 hours of each test day are engine-off "soak" time, during which the engine system cooled to ambient conditions; test time was accumulated only during the running segments. Several successful fuels and lubricant screening test programs have previously been performed with the Cat C7 engine utilizing the TWV cycle [2, 3].

For the HRD fuels testing the TWV cycle was accelerated in order to complete each 210 hours of operation in 10 operating days, which included 21 hours of daily operation and 3 hours of soak. The ratio of test time at rated power to test time at idle of the original procedure was kept the same for the accelerated TWV procedure.

For the purposes of this testing, the standard 210-hour TWV Cycle was extended to a total of 840 hours (which simulates 80,000 miles of proving ground operation). Coolant, fuel, inlet air, and intake manifold temperatures were controlled to the conditions shown in Table 7, for the appropriate test. The Baseline test was conducted under accelerated conditions for a different work directive, in which the daily test cycle was 20 hours (seven two-hour periods of rated operation, alternated with six one-hour periods of idle operation), followed by only four hours of "soak" time, in order to complete the doubled test hour duration in only twenty-one days of testing.

Table 7. Ambient and Desert Engine Operating Condition Targets

Parameter	Ambient Conditions	Desert Conditions
Fuel Inlet Temperature, °F	86 +/- 4	175 +/- 4
Intake Air Temperature, °F	77 +/- 4	120 +/- 4
Rated Manifold Air Temperature, °F	127 +/- 2	155 +/- 3
Idle Manifold Air Temperature, °F	Report	118 +/- 3
Coolant Outlet Temperature, °F	205 +/- 4	218 +/- 4

For this test sequence the lubricant was changed at 210 hours. Engine oil was sampled for analysis every 21 hours of test operation. After each sample, a quantity of new oil approximately equal in weight to the sample removed was added to the engine. This sample makeup oil was not included in the oil consumption calculations.

Gaseous emissions were measured during the power curves that were performed at each 210 hour interval for the duration of the 840 hour test.

During the daily 3-hour shutdown, the engine was inspected for loose fittings, leaks and any other visible sign of a current or impending problem. The oil level was checked and recorded 20 minutes into the soak period. If the oil was below the full mark, a quantity of new oil sufficient to restore the oil level to the full mark was measured, recorded and added.

2.2.4 Post-Test Engine Performance Checks

Following completion of the 840-hour test, engine performance was measured in exactly the same way as before testing, and at each 210-hour interval between, with the goal of comparing the engine performance measurements.

2.2.5 Post-Test Measurements, Ratings, and Photographs

Upon completion of all testing, the engine was removed from the test cell and disassembled to determine injector nozzle tip and piston crown and engine combustion chamber deposits. Post-test photographs of the same components imaged prior to testing were documented.

3.0 DISCUSSION OF TESTS

3.1 TEST 1: AMBIENT OPERATING CONDITIONS

The first test was conducted utilizing the batch of HRD fuel coded AF-8219, and was performed at the ambient operating conditions. The first of the two CAT C7 engines was installed on the test stand and a run-in was performed using an ULSD diesel fuel at the ambient operating conditions. Following a run-in, full-rack power curves were performed using the ULSD and HRD fuels. Following the power curves, the first 210 hour segment of the ambient temperature test with the HRD diesel fuel was initiated. At the 210 hour point, power curves were generated with ULSD and HRD fuels, and the injectors were removed for inspection and imaging to document deposition. An ambient condition engine parameter operating summary is included as Table 8 for the duration of the HRD ambient condition test.

At 420 hours, as the injectors were being removed for documentation of the injector tip deposits, it was noted that there were small pieces of spring steel in the injector bores. The spring steel pieces appeared to have come from injector check ball retaining springs. The spring band appeared to hold the check ball in place while the injector was being assembled. The failed check ball springs were only noticed because the injectors were being removed for documentation of deposits forming on the injector tips. It appeared the purpose of the check ball was to hold fuel inside the injector, to maintain fuel prime, for faster starting.

Before the engine was shut down for the injector documentation, power curves were generated, including exhaust emission measurements that did not reveal any significant change in either power or emissions from either the start of testing or from the 210 hour power check. A decision was made by TFLRF and TARDEC to continue on with HRD fuel testing.

The power curves for the HRD diesel fuel for the testing are shown in Figure 2. Due to the lower density, and lower energy density of the HRD fuel, the power was lower than the RDF power generated. The curves show that the power initially increased with time of operation, presumably due to the engine continuing to run-in, then over the last 210 hours of operation the power decreased.

The power curves for the DF2 diesel fuel for the testing are shown in Figure 3. The curves show that the power increased with time of operation, presumably due to the engine continuing to run-in, then over the last 210 hours of operation the power decreased. The power loss over the final 210 hours of operation appears similar with both fuels.

Table 8. Operating Condition Summary for HRD Fuel Ambient Condition Test

Parameter	Units	210-Hour				420-Hour				630-Hour				840-Hour			
		Rated		Idle		Rated		Idle		Rated		Idle		Rated		Idle	
		Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	StdD ev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
SPEED	RPM	2400	1	708	1	2400	1	707	1	2400	1	707	1	2400	1	709	1
TORQUE	lb-ft	598.1	13.3	11.3	0.9	604.5	12.6	11.2	0.9	587.0	10.3	11.0	0.9	583.9	11.3	11.3	1.0
Fuel Flow	lb/hr	100.88	2.86	2.92	0.12	102.36	2.21	2.90	0.14	99.75	1.39	2.88	0.12	99.39	2.50	2.96	0.11
POWER	bhp	273.3	6.1	1.5	0.1	276.3	5.8	1.5	0.1	268.2	4.7	1.5	0.1	266.8	5.1	1.5	0.1
BSFC	lb/bhp-hr	0.369	0.010	1.928	0.168	0.371	0.004	1.935	0.173	0.372	0.003	1.964	0.182	0.373	0.009	1.958	0.198
Mass Air Flow	lb/hr	3327	19	377	4	3303	15	372	3	3280	15	363	6	3269	19	353	11
Air/Fuel Ratio	:1	37.8	394.4	129.6	5.5	32.3	0.6	128.3	6.1	32.9	0.5	126.2	5.7	33.0	5.1	119.6	6.1
BMEP	psi	204.1	4.5	3.9	0.3	206.3	4.3	3.8	0.3	200.3	3.5	3.8	0.3	199.3	3.8	3.9	0.3
Crankcase Blow-by	SCFM	6.64	0.22	1.68	0.13	6.72	0.26	1.58	0.08	6.72	0.27	1.51	0.08	7.26	0.79	1.50	0.08
TEMPERATURES																	
Coolant In	°F	197	1	107	12	197	1	106	1	197	1	105	2	197	1	105	3
Coolant Out	**°F**	**205**	**1**	**111**	**12**	**205**	**1**	**110**	**1**	**205**	**1**	**110**	**1**	**205**	**0**	**110**	**1**
Oil Gallery	°F	230	1	126	11	230	1	125	4	230	1	125	4	229	1	125	5
Oil Sump	°F	244	1	131	11	244	1	130	6	243	1	130	6	242	1	129	6
Air Before Compressor	**°F**	**77**	**1**	**77**	**2**	**77**	**0**	**78**	**1**	**77**	**0**	**78**	**1**	**77**	**0**	**78**	**1**
Air After Compressor	°F	341	2	85	3	342	1	85	2	342	1	86	2	343	2	86	3
Manifold Air	**°F**	**127**	**1**	**83**	**2**	**127**	**1**	**83**	**2**	**127**	**1**	**84**	**2**	**127**	**1**	**84**	**2**
Cylinder 1	°F	987	20	192	7	1002	32	192	2	1006	14	202	6	1013	13	206	3
Cylinder 2	°F	1093	18	190	6	1113	15	186	2	1097	11	198	5	1103	7	203	2
Cylinder 3	°F	1050	14	205	7	1073	13	204	4	1084	12	215	6	1094	16	222	4
Cylinder 4	°F	1045	17	208	5	1068	8	214	4	1051	12	218	4	1029	21	216	4
Cylinder 5	°F	1056	19	210	6	1061	11	208	4	1008	30	201	6	1038	9	206	6
Cylinder 6	°F	1000	16	202	6	1005	9	201	3	971	22	176	12	978	8	181	7
Exhaust-Front Cylinders	°F	1124	16	219	6	1143	17	218	3	1145	10	231	5	1155	10	237	4
Exhaust-Rear Cylinders	°F	1115	18	222	6	1132	9	226	4	1104	18	222	6	1098	17	225	7
Exhaust Stack	°F	896	21	217	10	916	22	218	9	894	14	222	17	897	11	234	61
Fuel Inlet	**°F**	**86**	**2**	**86**	**0**	**86**	**0**	**86**	**0**	**86**	**0**	**86**	**0**	**86**	**1**	**86**	**1**
Fuel Return	°F	66	7	52	1	66	1	53	1	66	1	53	1	66	1	53	1
PRESSURES																	
Coolant	psig	6.99	1.04	3.50	1.25	6.46	0.85	3.03	1.02	6.84	0.70	3.34	1.01	6.41	0.70	2.62	0.98
Oil Gallery	psig	52.99	1.31	59.61	5.72	50.07	0.54	54.67	3.33	49.70	0.64	53.81	3.56	49.59	0.56	54.07	3.67
Fuel Inlet	psig	74.68	3.12	65.43	0.69	74.63	0.38	63.27	1.34	74.79	0.24	63.50	0.81	74.67	0.70	63.63	0.84
Air Before Compressor	psia	13.53	0.05	14.19	0.05	13.56	0.05	14.22	0.05	13.51	0.04	14.18	0.04	13.53	0.03	14.19	0.03
Air After Compressor	psia	39.97	0.09	14.34	0.08	39.93	0.07	14.32	0.06	39.90	0.06	14.27	0.05	39.94	0.07	14.30	0.06
Manifold Air	psig	25.68	0.10	0.08	0.04	25.68	0.07	0.10	0.01	25.74	0.06	0.10	0.01	25.74	0.07	0.10	0.01
Exhaust-Front Cylinders	psig	24.73	0.24	0.30	0.06	24.51	0.16	0.30	0.05	24.53	0.19	0.20	0.04	25.41	0.26	0.18	0.04
Exhaust-Rear Cylinders	psig	24.30	0.32	-0.12	0.17	24.10	0.27	-0.23	0.12	23.96	0.29	-0.34	0.10	23.75	0.50	-0.30	0.15
Exhaust Stack	psig	0.32	0.01	-0.24	0.01	0.33	0.01	-0.24	0.01	0.33	0.01	-0.24	0.01	0.32	0.01	-0.25	0.01
ATMOSPHERIC CONDITIONS																	
Atmospheric Pressure	psia	14.29	0.08	14.27	0.08	14.25	0.06	14.23	0.06	14.17	0.05	14.16	0.05	14.20	0.06	14.19	0.06
Dry Bulb Temperature	°F	92.1	9.4	92.2	9.0	102.3	6.4	99.4	5.3	105.2	5.5	104.1	4.6	102.2	6.8	101.5	6.9
Relative Humidity	%	13.6	4.8	11.3	3.8	18.6	5.4	18.5	7.4	15.2	4.9	11.3	5.9	15.6	5.1	13.1	3.9

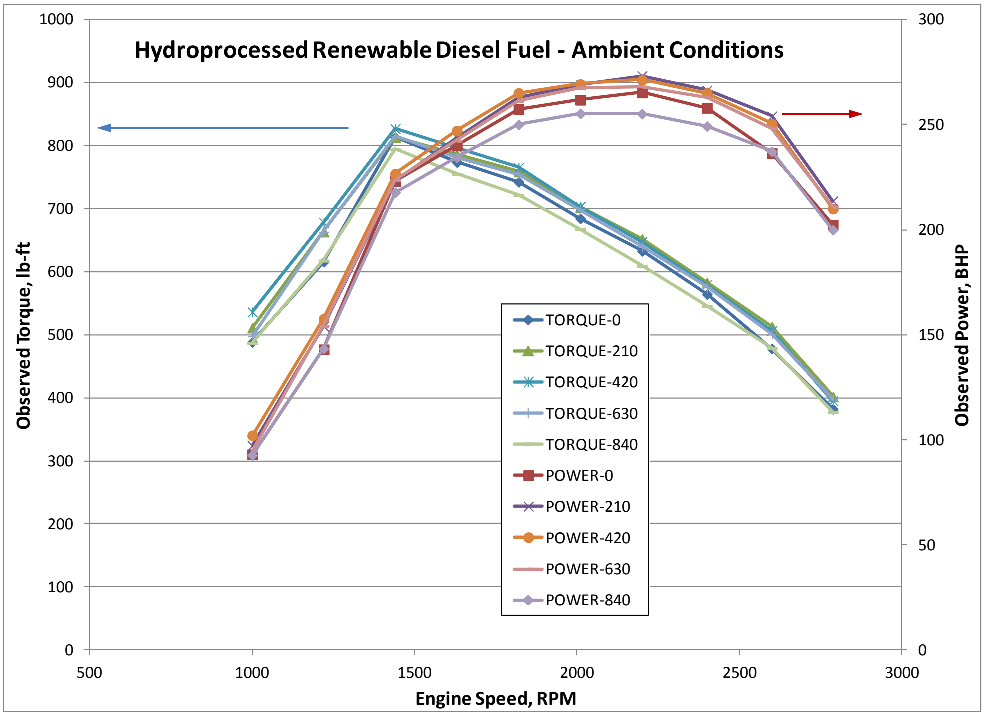


Figure 2. Ambient Condition Power and Torque with the HRD Fuel at 210-hour Intervals

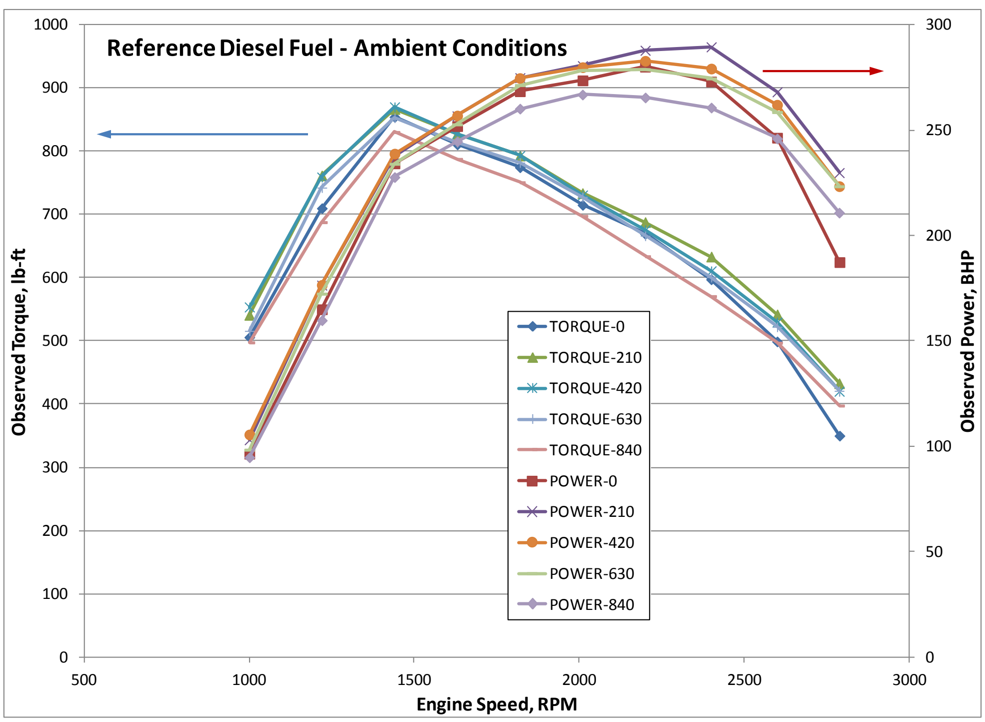


Figure 3. Ambient Condition Power and Torque with the RDF Fuel at 210-Hour Intervals

The fuel consumption was also measured during the power curves performed at each 210 hour interval. The fuel consumption measured with the engine operating on HRD fuel during the HRD fuel ambient condition test are shown in Figure 4. The fuel consumption values appear to reflect the power deviations seen throughout the 840 hours of testing with the HRD fuel.

The fuel consumption was also measured using the RDF fuel during the power curves performed at each 210 hour interval. The fuel consumption measured with the engine operating on RDF fuel during the ambient condition test is shown in Figure 5. The 0 hour fuel flow values were compromised by a malfunctioning regulator that maintained day tank level that was not noticed until the fuel was changed. The engine was still drawing fuel to make power, but the measurement system recorded erroneous readings. The fuel consumption values appear to reflect the power deviations seen throughout the 840 hours of testing with the HRD fuel.

A comparison of the brake specific carbon monoxide (CO) gaseous exhaust emissions for the durability test with each fuel at the 210 hour intervals is shown in Figure 6 for both the HRD and RDF fuels. The brake specific carbon monoxide emissions are consistent across the test duration with the exception of the 0-hour points that may be due to the engine still breaking in. The 0 hour higher speed points with the RDF fuel may indicate the faulty fuel regulator did affect the engine performance, by altering the fuel flow and fuel supply pressure to the engine. In relative terms, the HRD CO emissions are slightly lower than the RDF CO emissions.

Figure 7 shows a comparison of the brake specific oxides of nitrogen gaseous exhaust emissions for the durability test with each fuel at the 210 hour intervals both the HRD and RDF fuels. The brake specific oxides of nitrogen emissions are consistent across the test duration with the exception of the 0-hour points that may also be due to the engine still breaking in. The 0-hour oxides of nitrogen emissions with the HRD were elevated, suggesting the high cetane number of the HRD fuel caused early ignition, thus higher NOx emissions. In relative terms, the HRD NOx emissions are slightly lower than the RDF NOx emissions.

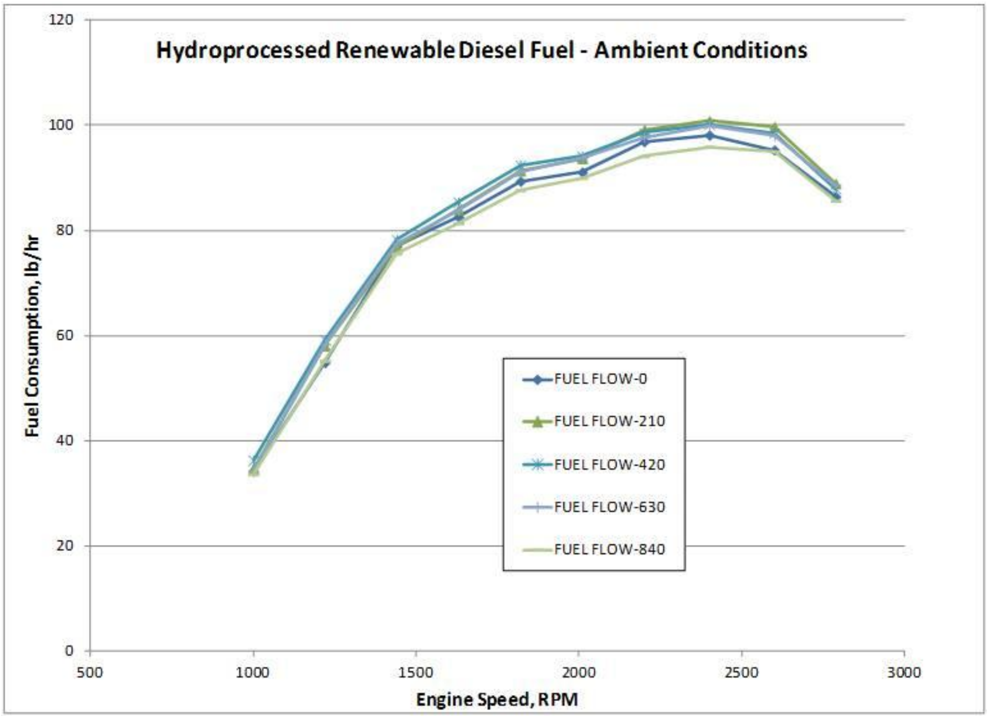


Figure 4. Fuel Consumption with HRD Fuel at Ambient Operating Conditions and 210-Hour Intervals

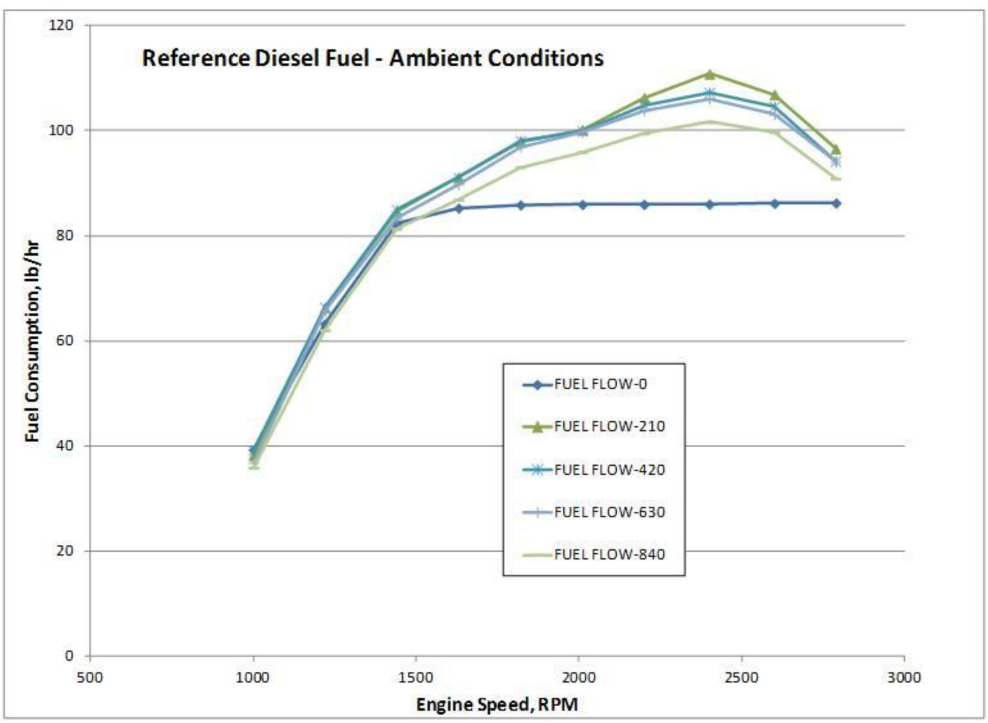


Figure 5. Fuel Consumption with RDF Fuel at Ambient Operating Conditions and 210-Hour Intervals

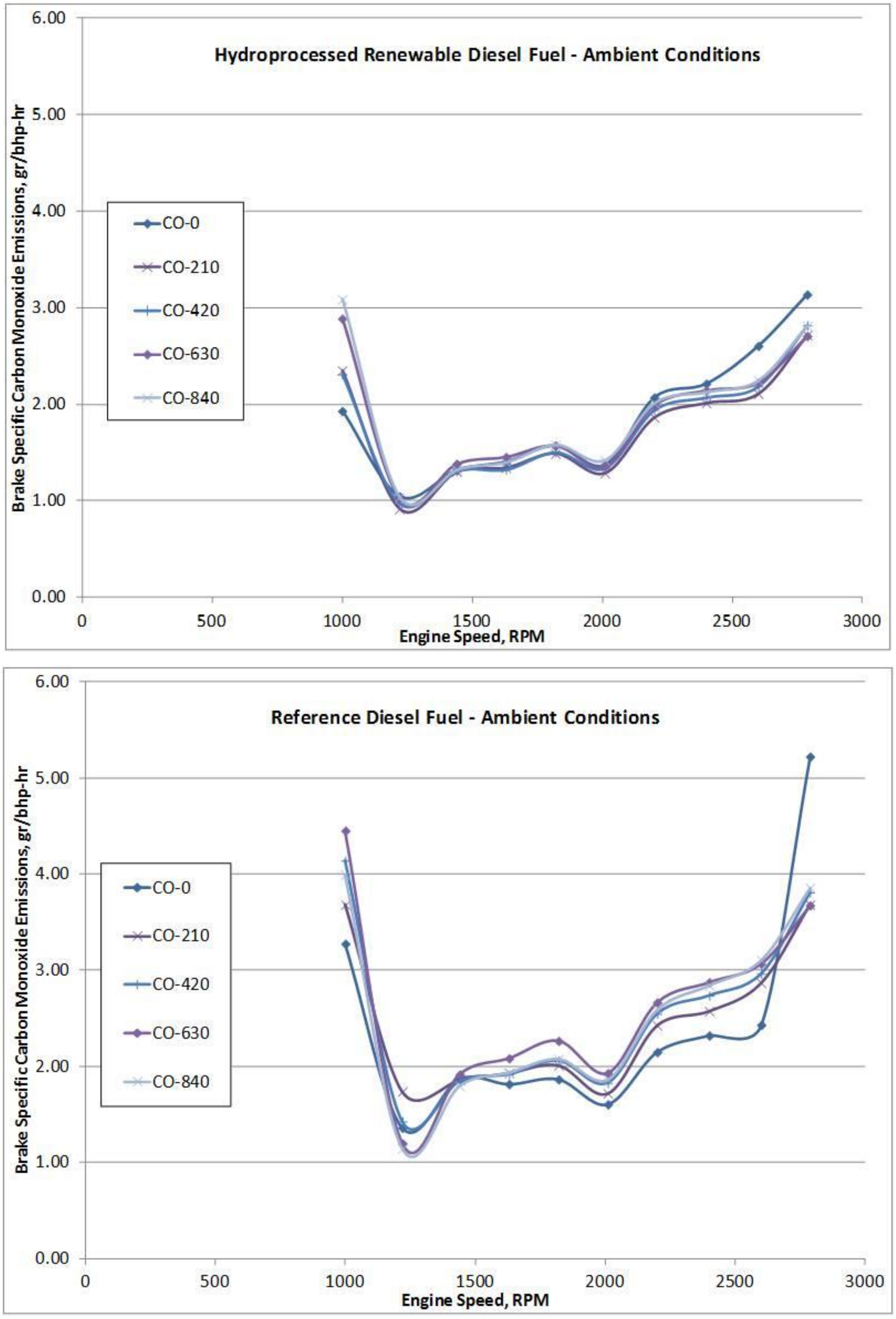
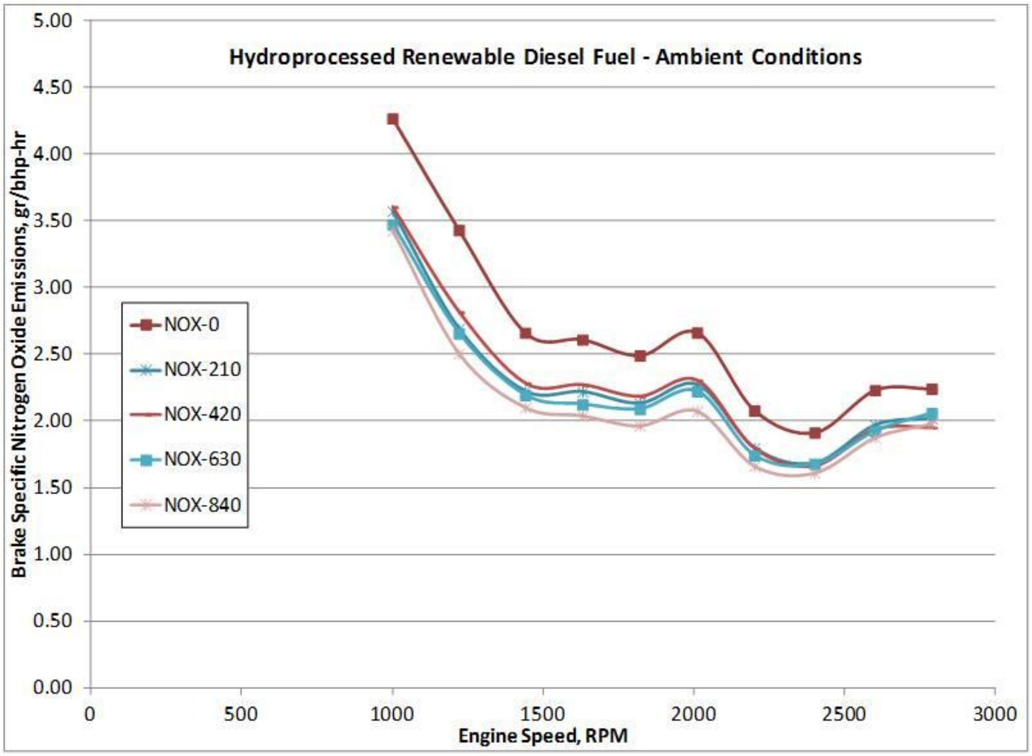


Figure 6. Brake Specific Carbon Monoxide Emissions at Ambient Conditions at 210-hour Intervals

Figure 8 shows a comparison of the brake specific hydrocarbon gaseous exhaust emissions for the durability test with each fuel at the 210 hour intervals both the HRD and RDF fuels. The brake specific hydrocarbon (HC) emissions are consistent across the test duration with the exception of the mid-range speed 210 hour points. The high HC could be from excessive oil consumption due to turbocharger oil seal leakage or the ring gaps lining up on a piston, but it was transient and did not return. In relative terms, the HRD HC emissions are slightly lower than the RDF HC emissions.

The accumulation of wear metals in the engine lubricant are shown in Figure 9 for the HRD fuel testing at ambient operating conditions. The initial 210 hours of testing showed increases of the wear metals that indicated further break-in of engine components was occurring. After the lubricant was changed at 210 hours, the accumulation rate of wear metals in the lubricant, decreased substantially. The wear metal accumulation rate after both the 420 hour and 630 hour oil change was similar to the accumulation rate seen after the 210 hour oil change. The levels of wear metals measured would be considered normal.

The additive element concentrations in the engine lubricant are shown in Figure 10 for the ambient operating condition test. The additive elements concentrations are quite consistent throughout the duration of the test. Likewise the engine lubricant kinematic viscosity also appears very consistent throughout the testing as shown in Figure 11. Major variations in the viscosity measured at 100 °C only occur when the lubricant was changed at the 210 hour intervals.



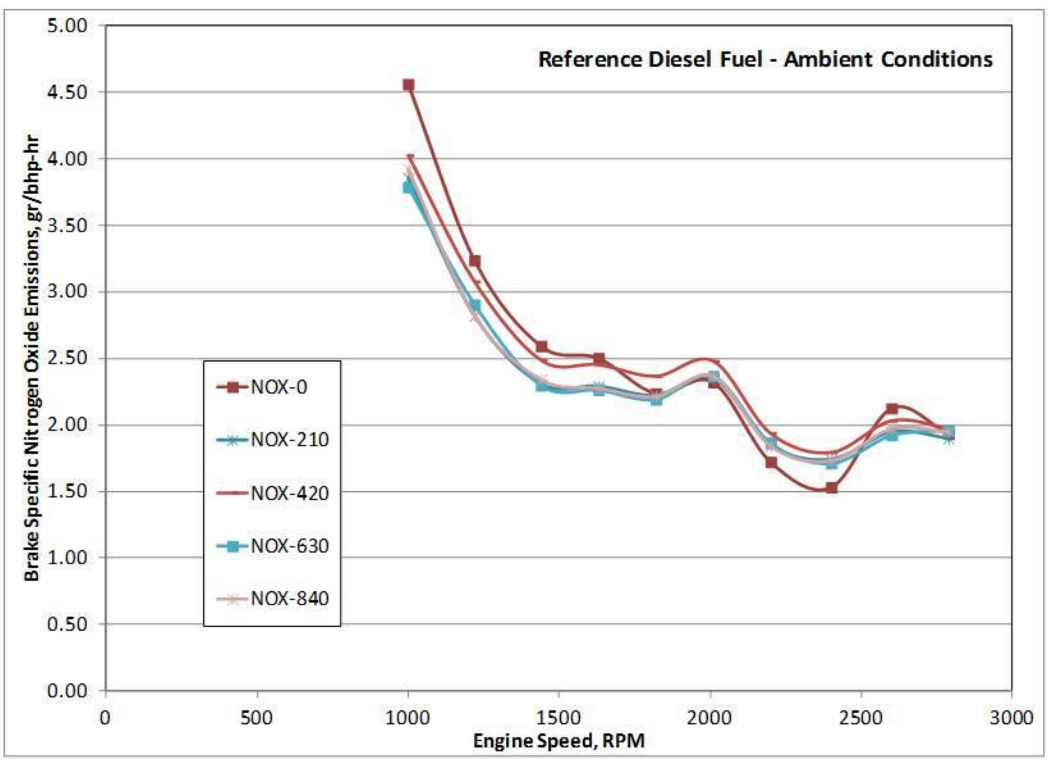
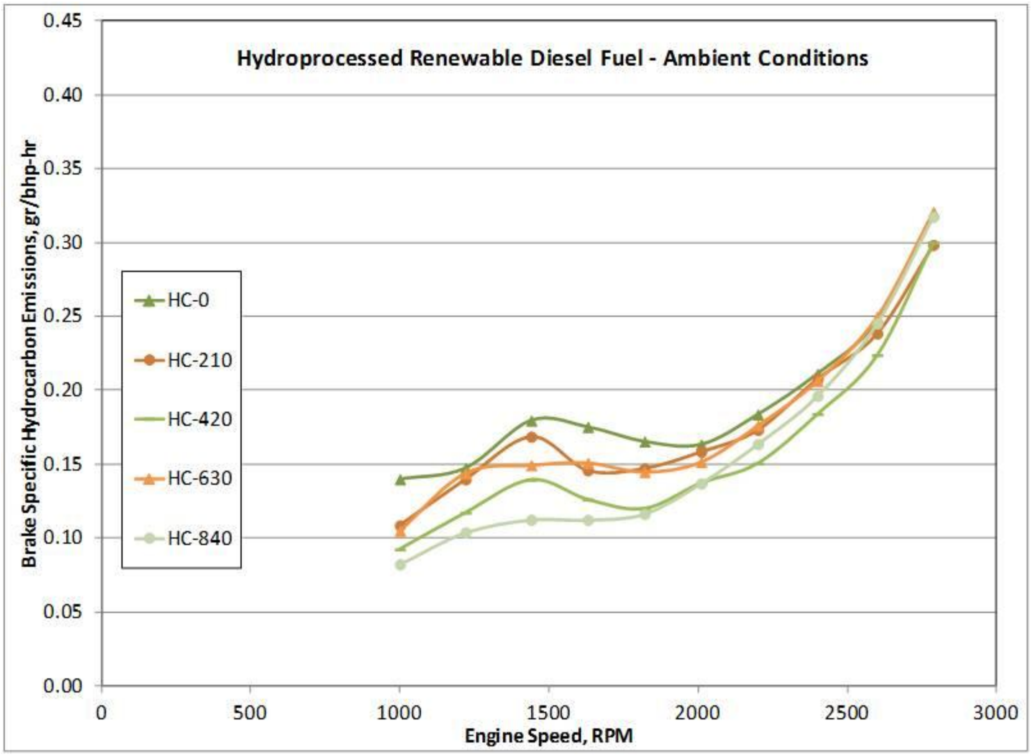


Figure 7. Brake Specific Oxides of Nitrogen Emissions at Ambient Conditions at 210-hour Intervals



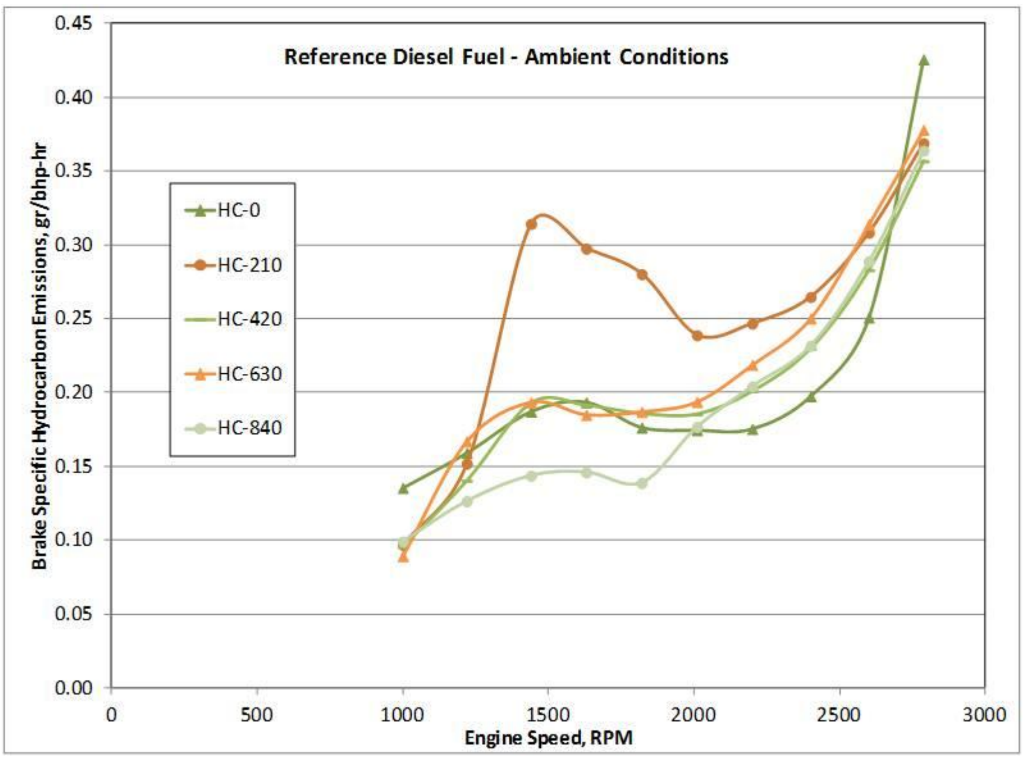


Figure 8. Brake Specific Hydrocarbon Emissions at Ambient Conditions at 210-hour Intervals

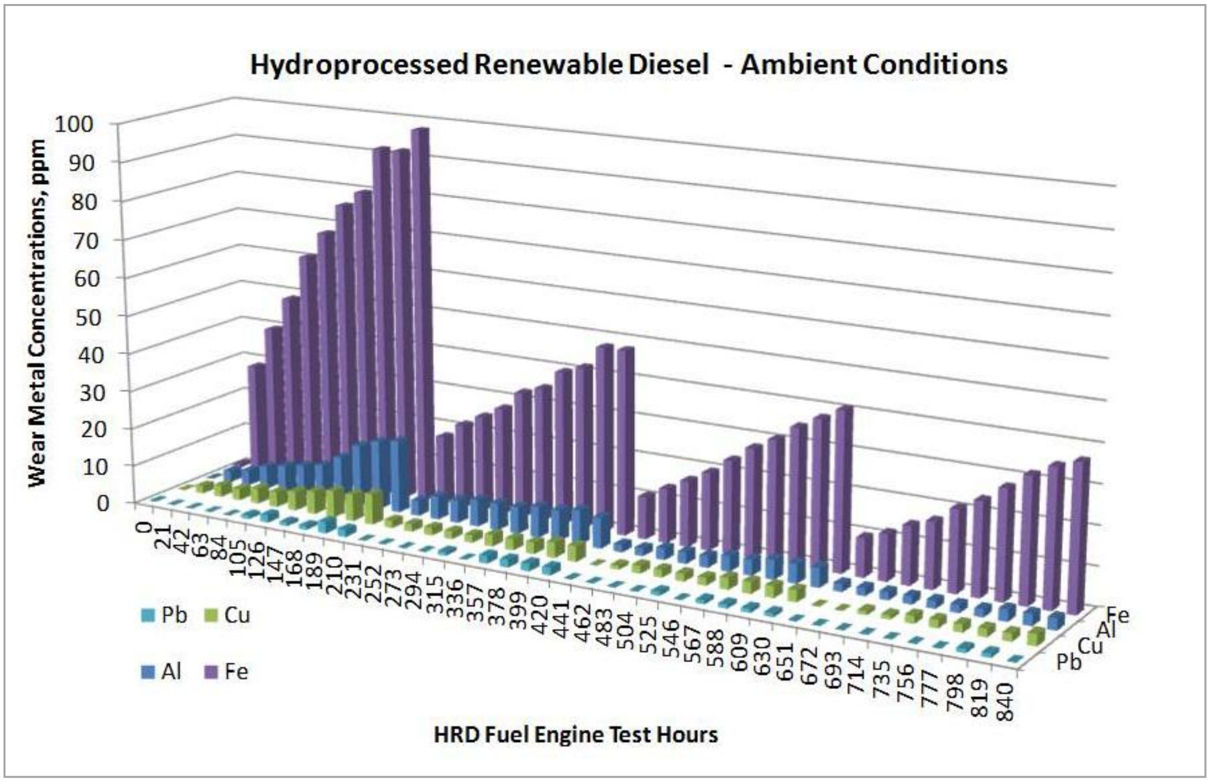


Figure 9. Engine Lubricant Wear Metals for Ambient Condition Operation with HRD Fuel

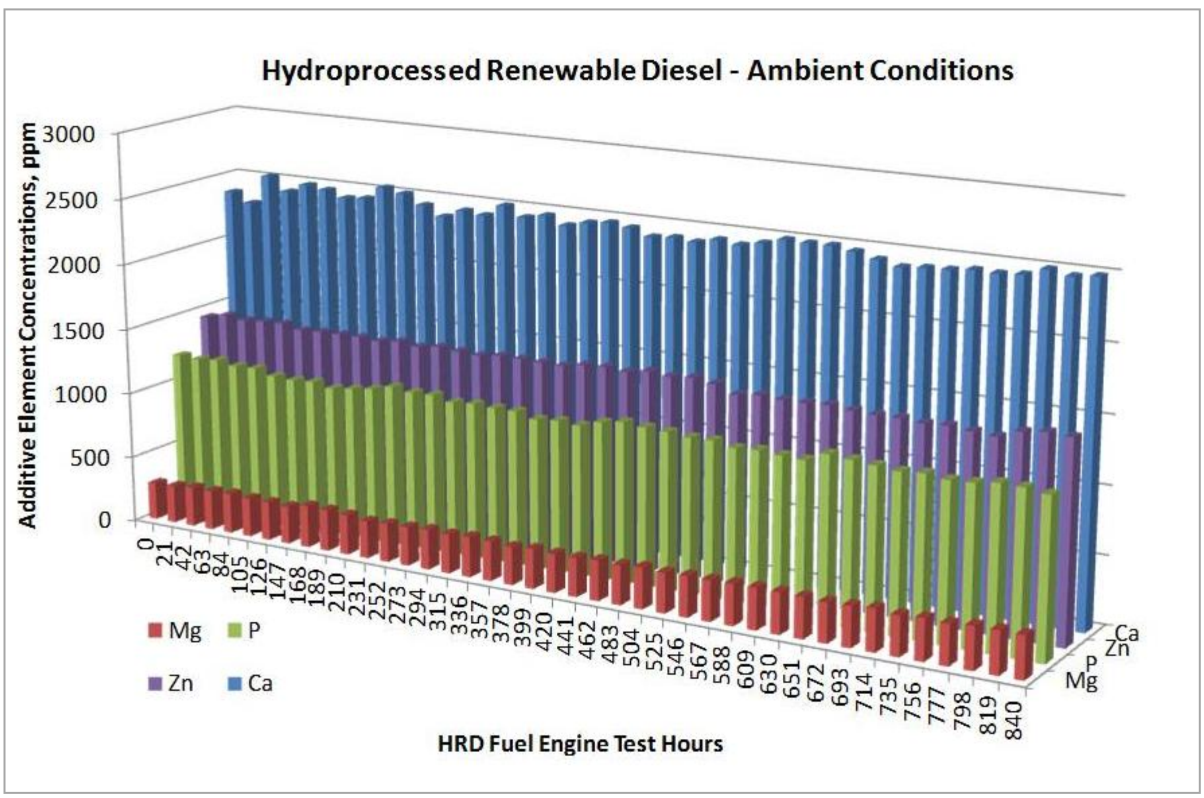


Figure 10. Engine Lubricant Additive Elements for Ambient Condition Operation with HRD Fuel

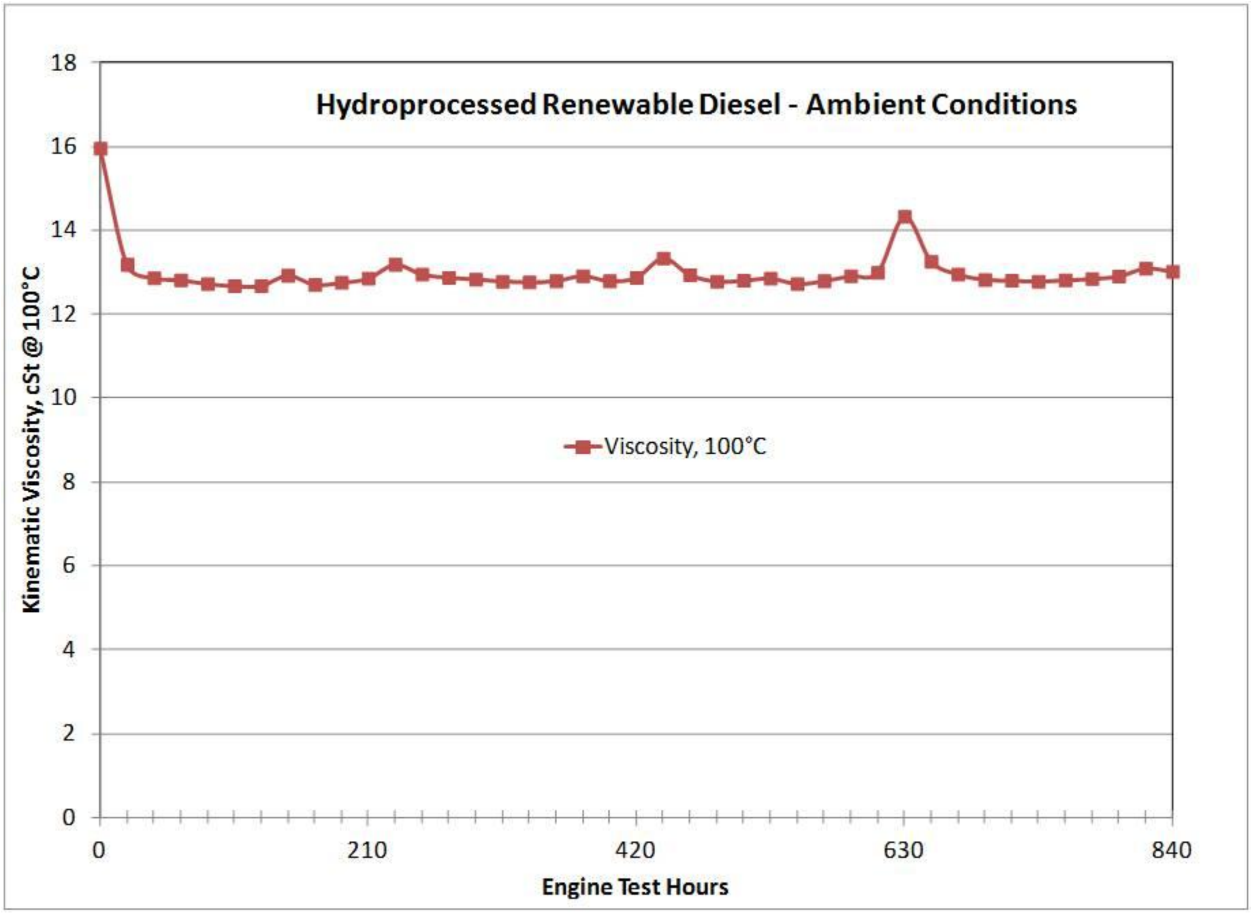


Figure 11. Engine Lubricant Kinematic Viscosity for Ambient Condition Operation with HRD Fuel

An attempt was made to document deposition that occurred with combustion of the HRD diesel fuel. The fuel injectors were photographed at the start of testing, and then every 210 hours thereafter, to ascertain deposition characteristics of the HRD test fuel at the ambient operating condition. Figure 12 through Figure 17 inclusive show the injector nozzle deposit development from the start of testing until the end of testing for each engine cylinder. Each figure has close-up images of the spray holes and tip. The images are remarkable only in that the deposition was very minimal throughout, and at the end of testing at the ambient operating conditions with the HRD fuel.

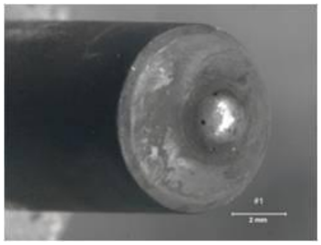
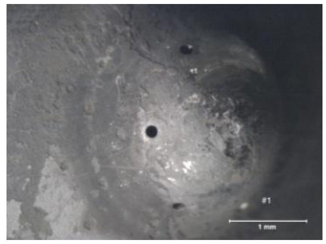
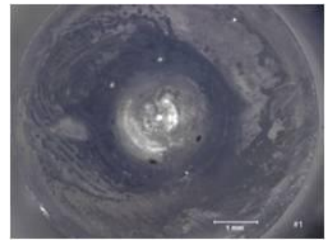
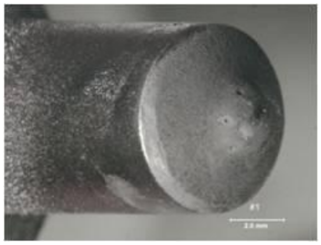
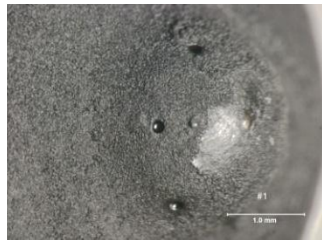
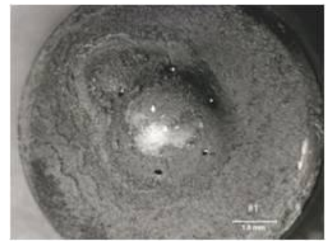
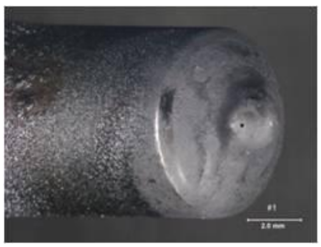
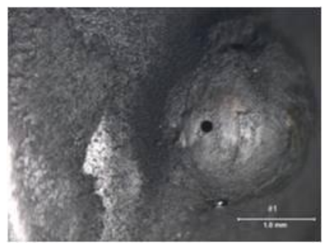
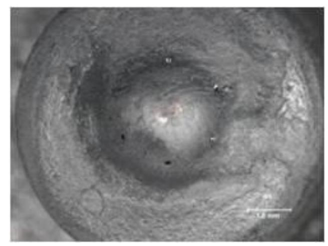
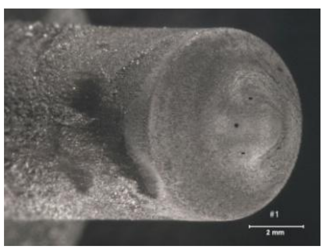
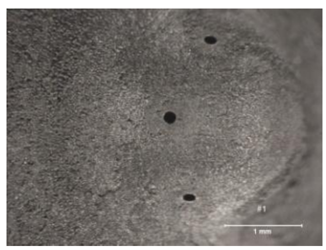
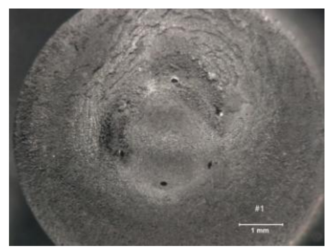
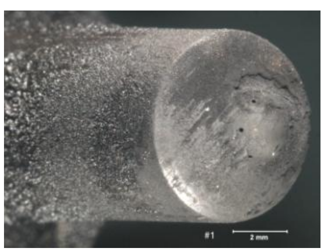
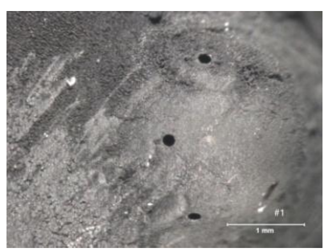
Cylinder 1 0-Hour Ambient			
Cylinder 1 210-Hour Ambient			
Cylinder 1 420-Hour Ambient			
Cylinder 1 630-Hour Ambient			
Cylinder 1 840-Hour Ambient			

Figure 12 . HRD Injector Cylinder 1 Deposition – Ambient Temperature Test

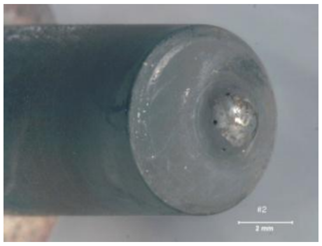
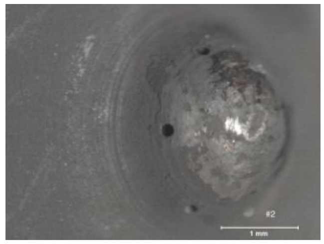
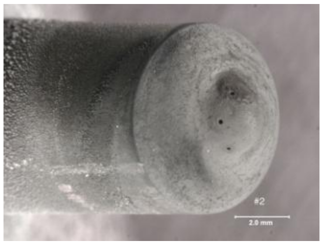
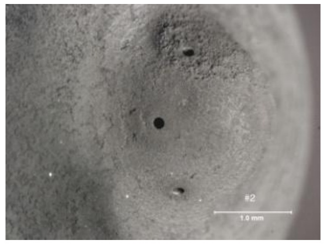
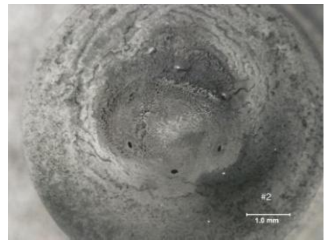
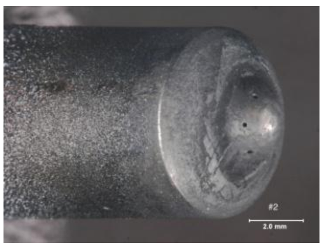
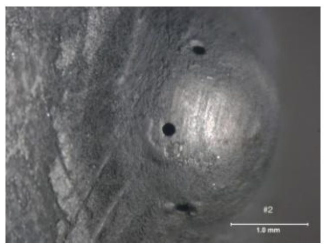
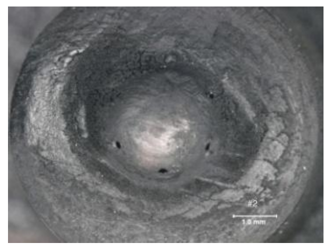
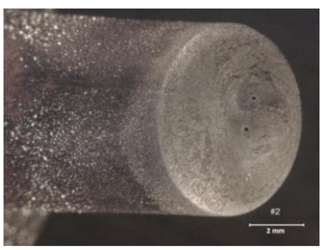
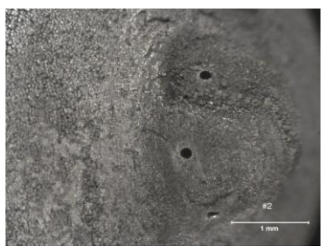
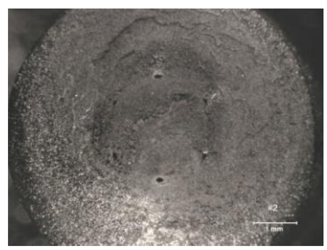
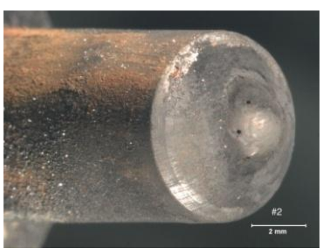
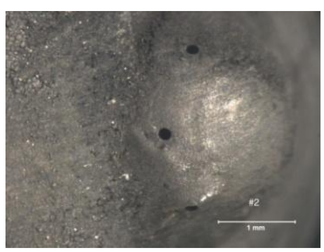
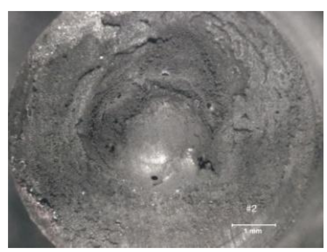
Cylinder 2 0-Hour Ambient			
Cylinder 2 210-Hour Ambient			
Cylinder 2 420-Hour Ambient			
Cylinder 2 630-Hour Ambient			
Cylinder 2 840-Hour Ambient			

Figure 13. HRD Injector Cylinder 2 Deposition – Ambient Temperature Test

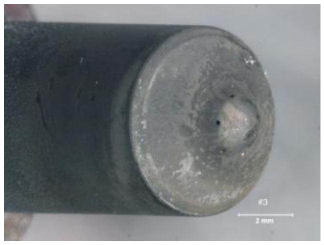
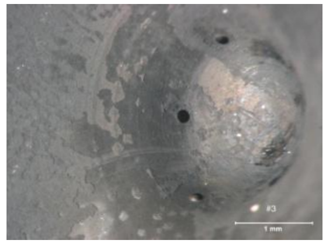
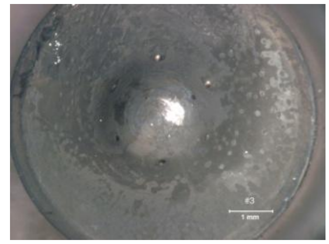
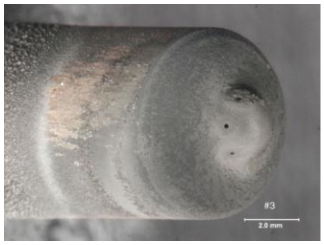
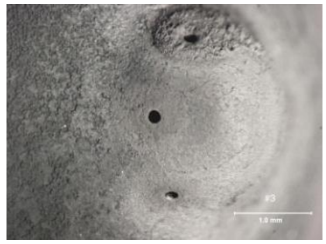
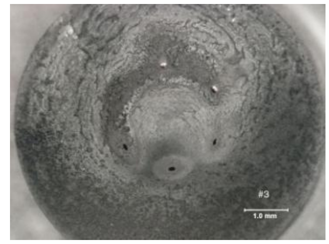
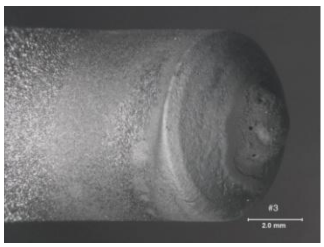
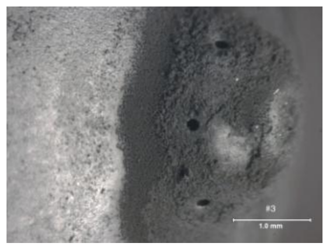
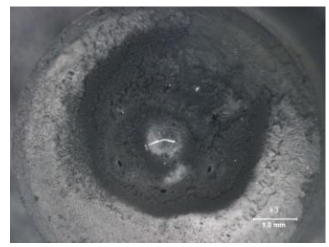
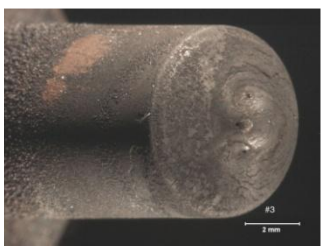
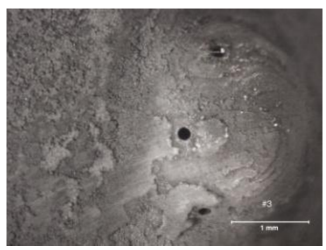
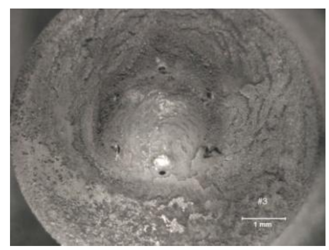
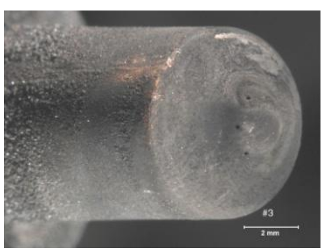
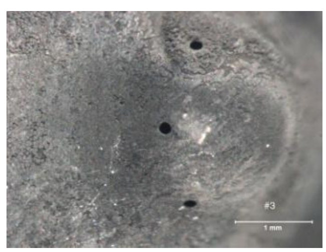
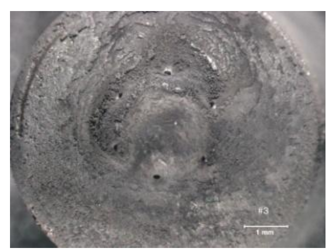
Cylinder 3 0-Hour Ambient			
Cylinder 3 210-Hour Ambient			
Cylinder 3 420-Hour Ambient			
Cylinder 3 630-Hour Ambient			
Cylinder 3 840-Hour Ambient			

Figure 14. HRD Injector Cylinder 3 Deposition – Ambient Temperature Test

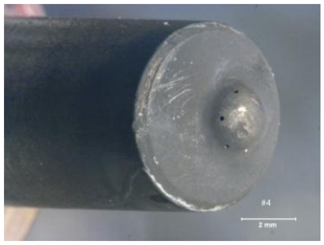
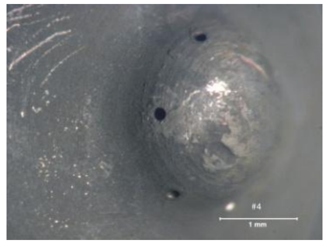
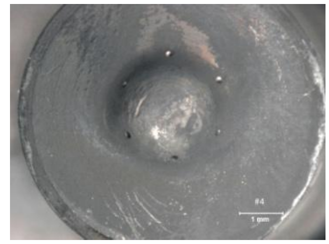
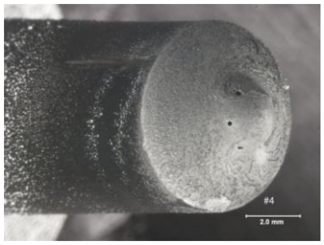
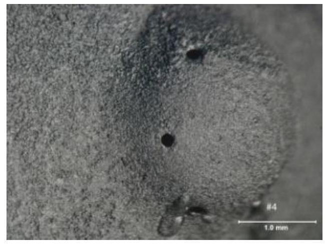
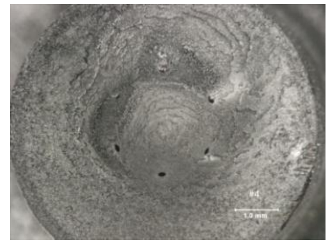
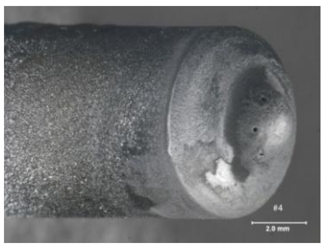
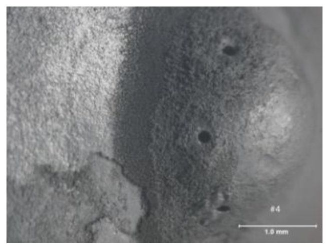
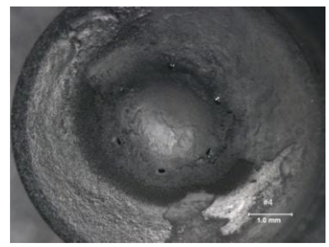
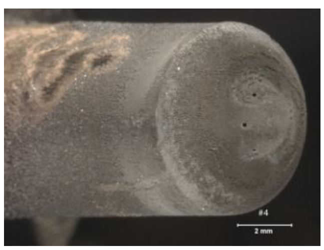
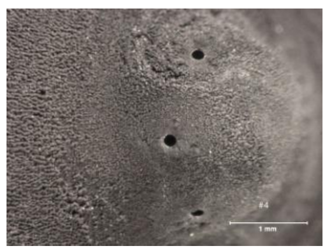
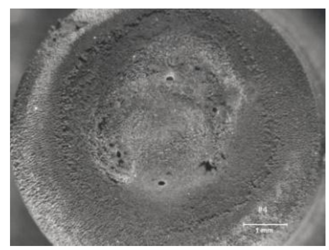
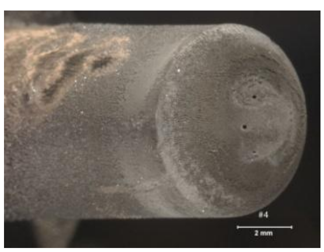
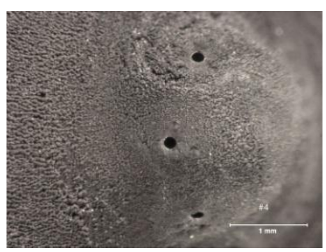
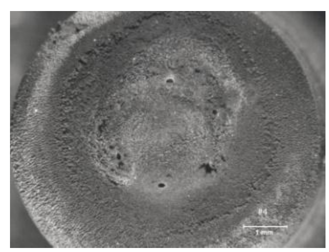
Cylinder 4 0-Hour Ambient			
Cylinder 4 210-Hour Ambient			
Cylinder 4 420-Hour Ambient			
Cylinder 4 630-Hour Ambient			
Cylinder 4 840-Hour Ambient			

Figure 15. HRD Injector Cylinder 4 Deposition – Ambient Temperature Test

Cylinder 5 0-Hour Ambient
Cylinder 5 210-Hour Ambient
Cylinder 5 420-Hour Ambient
Cylinder 5 630-Hour Ambient
Cylinder 5 840-Hour Ambient

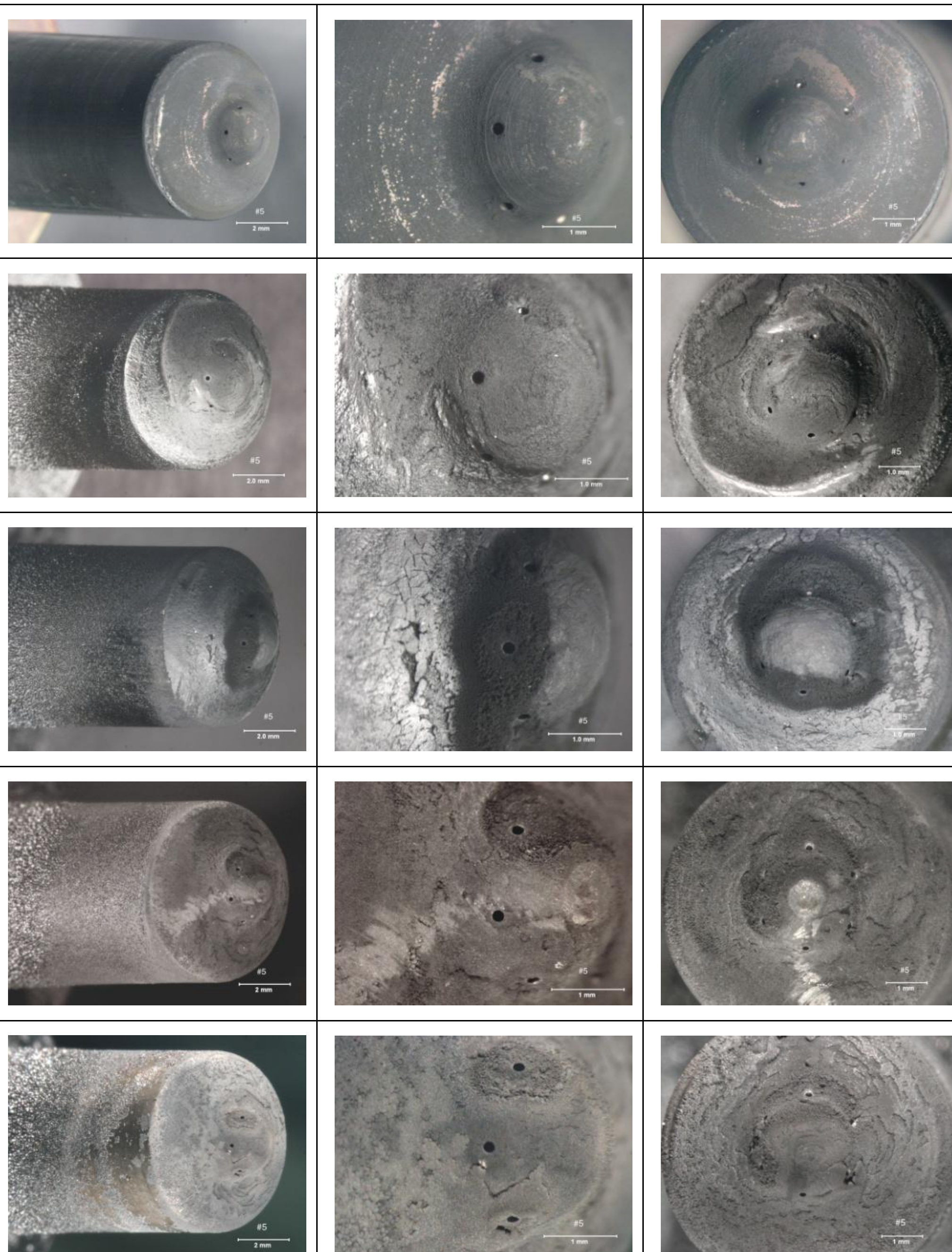


Figure 16. HRD Injector Cylinder 5 Deposition – Ambient Temperature Test

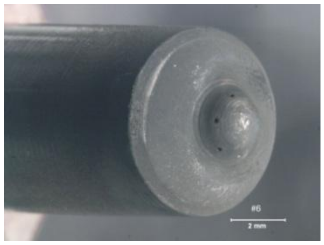
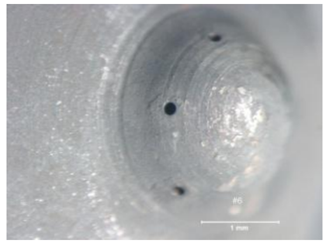
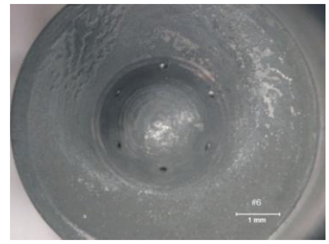
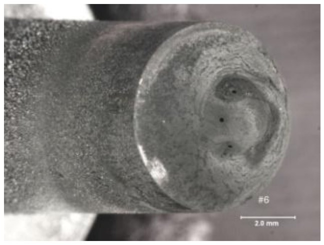
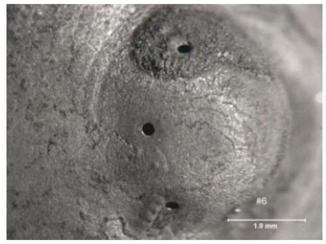
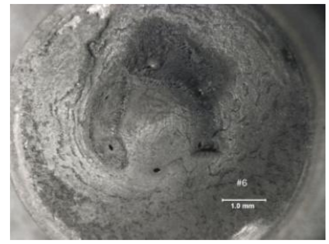
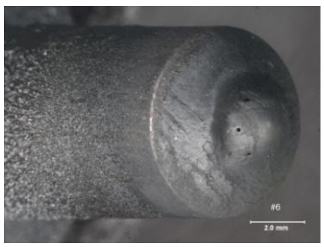
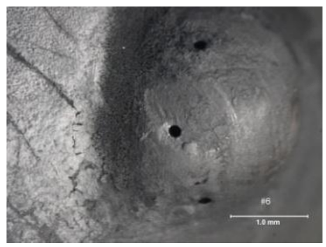
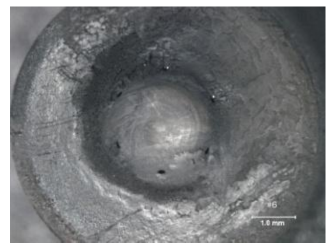
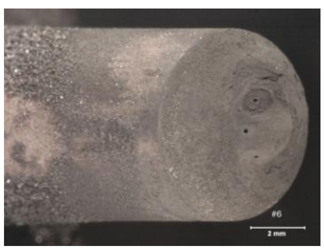
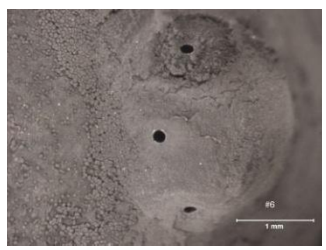
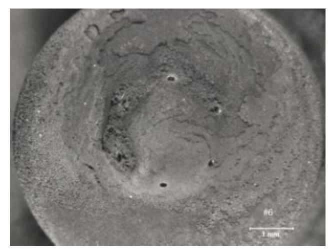
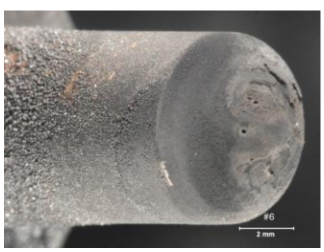
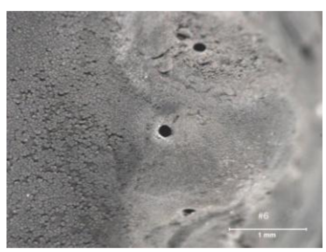
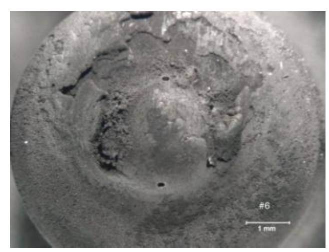
Cylinder 6 0-Hour Ambient			
Cylinder 6 210-Hour Ambient			
Cylinder 6 420-Hour Ambient			
Cylinder 6 630-Hour Ambient			
Cylinder 6 840-Hour Ambient			

Figure 17. HRD Injector Cylinder 6 Deposition – Ambient Temperature Test

The cylinder head was removed from the engine in order to obtain a cursory inspection of the piston crown combustion bowl deposits, and the cylinder head valve and fire deck deposits for the engine as received. Any deposits on those surfaces were likely from the engine proof run at the factory. No further disassembly of the engine was performed. The cylinder head was again removed at the completion of 840 hours at ambient operating conditions to ascertain the level of deposits generated by use of the HRD fuel. The cylinder head images shown in Figure 18 are comparing the 0 hour and the 840 hour deposition after consuming the HRD fuel at ambient operating conditions. The deposits at 840 hours do not appear to be significantly heavier than the before test deposits. A closer examination of the fire deck and valve deposits for each cylinder at the start and end of testing can be seen in Figure 19, and confirms the low level of deposits with the HRD fuel. Cylinder head deposition does not appear to be an issue when using the HRD fuel at ambient operating conditions.

The piston combustion bowl and piston crown were also documented for fuel related deposition prior to the start of testing and at the 840 hour end of testing with HRD at ambient operating conditions. The level of piston crown deposits generated by the HRD fuel usage at ambient conditions is shown in Figure 20. There appear to be very little additional deposits on the piston crowns due to the use of HRD fuel for 840 hours. Piston crown and combustion bowl deposition does not appear to be an issue with the HRD fuel at the ambient operating conditions.

0-Hour Ambient	
840-Hour Ambient	

Figure 18. HRD Ambient Condition Cylinder Head Fire Deck Deposition

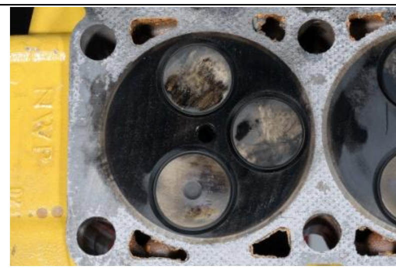
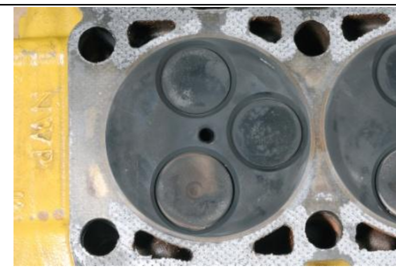
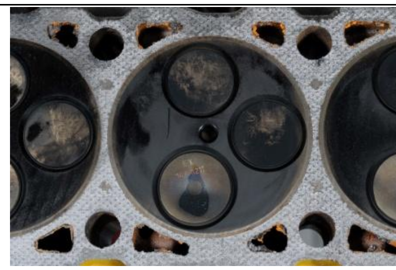
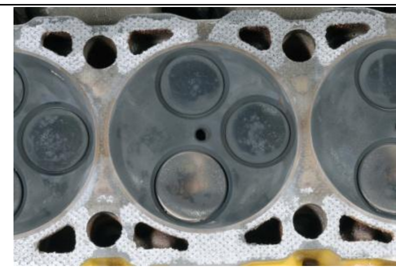
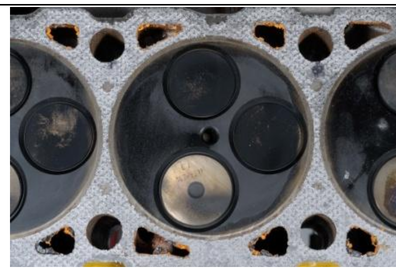
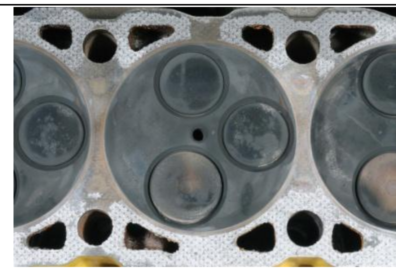
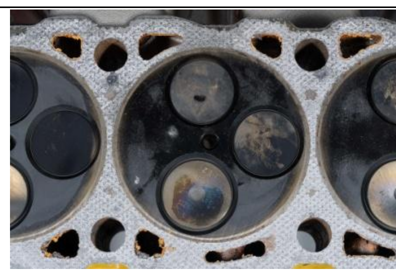
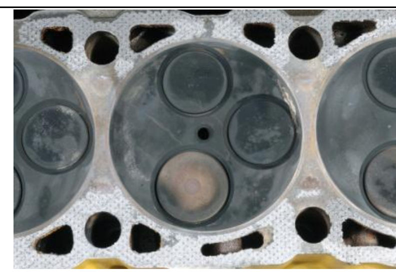
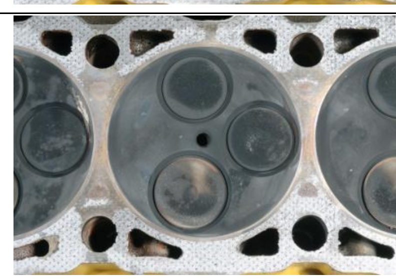
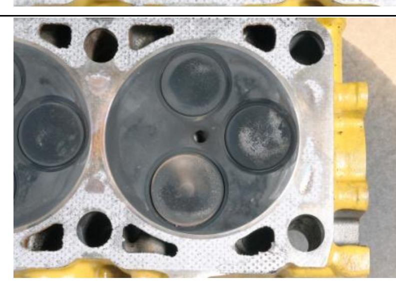
	0-Hour	840-Hour
Cylinder 1 Valves **Ambient**		
Cylinder 2 Valves **Ambient**		
Cylinder 3 Valves **Ambient**		
Cylinder 4 Valves **Ambient**		
Cylinder 5 Valves **Ambient**		
Cylinder 6 Valves **Ambient**		

Figure 19. HRD Ambient Condition Valve and Fire Deck Deposits

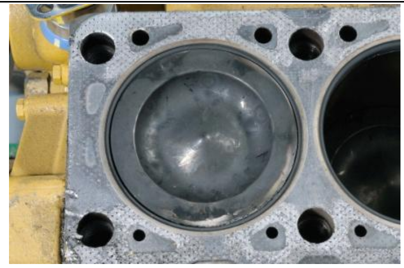
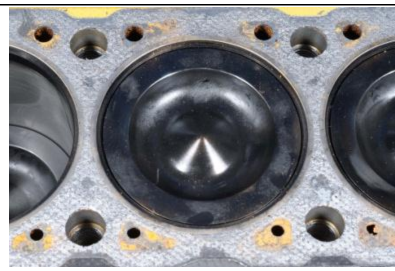
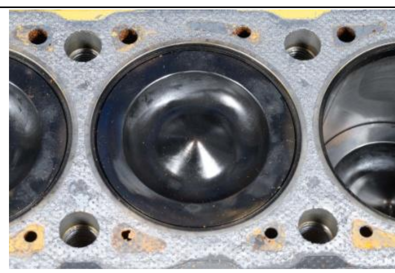
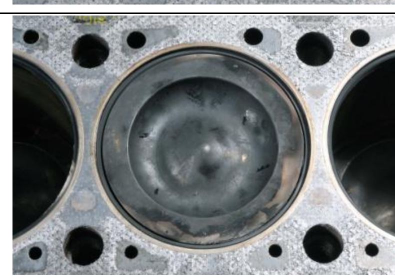
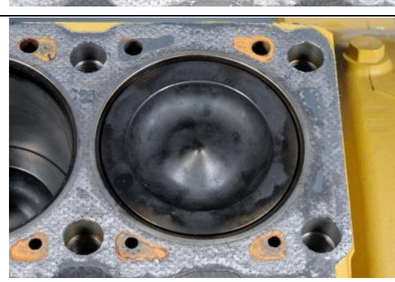
	0-Hour	840-Hour
Cylinder 1 Piston Ambient		
Cylinder 2 Piston Ambient		
Cylinder 3 Piston Ambient		
Cylinder 4 Piston Ambient		
Cylinder 5 Piston Ambient		
Cylinder 6 Piston Ambient		

Figure 20. HRD Ambient Condition Piston Crown Deposits

3.1 TEST 2: DESERT OPERATING CONDITIONS

The second test was conducted utilizing the batch of HRD fuel coded AF-8295, and was performed at the desert operating conditions. The first of the two CAT C7 engines was installed on the test stand and a run-in was performed using an ULSD diesel fuel at the desert operating conditions. Following a run-in, full-rack power curves were performed using the ULSD and HRD fuels. Following the power curves, the first 210 hour segment of the desert temperature test with the HRD diesel fuel was initiated. At the 210 hour point, power curves were generated with ULSD and HRD fuels, and the injectors were removed for inspection and imaging to document deposition. Injectors were inspected and power curves generated at every 210 hour interval until test completion at 840 hours. A desert condition engine parameter operating summary is included as Table 9 for the duration of the HRD desert condition test.

The power curves for the HRD diesel fuel for the testing are shown in Figure 21. For both fuels the power was down from the advertised 275-hp, due to the desert conditions. The lower density HRD fuel showed a greater deviation from advertised performance at the desert conditions than the RDF fuel.

Due to the lower density, and lower energy density of the HRD fuel, the power was lower than the RDF power generated. The curves showed that the power initially increased with time of operation; presumably due to the engine continuing to run-in, then remained consistent out to 840 hours of engine operation at desert conditions.

The power curves for the RDF diesel fuel for the testing are shown in Figure 22. The curves show that the power increased with time of operation; presumably due to the engine continuing to run-in, then remained remarkably steady even over the last 210 hours of operation. The power deviations over the 840 hours of operation appear similar with both fuels.

Table 9. Operating Condition Summary for HRD Fuel Desert Condition Test

Parameter	Units	210-Hour				420-Hour				630-Hour				840-Hour			
		Rated		Idle		Rated		Idle		Rated		Idle		Rated		Idle	
		Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	StdD ev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
SPEED	RPM	2400	1	708	1	2400	1	707	1	2400	1	708	1	2400	1	708	1
TORQUE	lb-ft	539.7	10.8	11.0	1.0	541.8	9.8	11.4	0.8	539.9	6.2	11.3	0.8	542.5	8.2	11.1	0.8
Fuel Flow	lb/hr	93.73	1.71	2.46	0.22	94.14	0.85	2.37	0.22	94.00	0.60	2.35	0.22	94.04	0.78	2.35	0.21
POWER	bhp	246.6	4.9	1.5	0.1	247.6	4.5	1.5	0.1	246.7	2.8	1.5	0.1	247.9	3.7	1.5	0.1
BSFC	lb/bhp-hr	0.380	0.005	1.662	0.183	0.380	0.004	1.550	0.176	0.381	0.003	1.542	0.174	0.379	0.004	1.568	0.177
Mass Air Flow	lb/hr	3179	20	356	5	3172	15	350	3	3163	15	350	4	3148	30	343	3
Air/Fuel Ratio	:1	33.9	0.6	145.8	13.5	33.7	0.4	148.9	13.3	33.7	0.3	150.4	13.1	33.5	0.4	147.2	12.7
BMEP	psi	184.2	3.7	3.8	0.3	184.9	3.3	3.9	0.3	184.2	2.1	3.9	0.3	185.1	2.8	3.8	0.3
Crankcase Blow-by	SCFM	7.01	0.40	1.60	0.10	6.88	0.39	1.80	0.36	6.99	0.35	1.58	0.11	7.10	0.42	1.60	0.09
TEMPERATURES																	
Coolant In	°F	210	1	165	12	210	1	173	2	210	1	173	2	210	1	173	2
Coolant Out	**°F**	**218**	**1**	**167**	**11**	**218**	**1**	**174**	**2**	**218**	**1**	**174**	**2**	**218**	**1**	**174**	**2**
Oil Gallery	°F	240	1	173	10	241	1	180	2	241	1	179	2	242	1	180	2
Oil Sump	°F	253	1	176	10	254	1	182	2	254	1	182	2	254	1	182	2
Air Before Compressor	**°F**	**120**	**3**	**118**	**3**	**120**	**1**	**119**	**3**	**120**	**0**	**119**	**3**	**120**	**0**	**119**	**3**
Air After Compressor	°F	403	5	124	3	404	1	125	2	404	1	125	2	404	1	125	2
Manifold Air	**°F**	**155**	**3**	**115**	**5**	**155**	**1**	**115**	**4**	**155**	**1**	**104**	**6**	**155**	**10**	**115**	**5**
Cylinder 1	°F	966	17	211	9	978	7	220	7	999	13	220	8	1004	10	227	11
Cylinder 2	°F	1078	19	242	7	1090	7	246	5	1088	5	244	6	1078	12	249	5
Cylinder 3	°F	1088	19	249	7	1106	5	254	6	1107	7	248	7	1104	11	250	7
Cylinder 4	°F	1054	11	228	8	1055	7	230	7	1055	12	224	7	1066	13	228	7
Cylinder 5	°F	1042	10	232	7	1032	7	231	7	1031	10	230	6	1030	17	235	7
Cylinder 6	°F	987	14	236	7	993	4	240	6	987	6	237	6	982	10	241	5
Exhaust-Front Cylinders	°F	1140	18	258	8	1156	6	264	9	1161	7	259	9	1159	13	264	10
Exhaust-Rear Cylinders	°F	1122	12	246	9	1123	5	248	9	1121	8	243	9	1127	14	249	9
Exhaust Stack	°F	881	16	246	9	887	5	252	16	891	6	248	18	893	13	252	17
Fuel Inlet	**°F**	**174**	**5**	**175**	**2**	**175**	**1**	**175**	**1**	**175**	**1**	**175**	**1**	**175**	**1**	**175**	**1**
Fuel Return	°F	193	4	157	8	194	2	163	4	194	1	162	3	193	4	161	4
PRESSURES																	
Coolant	psig	11.82	1.14	6.22	1.50	11.44	1.54	6.97	1.67	11.05	1.07	5.93	1.29	9.45	4.57	5.44	3.00
Oil Gallery	psig	51.12	0.55	34.88	4.17	50.73	0.47	32.14	0.77	49.80	0.56	31.61	0.81	48.98	0.63	31.31	0.85
Fuel Inlet	psig	70.65	3.35	44.67	1.50	69.81	0.39	41.90	0.45	69.29	0.42	41.90	0.52	68.83	0.41	40.72	0.69
Air Before Compressor	psia	13.55	0.03	14.22	0.03	13.55	0.03	14.24	0.03	13.54	0.03	14.22	0.03	13.53	0.04	14.20	0.04
Air After Compressor	psia	40.10	0.09	14.43	0.05	40.07	0.06	14.42	0.06	40.07	0.06	14.43	0.06	40.06	0.08	14.41	0.08
Manifold Air	psig	25.85	0.10	0.20	0.02	25.86	0.06	0.20	0.02	25.85	0.06	0.21	0.02	25.87	0.07	0.21	0.03
Exhaust-Front Cylinders	psig	25.63	0.21	0.22	0.04	25.34	0.72	-0.12	0.31	24.50	0.17	-0.50	0.09	24.39	0.32	-0.52	0.12
Exhaust-Rear Cylinders	psig	25.04	0.39	-0.27	0.15	23.85	0.35	-1.06	0.16	23.70	0.27	-1.08	0.14	23.67	0.42	-1.10	0.17
Exhaust Stack	psig	0.27	0.01	-0.25	0.01	0.28	0.01	-0.25	0.00	0.28	0.03	-0.24	0.04	0.29	0.01	-0.25	0.00
ATMOSPHERIC CONDITIONS																	
Atmospheric Pressure	psia	14.26	0.05	14.24	0.05	14.20	0.06	14.20	0.06	14.21	0.05	14.20	0.05	14.20	0.08	14.18	0.07
Dry Bulb Temperature	°F	99.2	6.0	99.6	6.1	107.2	8.9	106.2	8.9	103.2	6.2	103.1	6.4	103.1	7.8	103.6	7.0
Relative Humidity	%	14.3	5.6	14.0	5.7	10.7	3.0	10.4	2.8	10.0	2.7	10.0	1.9	9.2	3.1	9.2	2.3

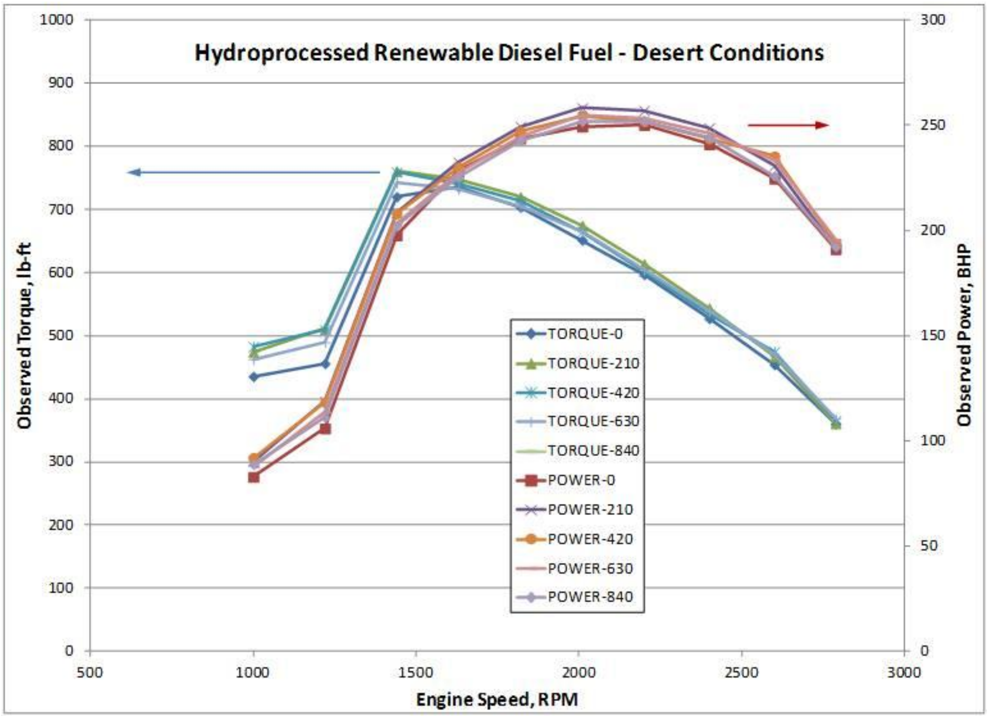


Figure 21. Desert Condition Power and Torque with the HRD Fuel at 210-hour Intervals

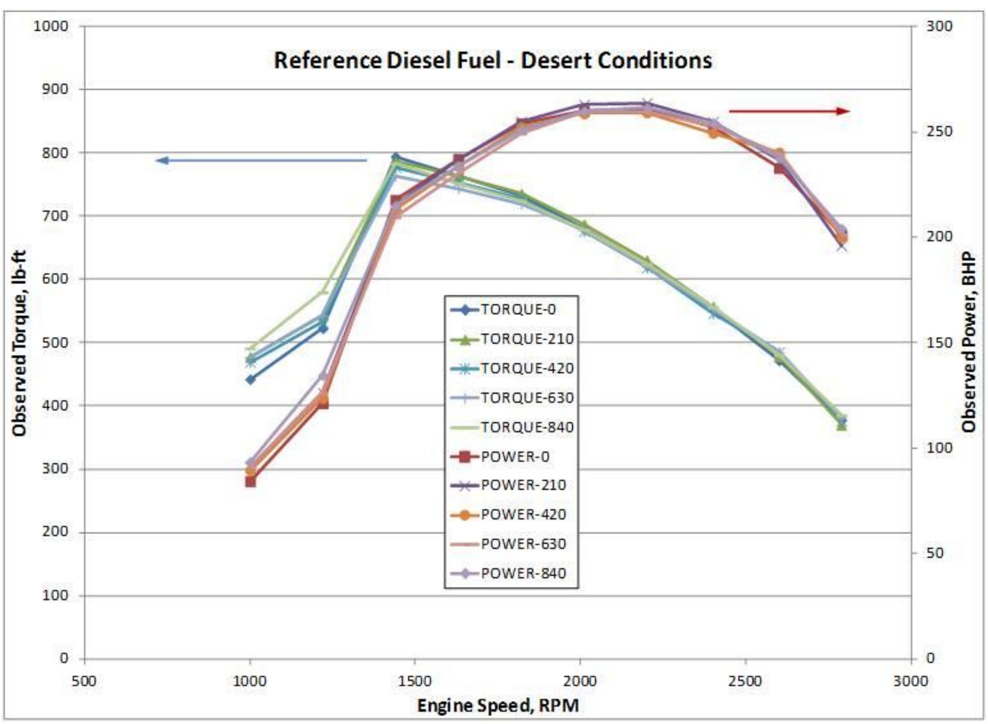


Figure 22. Desert Condition Power and Torque with the RDF Fuel at 210-hour Intervals

The fuel consumption was also measured during the power curves performed at each 210 hour interval. The fuel consumption measured with the engine operating on HRD fuel during the HRD fuel desert condition test are shown in Figure 23. The fuel consumption values appear to reflect the power deviations seen throughout the 840 hours of testing with the HRD fuel.

The fuel consumption was also measured using the RDF fuel during the power curves performed at each 210 hour interval. The fuel consumption measured with the engine operating on RDF fuel during the desert condition test is shown in Figure 24. The fuel consumption values appear to reflect the power deviations seen throughout the 840 hours of testing with the HRD fuel at desert operating conditions.

A comparison of the brake specific carbon monoxide (CO) gaseous exhaust emissions for the durability test with each fuel at the 210 hour intervals is shown in Figure 25 for both the HRD and RDF fuels. The brake specific carbon monoxide emissions are remarkably consistent across the test duration, for both the HRD and RDF fuels. The CO emissions with the RDF at the end of testing showed the largest deviations from the other interval measurements. In relative terms, the HRD CO emissions are slightly lower than the RDF CO emissions.

Figure 26 shows a comparison of the brake specific oxides of nitrogen (NOx) gaseous exhaust emissions for the durability test with each fuel at the 210 hour intervals both the HRD and RDF fuels. The brake specific oxides of nitrogen emissions are consistent across the test duration with the exception of the 0 hour points that may also be due to the engine still breaking in. With the exception of the 0 hour NOx emissions for both fuels, the emissions are remarkably consistent for this engine throughout the durability testing at desert conditions. In relative terms, the HRD NOx emissions are slightly lower than the RDF NOx emissions.

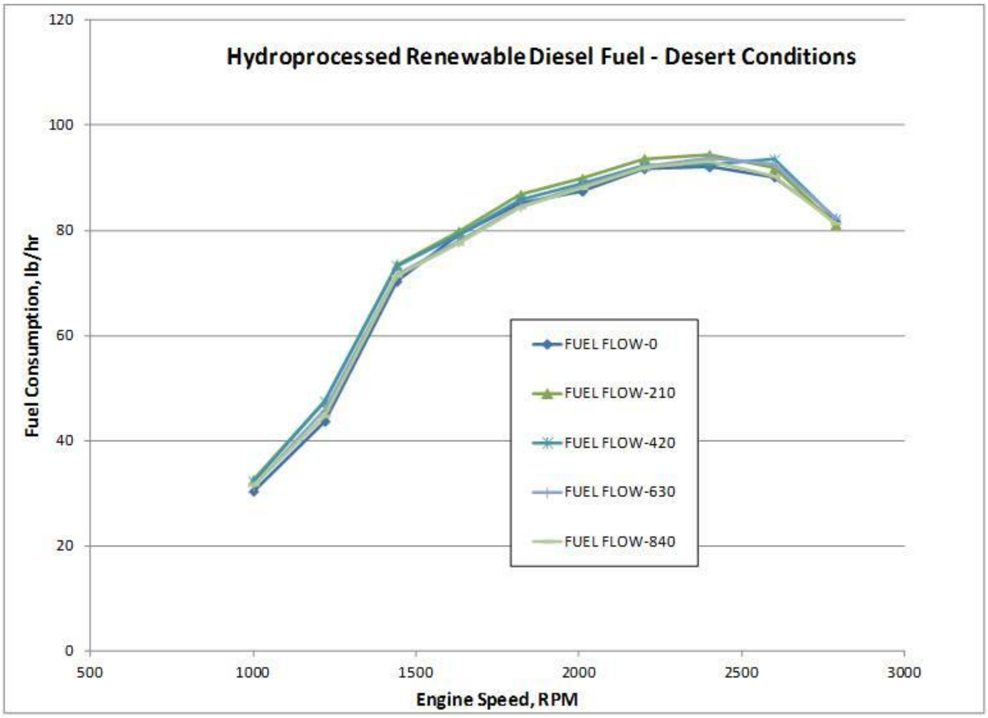


Figure 23. Fuel Consumption with HRD Fuel at Desert Operating Conditions and 210-Hour Intervals

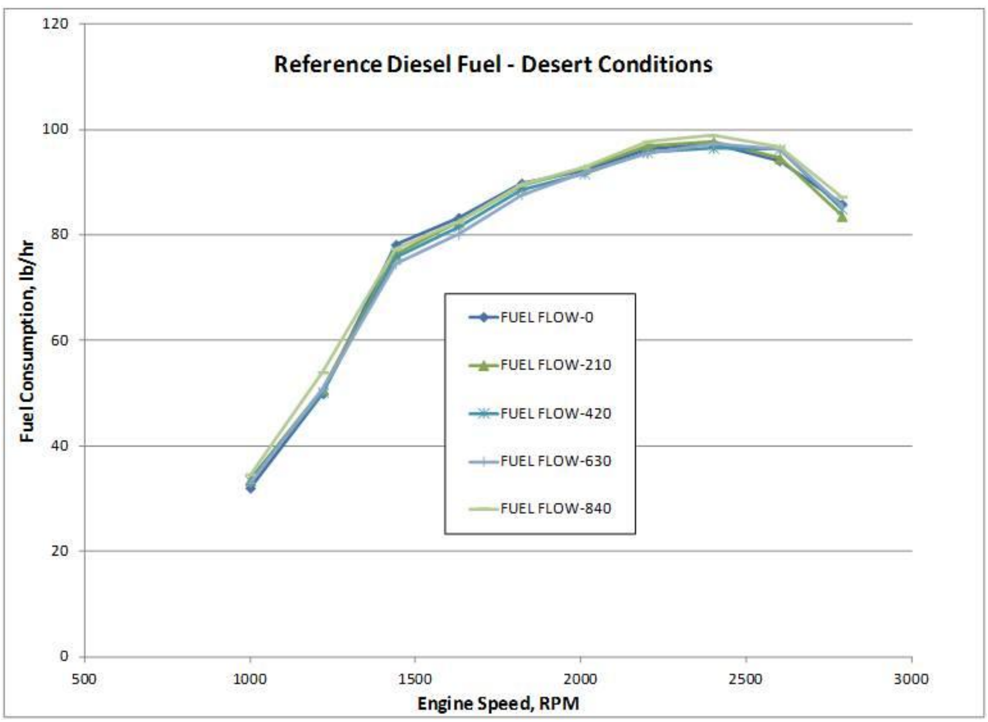


Figure 24. Fuel Consumption with RDF Fuel at Desert Operating Conditions and 210-Hour Intervals

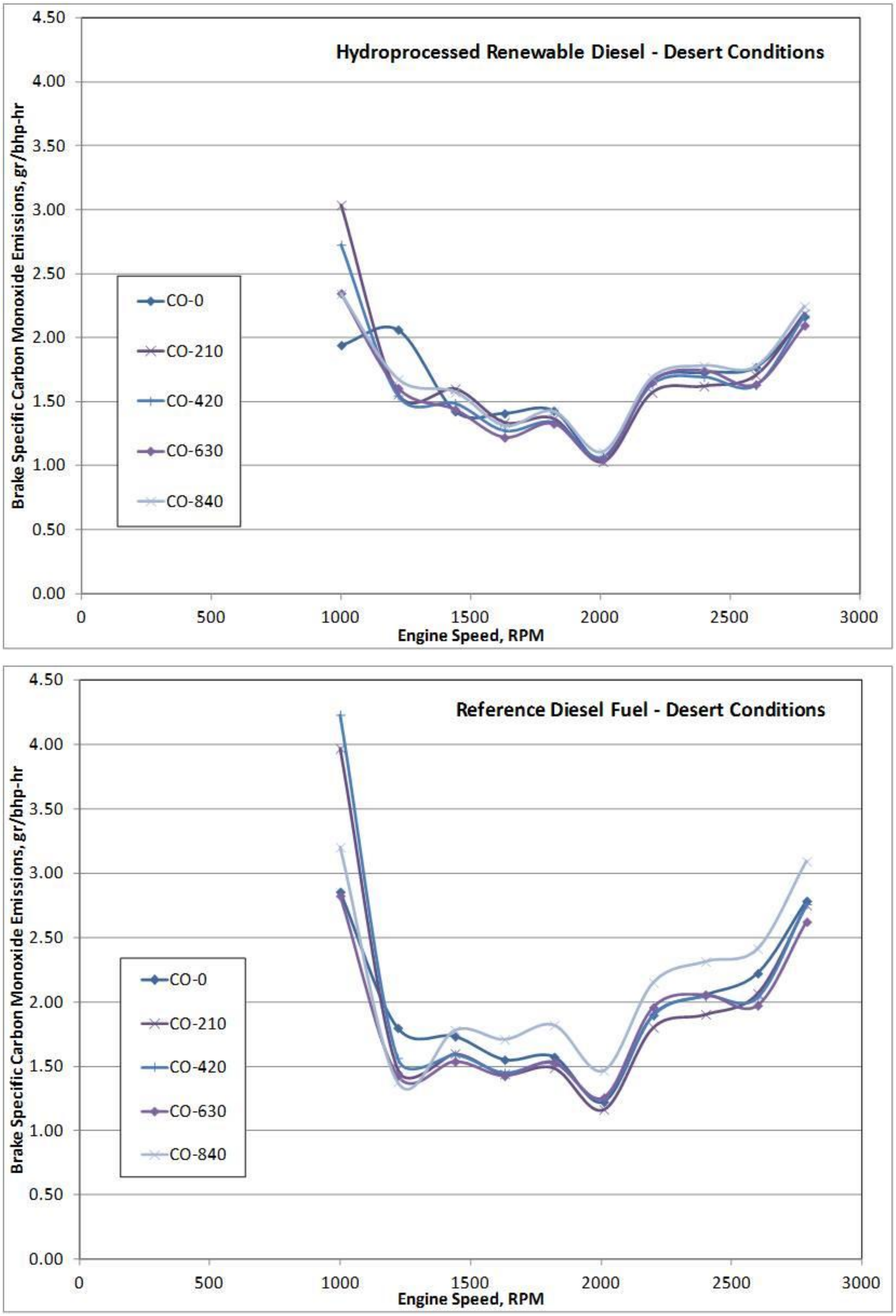
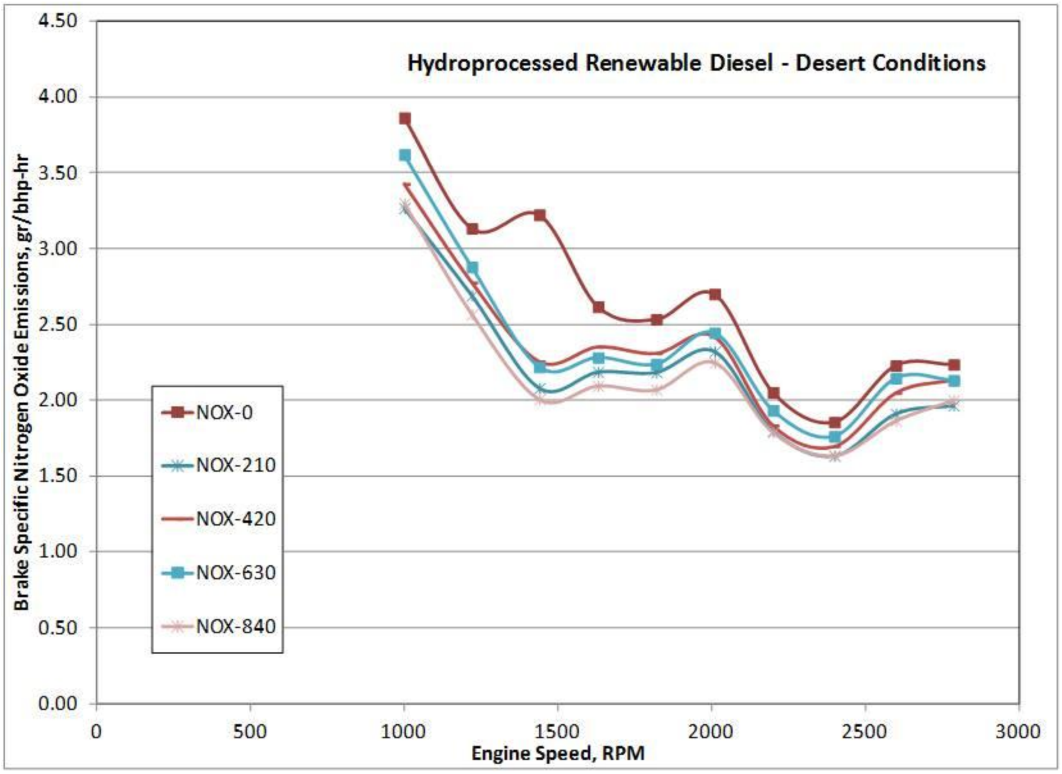


Figure 25. Brake Specific Carbon Monoxide Emissions at Desert Conditions at 210-hour Intervals



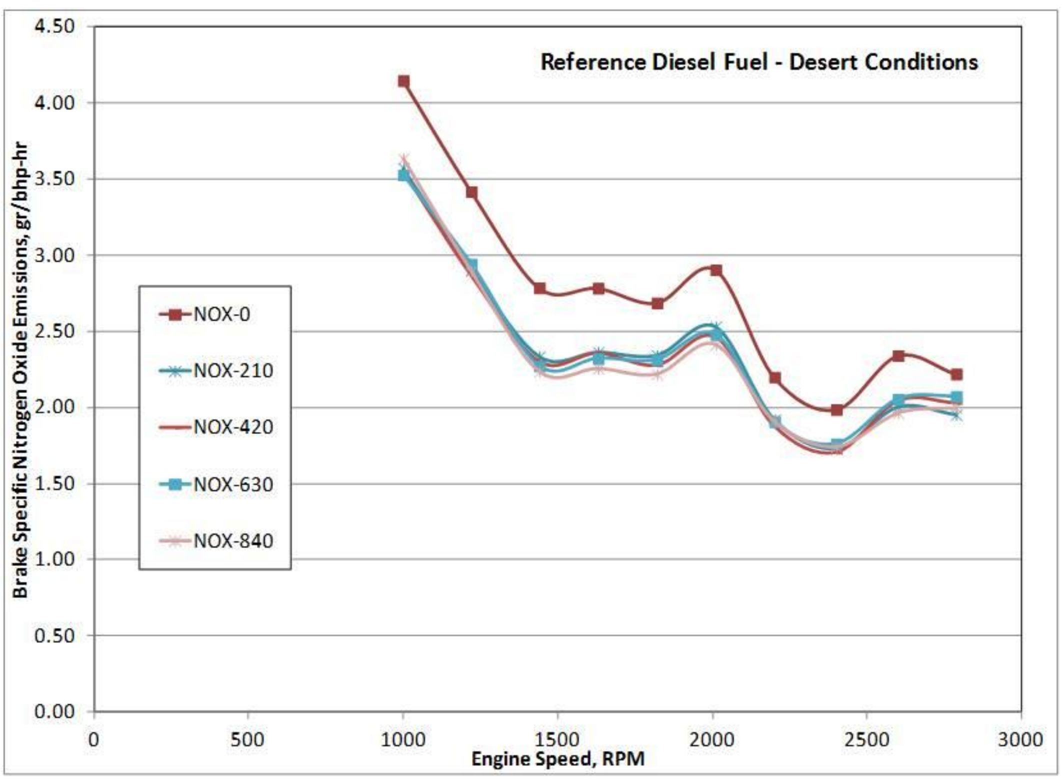
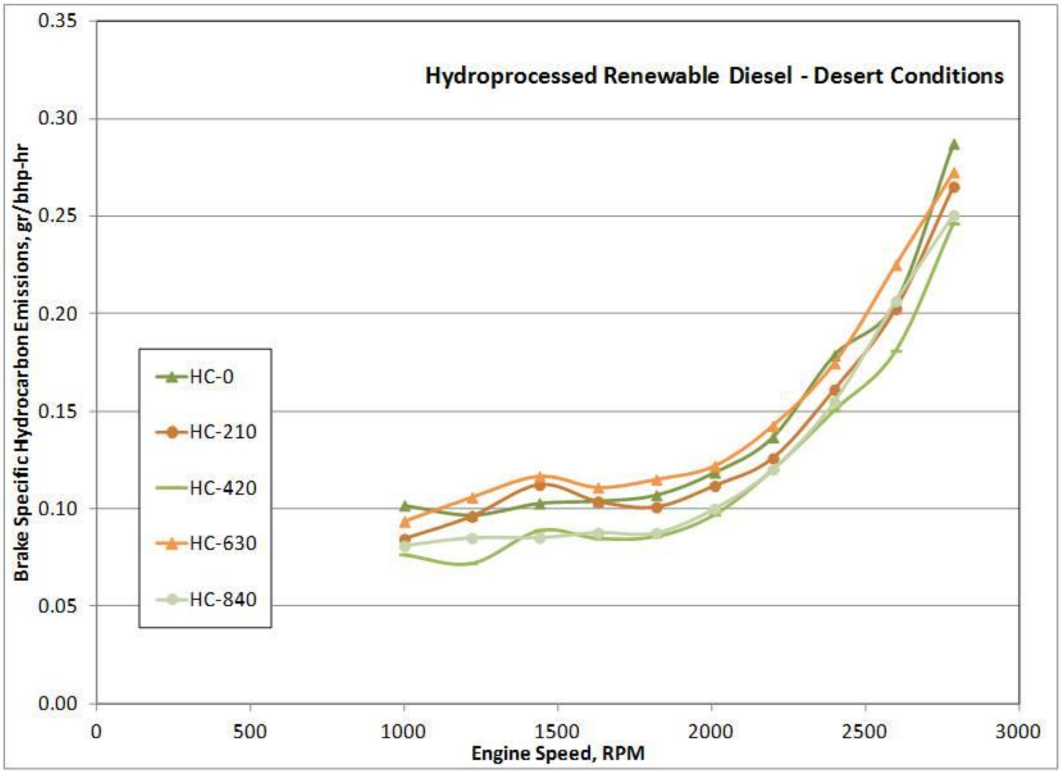


Figure 26. Brake Specific Oxides of Nitrogen Emissions at Desert Conditions at 210-hour Intervals

Figure 27 shows a comparison of the brake specific hydrocarbon (HC) gaseous exhaust emissions for the desert condition durability test with each fuel at the 210 hour intervals. For both the HRD and RDF fuels, the brake specific hydrocarbon (HC) emissions are very consistent across the test duration. The HRD fuel HC emissions are slightly lower than the RDF fuel HC emissions at the desert conditions.

The accumulation of wear metals in the engine lubricant are shown in Figure 28 for the HRD fuel testing at desert operating conditions. The initial 210 hours of testing shows increases of the wear metals that indicate further break-in of engine components was occurring. After the lubricant was changed at 210 hours, the accumulation rate of wear metals in the lubricant, decreased substantially. Curiously the wear metal accumulation rate after the 420 hour oil change was similar to the initial 210 hour accumulation rate. After the 630 hour oil change the accumulation rate was similar to that seen after the 210 hour oil change. The levels of wear metals measured would be considered normal.

The additive element concentrations in the engine lubricant are shown in Figure 29 for the desert operating condition test. The additive elements concentrations are quite consistent throughout the duration of the test. Likewise the engine lubricant kinematic viscosity also appears very consistent throughout the testing as shown in Figure 30. Major variations in the viscosity measured at 100 °C only occur when the lubricant was changed at the 210 hour intervals.



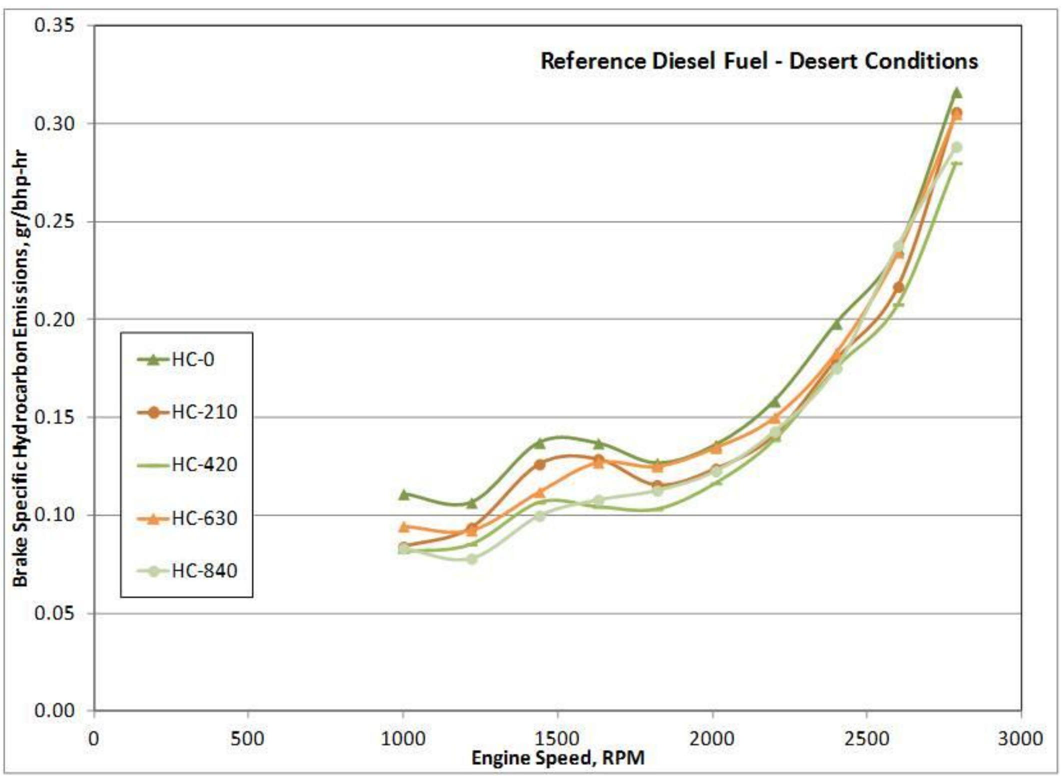


Figure 27. Brake Specific Hydrocarbon Emissions at Desert Conditions at 210-hour Intervals

An attempt was made to document deposition that occurred during desert operation with combustion of the HRD diesel fuel. The fuel injectors were photographed at the start of testing, and then every 210 hours thereafter, to ascertain deposition characteristics of the HRD test fuel at the desert operating condition. Figure 31 through Figure 36 inclusive show the injector nozzle deposit development from the start of testing until the end of testing for each engine cylinder. Each figure has close-up images of the spray holes and tip. The images are remarkable only in that the deposition was very minimal throughout, and at the end of testing, at the desert operating conditions with the HRD fuel.

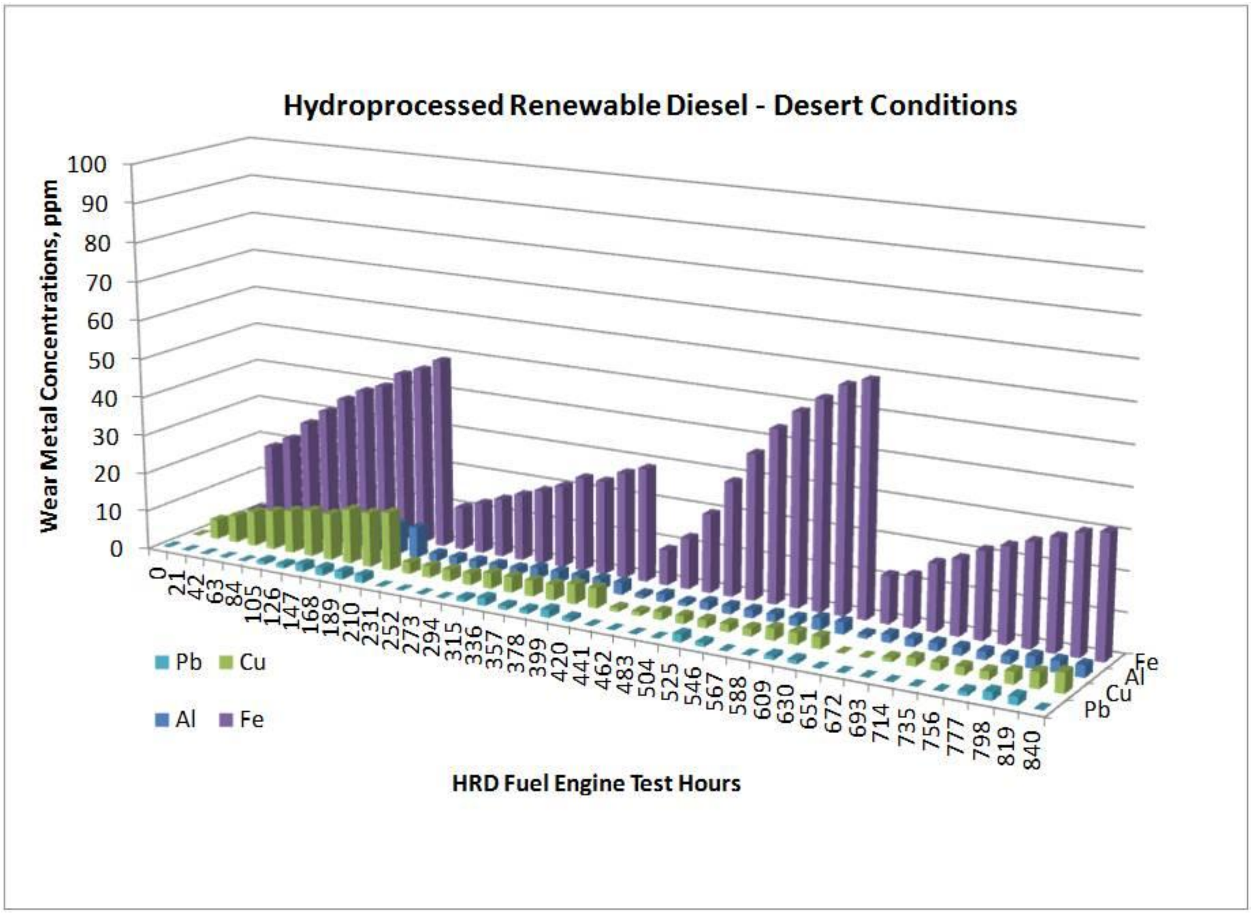


Figure 28. Engine Lubricant Wear Metals for Desert Condition Operation with HRD Fuel

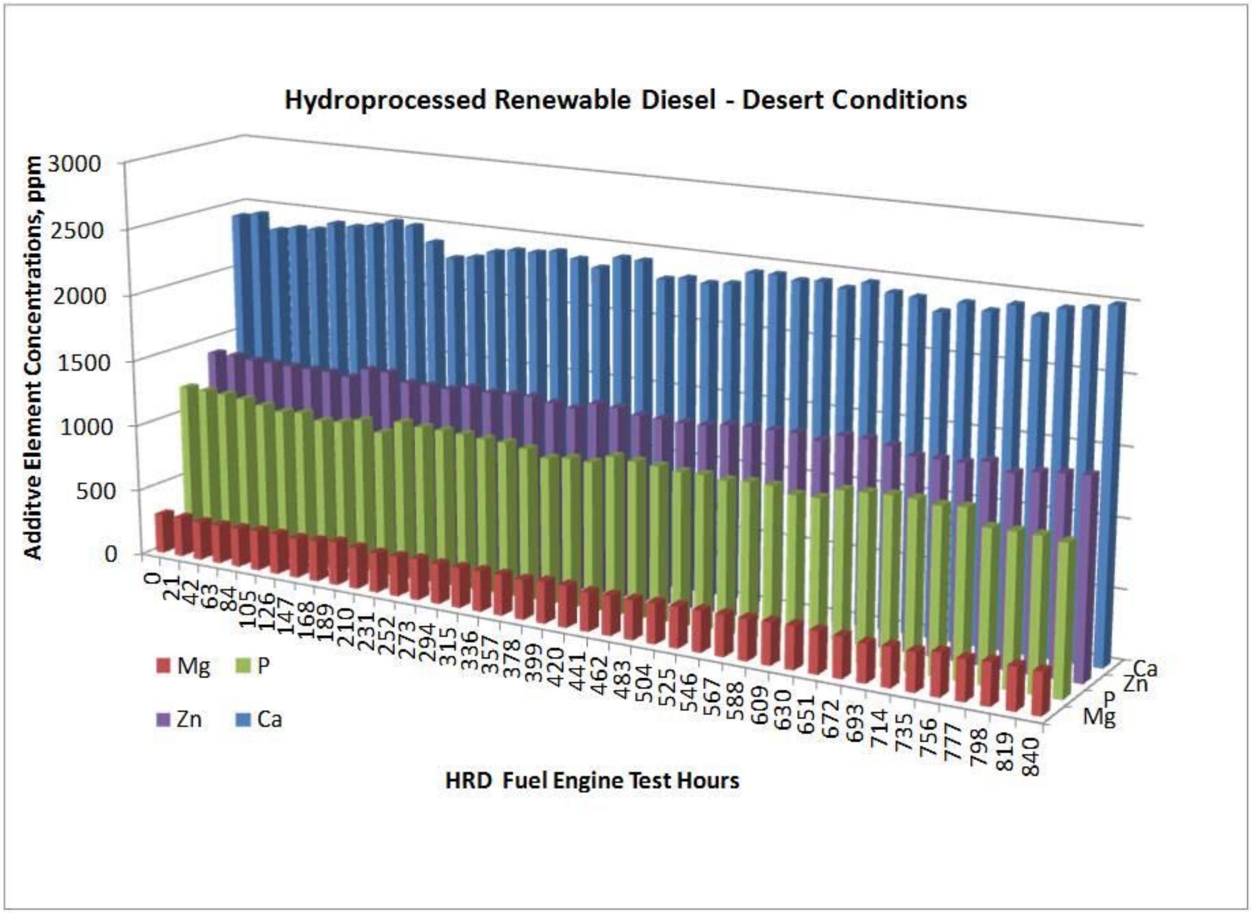


Figure 29. Engine Lubricant Additive Elements for Desert Condition Operation with HRD Fuel

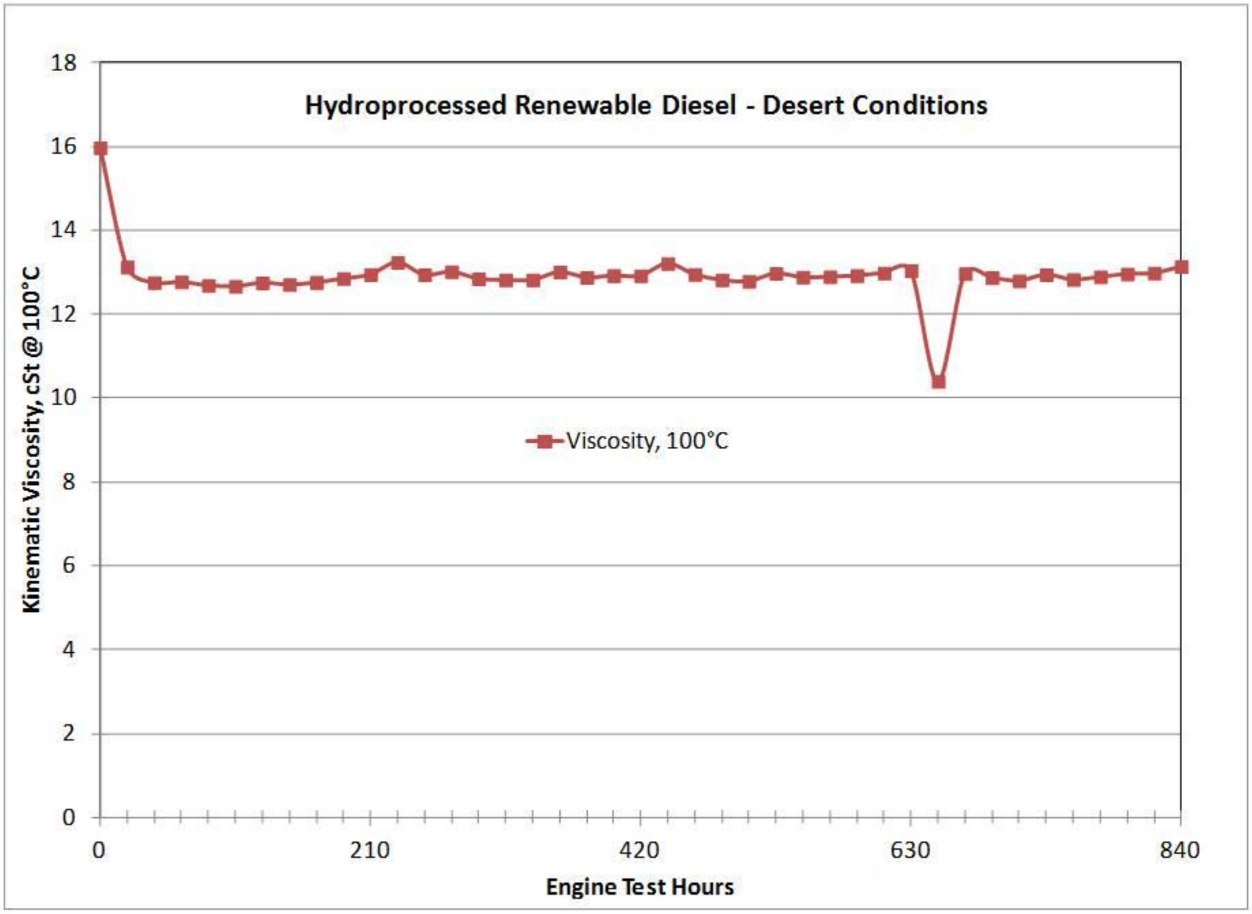


Figure 30. Engine Lubricant Kinematic Viscosity for Desert Condition Operation with HRD Fuel

The cylinder head was removed from the engine in order to obtain a cursory inspection of the piston crown combustion bowl deposits, and the cylinder head valve and fire deck deposits for the engine as received. Any deposits on those surfaces were likely from the engine proof run at the factory. No further disassembly of the engine was performed. The cylinder head was again removed at the completion of 840 hours at ambient operating conditions to ascertain the level of deposits generated by use of the HRD fuel. The cylinder head images shown in Figure 37 are comparing the 0 hour and the 840 hour deposition after consuming the HRD fuel at desert operating conditions. The deposits at 840 hours do not appear to be significantly heavier than the before test deposits. A closer examination of the fire deck and valve deposits for each cylinder at the start and end of testing can be seen in Figure 38, and confirms the low level of deposits with the HRD fuel. Cylinder head deposition does not appear to be an issue when using the HRD fuel at desert operating conditions.

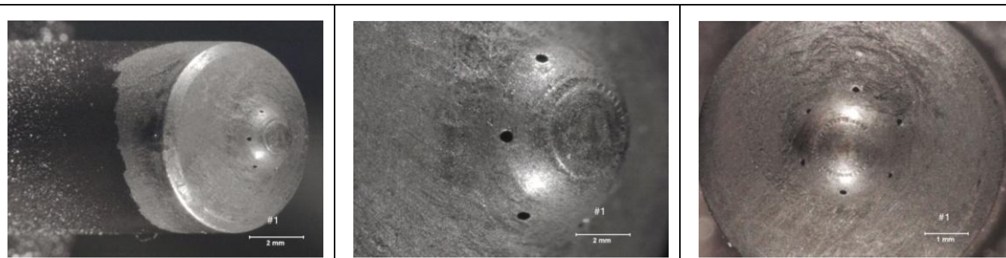
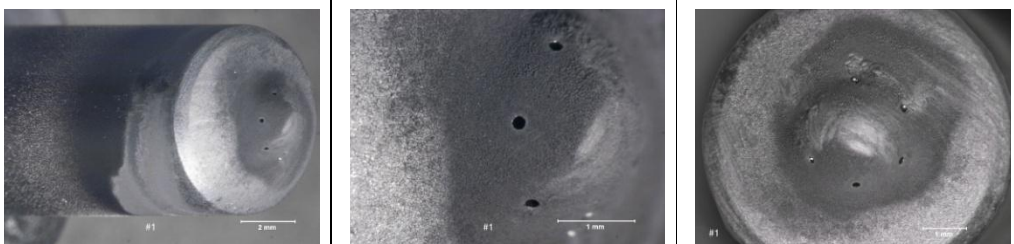
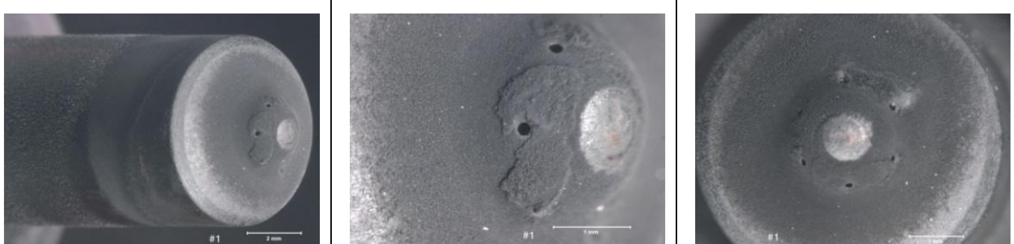
Cylinder 1 0-Hour Desert	
Cylinder 1 210-Hour Desert	
Cylinder 1 420-Hour Desert	
Cylinder 1 630-Hour Desert	
Cylinder 1 840-Hour Desert	

Figure 31. HRD Injector Cylinder 1 Deposition – Desert Temperature Test

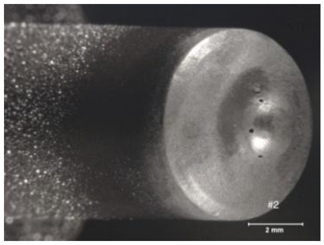
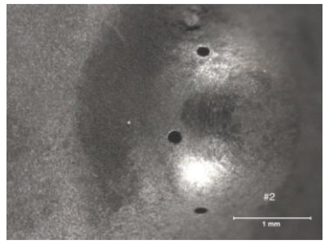
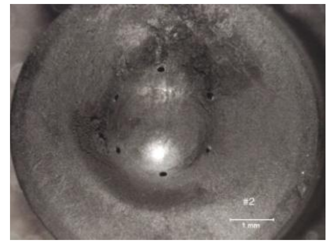
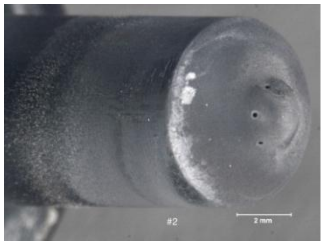
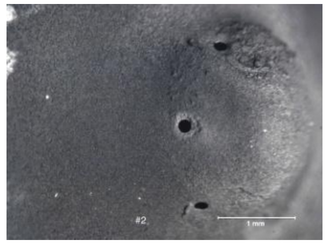
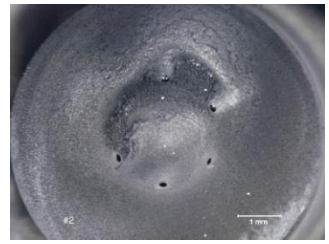
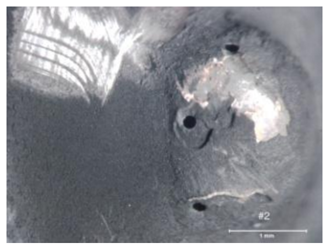
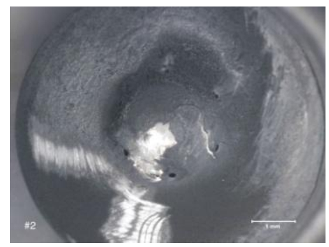
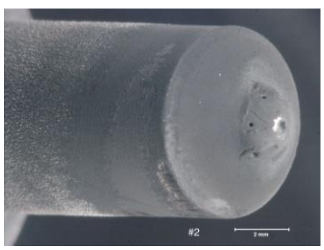
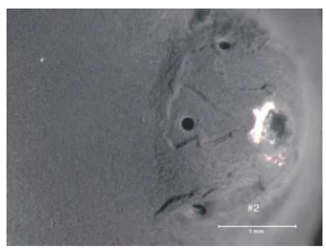
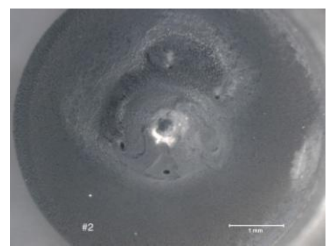
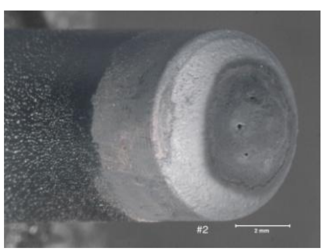
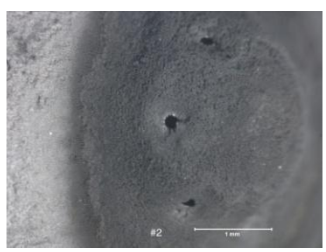
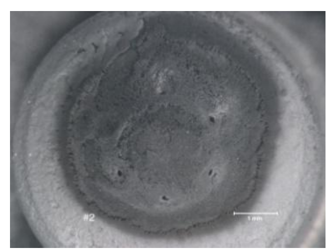
Cylinder 2 0-Hour Desert			
Cylinder 2 210-Hour Desert			
Cylinder 2 420-Hour Desert			
Cylinder 2 630-Hour Desert			
Cylinder 2 840-Hour Desert			

Figure 32. HRD Injector Cylinder 2 Deposition – Desert Temperature Test

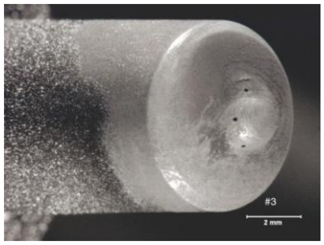
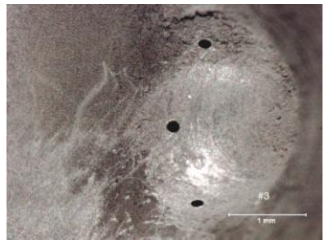
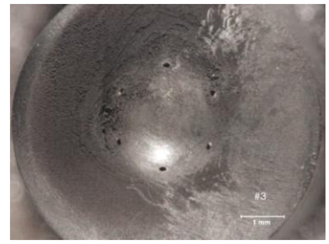
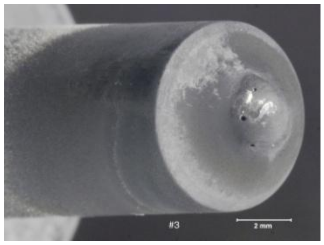
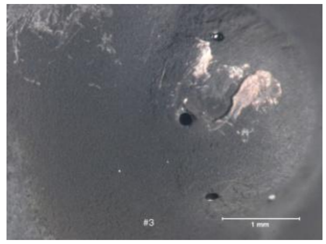
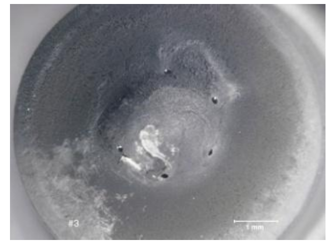
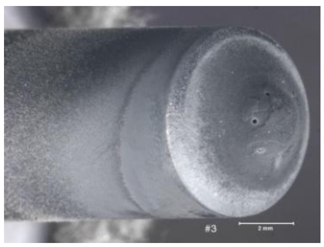
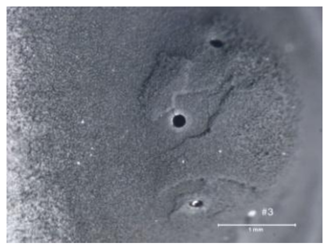
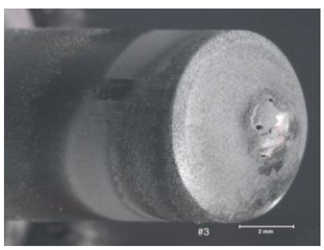
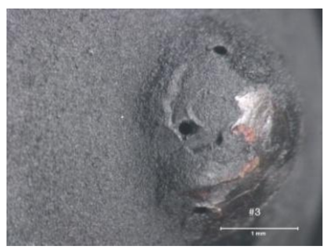
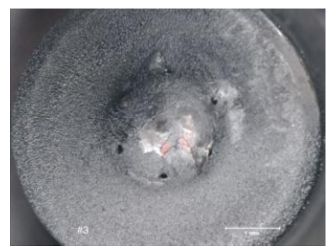
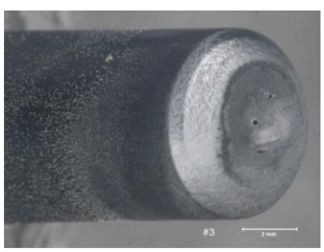
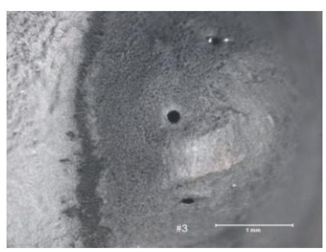
Cylinder 3 0-Hour Desert			
Cylinder 3 210-Hour Desert			
Cylinder 3 420-Hour Desert			
Cylinder 3 630-Hour Desert			
Cylinder 3 840-Hour Desert			

Figure 33. HRD Injector Cylinder 3 Deposition – Desert Temperature Test

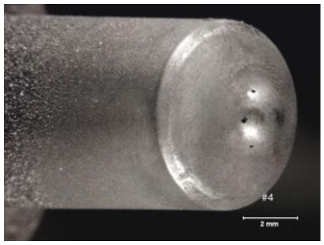
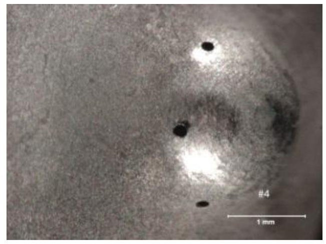
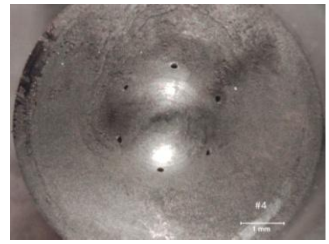
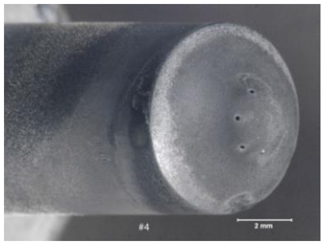
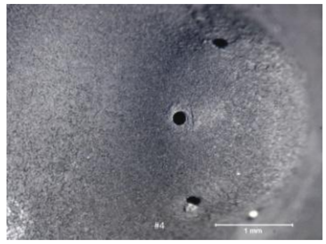
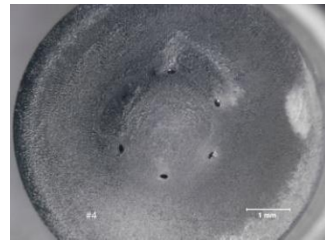
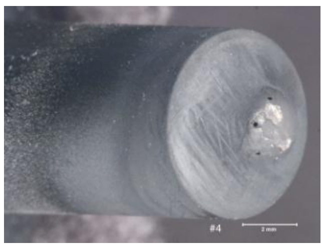
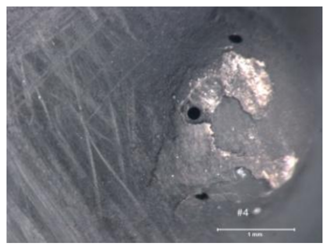
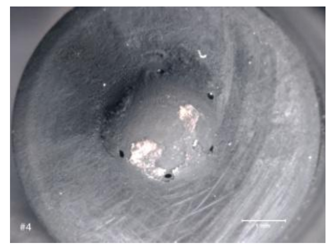
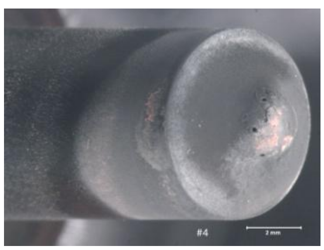
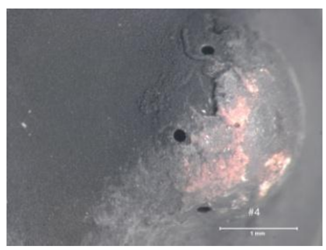
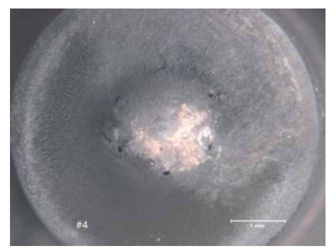
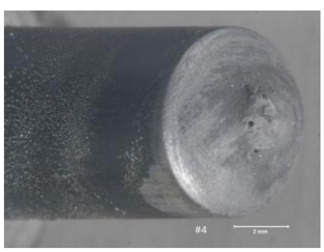
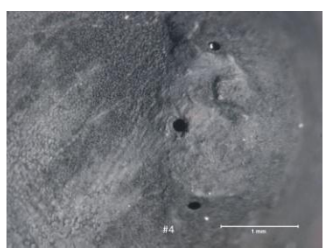
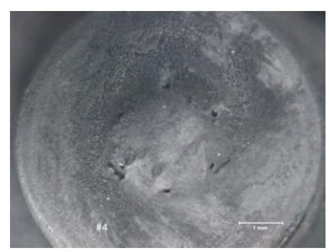
Cylinder 4 0-Hour Desert			
Cylinder 4 210-Hour Desert			
Cylinder 4 420-Hour Desert			
Cylinder 4 630-Hour Desert			
Cylinder 4 840-Hour Desert			

Figure 34. HRD Injector Cylinder 4 Deposition – Desert Temperature Test

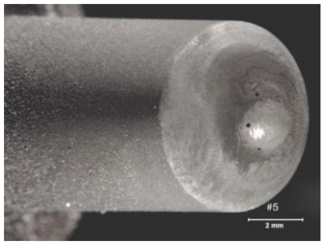
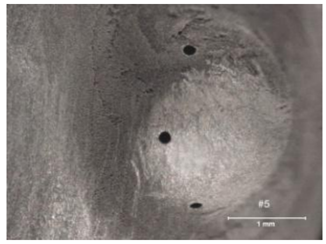
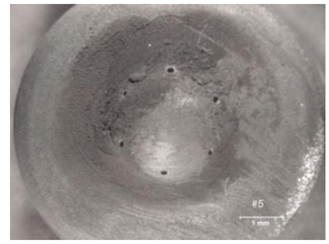
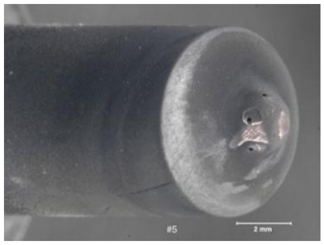
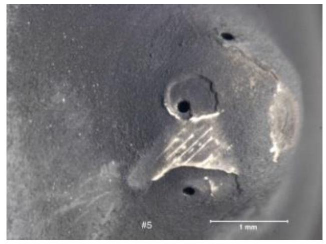
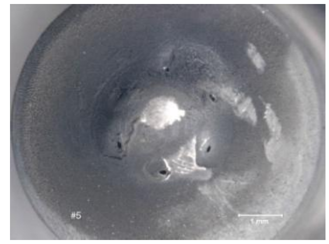
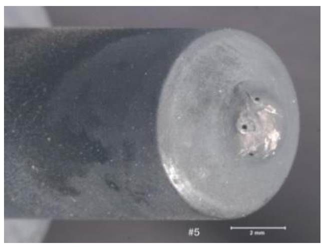
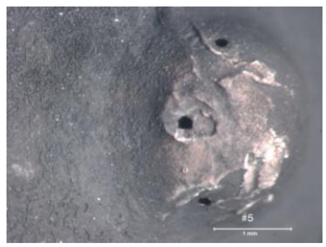
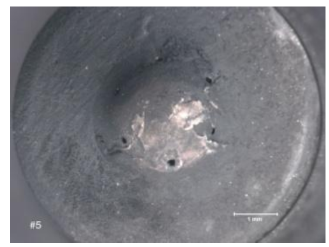
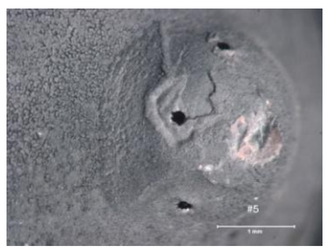
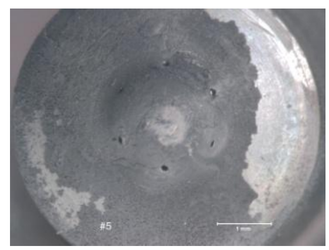
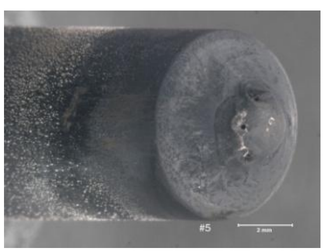
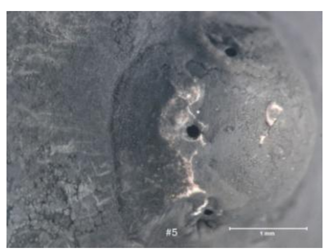
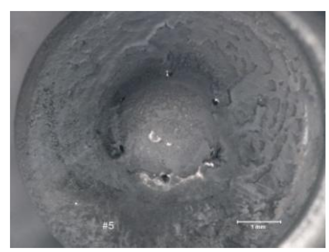
Cylinder 5 0-Hour Desert			
Cylinder 5 210-Hour Desert			
Cylinder 5 420-Hour Desert			
Cylinder 5 630-Hour Desert			
Cylinder 5 840-Hour Desert			

Figure 35. HRD Injector Cylinder 5 Deposition – Desert Temperature Test

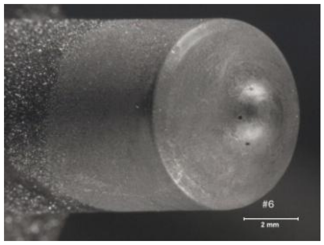
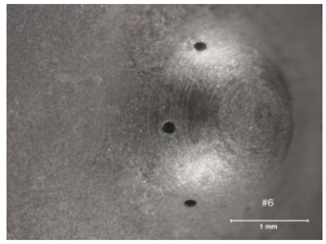
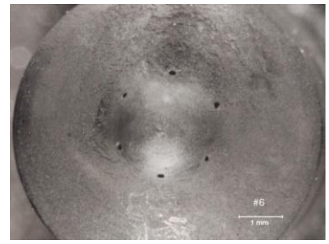
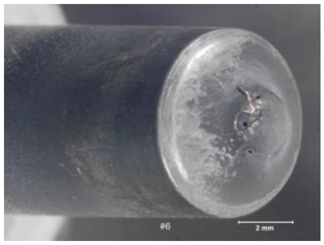
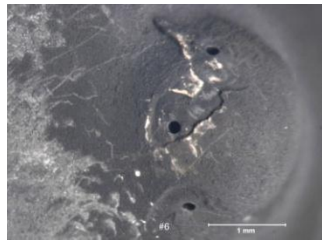
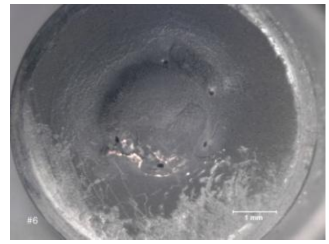
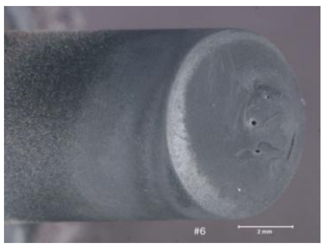
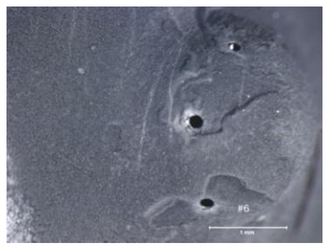
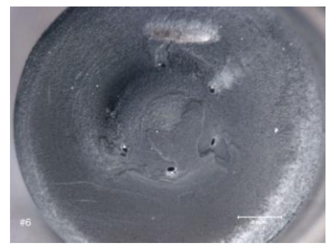
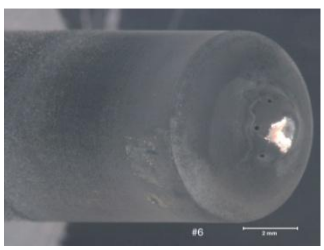
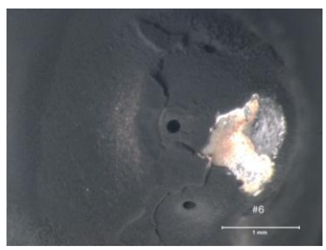
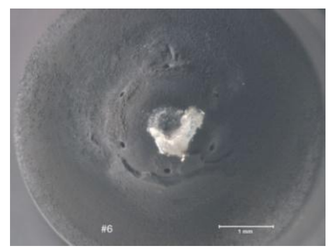
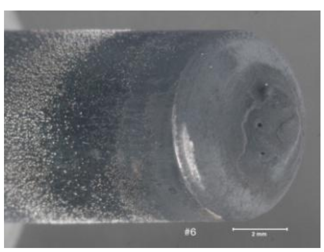
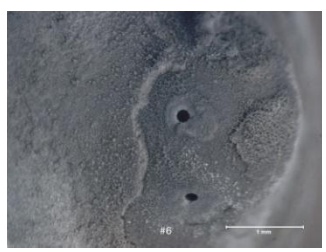
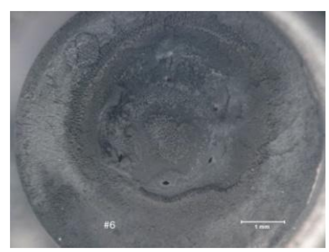
Cylinder 6 0-Hour Desert			
Cylinder 6 210-Hour Desert			
Cylinder 6 420-Hour Desert			
Cylinder 6 630-Hour Desert			
Cylinder 6 840-Hour Desert			

Figure 36. HRD Injector Cylinder 6 Deposition – Desert Temperature Test

The piston combustion bowl and piston crown were also documented for fuel related deposition prior to the start of testing and at the 840 hour end of testing with HRD at the desert operating conditions. The level of piston crown deposits generated by the HRD fuel usage at desert conditions are shown in Figure 39. There appear to be very little additional deposits on the piston crowns due to the use of HRD fuel for 840 hours. Piston crown and combustion bowl deposition does not appear to be an issue with the HRD fuel at the desert operating conditions.

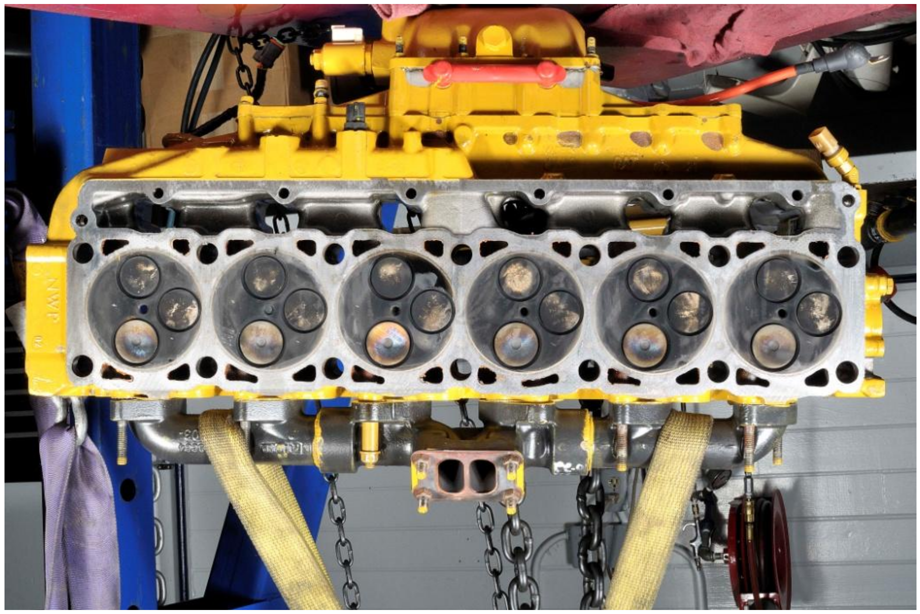
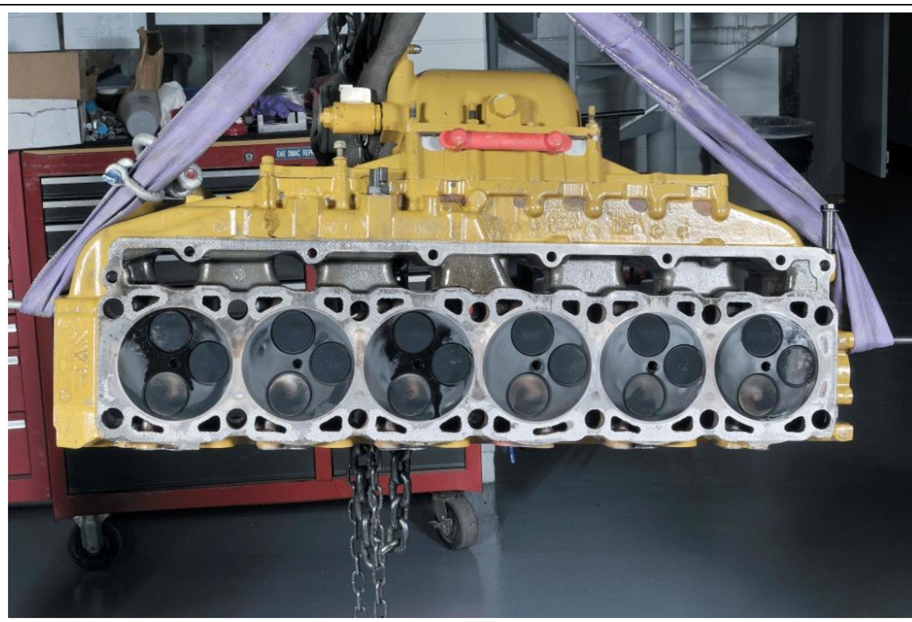
0-Hour Desert	
840-Hour Desert	

Figure 37. HRD Desert Condition Cylinder Head Fire Deck Deposition

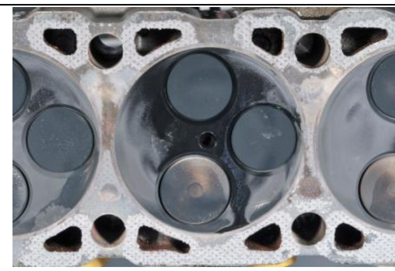
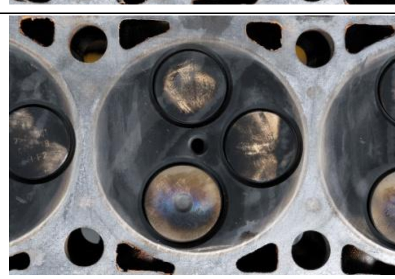
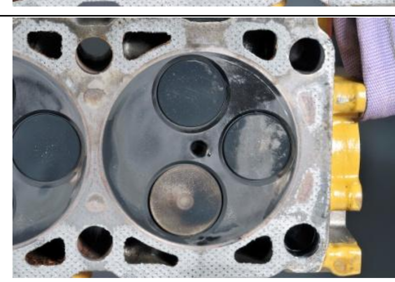
	0-Hour	840-Hour
Cylinder 1 Valves **Desert**		
Cylinder 2 Valves **Desert**		
Cylinder 3 Valves **Desert**		
Cylinder 4 Valves **Desert**		
Cylinder 5 Valves **Desert**		
Cylinder 6 Valves **Desert**		

Figure 38. HRD Desert Condition Valve and Fire Deck Deposits

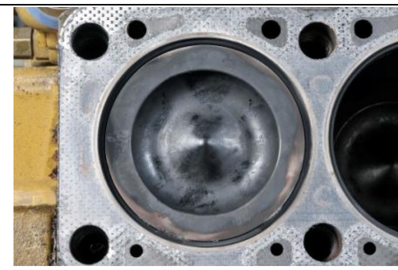
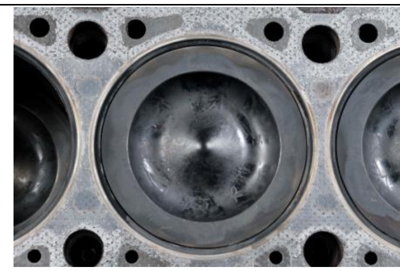
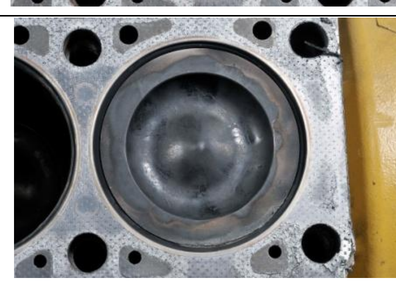
	0-Hour	840-Hour
Cylinder 1 Piston **Desert**		
Cylinder 2 Piston **Desert**		
Cylinder 3 Piston **Desert**		
Cylinder 4 Piston **Desert**		
Cylinder 5 Piston **Desert**		
Cylinder 6 Piston **Desert**		

Figure 39. HRD Desert Condition Piston Crown Deposits

4.0 DISCUSSION OF RESULTS

4.1 ENGINE PERFORMANCE COMPARISON

For both engine tests with the HRD fuel, ambient and desert operating conditions, the engines reached the 840 hour conclusion without any fuel related component issues. The CAT C7 engines produced less power with the HRD fuel, versus the RDF, primarily due to the difference in densities of the fuels. The C7 engines at desert operating conditions exhibited further power deviations from advertised power, likely due to reduced fuel viscosity at the elevated fuel temperature of the desert operating condition.

4.2 EXHAUST EMISSIONS COMPARISON

The engine exhaust emission response was quite similar at each of the two operating conditions. Subtle variations in the brake specific exhaust emissions suggest the desert operating condition reveals slightly lower exhaust emissions than the ambient operating conditions. This finding is likely due to the slightly lean combustion that results from lower fuel consumption due to hot fuel, and the better fuel and air mixing and vaporization during injection due to the hotter intake air. The HRD fuel revealed lower emissions than the RDF fuel at both operating conditions.

4.3 LUBRICANT CHEMICAL ANALYSES

The used oil analysis was quite similar for both the ambient and desert operating conditions for the C7 engine using the HRD fuel. The lubricant charge at each 210 hour interval did not reveal any major shearing or thickening as evidenced by viscosity change, nor were there significant wear metal accumulations or additive element depletion.

4.4 INJECTOR CONDITIONS AND PERFORMANCE

Photographic documentation of the fuel injectors from each cylinder suggest that fuel deposition in the CAT C7 engine would not be an issue with HRD fuel at either the ambient or the desert operating conditions.

Discussions were held with Caterpillar to obtain a measure of injector performance from the conclusion of HRD fuels testing with respect to the end-of-line testing when the injectors were manufactured. The end-of-line testing was used to validate injector performance and was also used to generate the trim codes for programming into the engine ECM when the fuel injectors were installed.

TFLRF shipped both sets of the test fuel injectors to Caterpillar for the flow checks. Caterpillar returned a set of data for five check conditions, where each set of six injectors were averaged together as shown in Table 10. The delivery values in the table are cc/1000 strokes, but the timing values units are uncertain. The overall averaged data suggests the desert temperature tests, the set 2 averages, had slightly larger deviations from the end-of-line (2009) injector test data than the ambient temperature test, set 1. Closer examination suggests only subtle, seemingly random, variations of either the pilot delivery or the main delivery quantities depending on the test point. Overall it appears the use of HRD fuel for 840 hours at either operating condition did not greatly impact averaged injector performance with respect to the averaged end-of-line values.

Table 10. Caterpillar C7 Injector Rating Data

		Point 1		Point 2				Point 3				Point 4		Point 5			
		D1_MAIN_DELIVERY	D1_MAIN_TIMING	D2_PILOT_DELIVERY	D2_PILOT_TIMING	D2_MAIN_DELIVERY	D2_MAIN_TIMING	D3_PILOT_DELIVERY	D3_PILOT_TIMING	D3_MAIN_DELIVERY	D3_MAIN_TIMING	D4_MAIN_DELIVERY	D4_MAIN_TIMING	D5_PILOT_DELIVERY	D5_PILOT_TIMING	D5_MAIN_DELIVERY	D5_MAIN_TIMING
set 1 average	**2009**	68.82	1.18	10.79	1.05	188.37	0.75	13.96	1.09	118.13	1.23	118.68	0.72	15.81	1.37	11.67	1.53
set 1 average	**2013**	71.18	1.19	11.63	1.05	193.73	0.76	14.62	1.08	125.32	1.20	119.33	0.77	15.09	1.44	10.72	1.57
set 2 average	**2009**	72.59	1.13	12.21	1.03	186.81	0.78	15.16	1.06	121.52	1.17	119.11	0.75	16.23	1.37	11.43	1.55
set 2 average	**2013**	69.81	1.21	10.93	1.07	190.40	0.80	14.55	1.10	123.53	1.21	117.74	0.79	15.54	1.43	11.28	1.55

4.5 ENGINE DEPOSIT EVALUATIONS

Prior to testing, at both operating conditions, and at the conclusion of testing, efforts were made to quantify the level of deposits on the piston crown and bowl surface and the cylinder head valves and combustion chamber surfaces. Any deposits evident at the start of testing were from the engine proof run at the factory. The deposit ratings for both operating conditions are shown in Table 11. The ratings are a merit rating, where 10 is clean, thus a low number represents more deposition. At each operating condition the rater indicated the piston and combustion chamber surfaces were only slightly dirtier at the conclusion of the 840 hour HRD fuels testing. Likewise the desert condition testing also resulted in slightly dirtier surfaces than the ambient condition.

Table 11. Hydroprocessed Renewable Diesel Piston and Combustion Chamber Deposit Ratings

Location	Ambient Condition				Desert Condition			
	Pistons		Combustion Chamber		Pistons		Combustion Chamber	
	0-hour	840-hour	0-hour	840-hour	0-hour	840-hour	0-hour	840-hour
Cyl inder 1	8.77	8.35	8.80	8.25	9.00	7.80	8.50	8.30
Cyl inder 2	8.35	8.31	8.80	8.46	8.73	7.95	8.50	8.35
Cyl inder 3	8.63	8.28	8.80	8.40	8.95	8.01	8.50	8.33
Cyl inder 4	8.75	8.23	8.80	8.45	8.90	7.78	8.50	8.32
Cyl inder 5	8.65	8.25	8.80	8.49	9.00	7.85	8.50	8.31
Cyl inder 6	8.67	8.25	8.80	8.41	8.94	7.68	8.50	8.39
Deposit Rating	Average		Average		Average		Average	
	8.64	8.28	8.80	8.41	8.92	7.85	8.50	8.33

5.0 CONCLUSIONS

The Caterpillar C7 engine operating on Hydroprocessed Renewable Diesel fuel appeared to operate satisfactorily for 840 hours, simulating 80,000 miles of proving ground operation, without significant power, emissions, lubricant, or fuel injector degradation. In addition internal engine component deposition was relatively light at the ambient operating conditions.

Despite the elevated air, coolant and fuel temperatures, a C7 engine also completed the 840 hour desert condition test cycle without significant degradation of any engine performance parameter while utilizing Hydroprocessed Renewable Diesel fuel. Component conditions and cleanliness for the desert conditions were very similar to the component conditions seen at the ambient operating conditions.

The use of Hydroprocessed Renewable Diesel fuel in the Caterpillar C7 engine provides adequate performance without any negative impact on engine durability, emissions, performance, fuel consumption, lubricant degradation, or cleanliness. The use of the Hydroprocessed Renewable Diesel fuel for the C7 engine was sufficient for both the ambient operating condition and the desert operating condition.

6.0 REFERENCES

1. Coordinating Research Council, Inc., “Development of Military Fuel/Lubricant/Engine Compatibility Test,” CRC Report No. 406, January 1967.

2. Schulman, Matthew E. and Frame, Edwin A., “Evaluation of Oil Management Systems (OMS) Using Caterpillar C7 Engine,” TFLRF Interim Report No. 388, ADB326177, April 2007.

3. Schulman, Matthew E. and Frame, Edwin A., “ENGINE DURABILITY EVALUATION USING SYNTHETIC FUEL, CATERPILLAR C7 ENGINE,” TFLRF Interim Report No. 391, ADA494498, October 2008.