

UNCLASSIFIED

**CATERPILLAR C7 FUEL SYSTEM BASELINE
DURABILITY USING F-24 FUEL**

**INTERIM REPORT
GFLRF No. 495**

by
**Douglas M. Yost
Kira L. Turner**

**GVSC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX**

for
Mr. Eric Sattler

**Force Projection Technology
U.S. Army CCDC Ground Vehicle Systems Center
FCDD-GVS-ES (M/S 110)
6501 E. 11 Mile Road
Warren, MI 48397-5000**

Contract No. W56HZV15C0030 (WD 022)

**UNCLASSIFIED: Distribution Statement A. Approved for public release
(OPSEC #4435)**

June 2020

UNCLASSIFIED

Disclaimers

Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes.

Contracted Author

As the author(s) is(are) not a Government employee(s), this document was only reviewed for export controls, and improper Army association or emblem usage considerations. All other legal considerations are the responsibility of the author and his/her/their employer(s).

DTIC Availability Notice

Qualified requestors may obtain copies of this report from the Defense Technical Information Center, Attn: DTIC-OCC, 8725 John J. Kingman Road, Suite 0944, Fort Belvoir, Virginia 22060-6218.

Disposition Instructions

Destroy this report when no longer needed. Do not return it to the originator.

UNCLASSIFIED

**CATERPILLAR C7 FUEL SYSTEM BASELINE
DURABILITY USING F-24 FUEL**

**INTERIM REPORT
GFLRF No. 495**

by
**Douglas M. Yost
Kira L. Turner**

**GVSC Fuels and Lubricants Research Facility Southwest
Research Institute® (SwRI®)
San Antonio, TX**

for
Mr. Eric Sattler

**Force Projection Technology
U.S. Army CCDC Ground Vehicle Systems Center
FCDD-GVS-ES (M/S 110)
6501 E. 11 Mile Road
Warren, MI 48397-5000**

Contract No. W56HZV15C0030

SwRI® Project No. 08.23870 (WD 022)

**UNCLASSIFIED: Distribution Statement A. Approved for public release
(OPSEC #4435)**

June 2020

Approved by:



**Scott A. Hutzler, Director
GVSC Fuels and Lubricants Research Facility (SwRI®)**

UNCLASSIFIED

UNCLASSIFIED

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> <i>OMB No. 0704-0188</i>		
<small>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.</small>					
1. REPORT DATE (DD-MM-YYYY) 06/25/2020		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) Jul 2018 to Jun 2020	
4. TITLE AND SUBTITLE Caterpillar C7 Fuel System Baseline Durability Using F-24 Fuel Blend			5a. CONTRACT NUMBER W56HZV15C0030		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Yost, Douglas M.; Turner, Kira L.			5d. PROJECT NUMBER SwRI 08.23870		
			5e. TASK NUMBER WD 022		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) GVSC Fuels and Lubricants Research Facility (SwRI®) Southwest Research Institute® P.O. Drawer 28510 San Antonio, TX 78228-0510			8. PERFORMING ORGANIZATION REPORT NUMBER GFLRF No. 495		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Force Projection Technologies, U.S. Army CCDC Ground Vehicle Systems Center FCDD-GVS-ES (M/S 110) 6501 E. 11 Mile Road Warren, MI 48397-5000			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT UNCLASSIFIED: Distribution Statement A. Approved for public release Pending OPSEC review (OPSEC #)					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The U.S. Army has a desire to reduce its dependence on traditional petroleum based fuels. Recent investigation has focused on the viability of alcohol to jet (ATJ) based fuels as a blending component for use with traditional petroleum based aviation fuels. This report covers the establishment of a baseline performance envelope using F-24 in the Caterpillar (CAT) C7 engine. Testing was conducted to allow for comparison to the same envelope developed for the F-24 and ATJ fuel blend that was performed in WD 012. The testing followed an accelerated 210-hour Tactical Wheeled Vehicle (TWV) cycle to determine engine performance, combustion, fuel system durability, raw gas emissions, and combustion related deposits. Overall performance degradation over the 210 hour test duration was approximately 2.5% for the F-24 post-test power curves. End of test power levels and emissions are included in this report, as well as post-test inspection of the fuel injector tips, combustion chambers, and fire deck. Performance deviations were seen due to lubricant degradation and not attributed to F-24 fuel.					
15. SUBJECT TERMS Caterpillar, C7, HEUI, alternative fuels, F-24					
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	58	19b. TELEPHONE NUMBER (include area code)

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

UNCLASSIFIED

EXECUTIVE SUMMARY

The U.S. Army has a desire to reduce its dependence on traditional petroleum based fuels. Recent investigation has focused on the viability of alcohol to jet (ATJ) based fuels as a blending component for use with traditional petroleum based aviation fuels. Previous testing included investigation into the use of an ATJ blended fuel in the Caterpillar (CAT) C7 engine. This report covers the establishment of baseline performance by using the standard F-24 fuel in the C7 engine. This engine is representative of high density vehicles fielded by the U.S. Army Tactical Wheeled Vehicle (TWV) fleet, including the Family of Medium Tactical Vehicles (FMTV), Stryker combat vehicle, and Mine Resistant Ambush Protected All-Terrain Vehicle (M-ATV).

For this evaluation, the fuel used was standard F-24. Testing was conducted following an accelerated 210-hour Tactical Wheeled Vehicle cycle to determine a baseline standard for engine performance, combustion, fuel system durability, raw gas emissions, and combustion related deposits. Overall performance degradation as a result of using the F-24 fuel over the 210 hour test duration was approximately 2.5% for the F-24 post-test power curves. Post-test inspection of the fuel injector tips, combustion chambers, and fire deck did not yield any abnormal deposit generation, and internal component inspection suggested that the F-24 fuel did not negatively affect the performance or durability of the C7 engine fuel system.

In general, all results support the use of the F-24 fuel in the C7 engine. The results of the F-24 test compare favorably with prior work and provide a baseline comparison for alternative fuel use in this engine.

FOREWORD/ACKNOWLEDGMENTS

The GVSC Fuel and Lubricants Research Facility (GFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period of July 2018 to June 2020 under Contract No. W56HZV15C0030. The Force Projection Technology U.S. Army CCDC Ground Vehicle Systems Center FCDD-GVS-ES (M/S 110), Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the GVSC contracting officer's technical representative and as the project technical monitor.

The authors would like to acknowledge the contribution of the GFLRF technical support staff and administrative and report-processing support.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
EXECUTIVE SUMMARY	v
FOREWORD/ACKNOWLEDGMENTS	vi
LIST OF FIGURES	viii
LIST OF TABLES	ix
ACRONYMS AND ABBREVIATIONS	x
1.0 Background & Introduction	1
2.0 Objective	1
3.0 Approach	1
4.0 Fuel Properties	2
5.0 Engine Description	7
6.0 Engine Installation & Test Cell	7
7.0 Results & Discussion	9
7.1 PRE-TEST POWER CURVES	10
7.2 PRE-TEST BSFC MAPS	11
7.3 210-HOUR TACTICAL WHEELED VEHICLE CYCLE TEST	13
7.3.1 Overall Operating Summary	13
7.3.2 Used Oil Analysis	14
7.3.3 Oil Additions, Subtractions, and Consumption	15
7.3.4 Post-Test Power Curves	16
7.3.5 Pre & Post-Test Injector and Engine Photos	20
7.3.6 Gaseous Exhaust Emissions	26
7.4 PRE & POST-TEST BSFC MAPS	30
7.5 POST-TEST FUEL INJECTOR FLOW MEASUREMENTS	34
7.6 POST-TEST FUEL INJECTOR TEARDOWN	36
8.0 Conclusions	41
9.0 RECOMMENDATIONS	41
10.0 References	42
APPENDIX A. C7 FUEL INJECTOR COMPONENT PHOTOGRAPHS	A-1

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
Figure 1. ULSD Pre-Test Output	10
Figure 2. F-24 Pre-Test Output	11
Figure 3. F-24, BSFC Map, Pre-Test, AMB & DOC	12
Figure 4. F-24, Pre to Post Power Output, AMB & DOC	16
Figure 5. F-24, Pre to Post Torque Output, AMB & DOC	17
Figure 6. F-24, Pre to Post BSFC, AMB & DOC	18
Figure 7. F-24, Post Power Output, Ambient, Test Oil and Fresh Oil.....	19
Figure 8. F-24, Post Power Output, DOC, Test Oil and Fresh Oil	19
Figure 9. Injector Tip – Cylinder 1	20
Figure 10. Injector Tip – Cylinder 2	21
Figure 11. Injector Tip – Cylinder 3	21
Figure 12. Injector Tip – Cylinder 4	22
Figure 13. Injector Tip – Cylinder 5	22
Figure 14. Injector Tip – Cylinder 6	23
Figure 15. Fire Deck – ALL	24
Figure 16. Piston Crown – ALL.....	25
Figure 17. F-24, Pre to Post CO, AMB & DOC	27
Figure 18. F-24, Pre to Post NO _x , AMB & DOC	27
Figure 19. F-24, Pre to Post UHC, AMB & DOC	28
Figure 20. F-24, Pre to Post CO ₂ , AMB & DOC	29
Figure 21. F-24, Pre to Post Smoke, AMB	29
Figure 22. F-24, Pre to Post Smoke, DOC.....	30
Figure 23. F-24, BSFC Map, AMB, Pre to Post-Test.....	32
Figure 24. F-24, BSFC Map, DOC, Pre to Post-Test.....	33
Figure 25. Caterpillar C7 HEUI Injector – Barrel Assembly Removal	36
Figure 26. C7 HEUI Injector Barrel Assembly Exploded View.....	37
Figure 27. C7 HEUI Injector Plunger (CYL#5 shown left, NEW shown right).....	38
Figure 28. C7 HEUI Injector Plunger (CYL#4 shown left, NEW shown right).....	39
Figure 29. C7 HEUI Injector Stop Plate (CYL#4 shown left, NEW shown right).....	39
Figure 30. C7 HEUI Injector Lift Spacer (CYL#4 shown left, NEW shown right)	40
Figure 31. C7 HEUI Injector Needle (CYL#4 shown left, NEW shown right).....	40

LIST OF TABLES

<u>Table</u>	<u>Page</u>
Table 1. Accelerated 210-hour Tactical Wheeled Vehicle Cycle	2
Table 2. F-24 Chemical & Physical Properties	3
Table 3. F-24 Fuel Bulk Modulus	4
Table 4. ULSD Chemical & Physical Properties	5
Table 5. ULSD Bulk Modulus	6
Table 6. Caterpillar C7, Evaluated Injector Serial Numbers	7
Table 7. Engine Operation Conditions per SOW	10
Table 8. F-24 210-hour Test Engine Operating Summary	13
Table 9. Used Oil Analysis	14
Table 10. C7 F-24 Evaluation Oil Consumption	15
Table 11. Caterpillar HEUI Fuel Injector Test Parameters	35

ACRONYMS AND ABBREVIATIONS

AMB – ambient operating conditions
ATJ – alcohol to jet
bhp – brake horsepower
BSFC – brake specific fuel consumption
CAT – Caterpillar
CI/LI – corrosion inhibitor, lubricity improver
CO – carbon monoxide
CO₂ – carbon dioxide
CRC – Coordinating Research Council
DOC – desert operating conditions
FMTV – Family of Medium Tactical Vehicles
FSN – filter smoke number
Ft-lb – pound feet torque
FTIR - Fourier-transform infrared spectroscopy
GFLRF – GVSC Fuels and Lubricants Research Facility
HEUI – Hydraulically-actuated, Electronically-controlled, Unit Injector
hp – horsepower
hr/hrs – hour/hours
JP8 – jet propellant 8
L - liter
MATV – MRAP All-Terrain Vehicle
MRAP – Mine Resistant Ambush Protected
NO_x – nitrogen oxides
O₂ – oxygen
rpm – revolution per minute
SOW – scope of work
SwRI – Southwest Research Institute
TWV – tactical wheeled vehicle
TWVC – tactical wheeled vehicle cycle
UHC – Unburned hydrocarbon
ULSD – ultra low sulfur diesel

1.0 BACKGROUND & INTRODUCTION

The U.S. Army has a desire to reduce its dependence on traditional petroleum based fuels. Extensive research has been conducted to investigate various alternative jet fuels to determine their impact on engine durability and performance, and to qualify fuels for use in military ground equipment. Recent investigation has focused on the viability of using alcohol to jet (ATJ) based fuels as a blending component with traditional aviation fuel. This report covers the establishment of baseline performance by using the standard F-24 fuel in the Caterpillar (CAT) C7 engine. This engine is representative of high density vehicles fielded by the U.S. Army Tactical Wheeled Vehicle (TWV) fleet. All testing was conducted at the GVSC Fuels and Lubricants Research Facility (GFLRF), located at Southwest Research Institute (SwRI), San Antonio TX.

2.0 OBJECTIVE

The objective of this testing was to establish a baseline performance envelope for the C7 using standard F-24 fuel. This baseline provides a comparison to the same testing previously performed using F-24 and ATJ fuel blends. Testing was conducted to determine impact on engine performance, combustion, fuel system durability, combustion related deposits, and raw exhaust gas emissions.

3.0 APPROACH

An engine dynamometer test stand was used to evaluate the F-24 in the C7 engine. Durability testing was preceded by full load engine power curves on both Ultra Low Sulfur Diesel (ULSD) fuel and F-24 to map engine maximum output power and emissions as a function of engine speed (at max load). In addition, a fuel mapping exercise was conducted at the start of testing to determine the Brake Specific Fuel Consumption (BSFC) across the full range of engine speeds and loads. For the durability test, an accelerated version of the 210-hour Tactical Wheeled Vehicle Cycle (TWVC) was completed. This test cycle, outlined in CRC Report No. 406 [1], was originally developed to determine fuel and lubricant compatibility with military engines. Modifications were

made to the standard 210-hour cycle to increase the daily operation time from 14hrs to 21hrs. This was accomplished by adjusting the rated speed step lengths, and reducing the daily engine off soak time. Table 1 shows the break-down of the adjusted step length durations.

Table 1. Accelerated 210-hour Tactical Wheeled Vehicle Cycle

Cycle	Duration	Description
1	2hr 10min	Rated Speed & Load
	1hr	Idle
2	2hr 10min	Rated Speed & Load
	1hr	Idle
3	2hr 10min	Rated Speed & Load
	1hr	Idle
4	2hr 10min	Rated Speed & Load
	1hr	Idle
5	2hr 10min	Rated Speed & Load
	1hr	Idle
6	2hr 10min	Rated Speed & Load
	1hr	Idle
7	2hr	Rated Speed & Load
Soak	3hr	Engine Off

After the 210 hour test was completed, post-test power curves were completed again using F-24 fuel at both operating conditions. Post-test BSFC fuel maps were also conducted to document the change in engine efficiency over the test cycle.

4.0 FUEL PROPERTIES

Commercially available ultra-low sulfur diesel (ULSD) and standard F-24 were utilized for pre-test power curve checks (USLD & F-24) and post-test power curve checks (F-24 only) to establish performance against specified engine ratings, and document change in performance over the test duration. The F-24 was treated with the maximum level of the lubricity improver DCI-4A (22.5 ppm). Table 2 presents the chemical and physical properties of the tested F-24. Table 3 is the test fuel bulk modulus by speed-of-sound method for the F-24 fuel. Table 4 presents the chemical and physical properties of the USLD in accordance with ASTM D975. The Cetane Number is 54.1, the Cetane Index is 55.6, and the Derived Cetane Number is 54.0 also, indicating a good ignition quality ULSD fuel. Table 5 is the bulk modulus table for the ULSD fuel.

Table 2. F-24 Chemical & Physical Properties

Test	Method	Units	Sample Code CL19-3497 F-24
Acid Number	D3242	mg KOH / g	0.006
Aromatic Hydrocarbon Types	D6379		
Total Aromatics		vol%	12.91
Monoaromatics		vol%	11.7
Diaromatics		vol%	1.21
Sulfur Mercaptan	D3227	mass%	0.001
Total Sulfur Content	D5453	mg/kg	257.07
Distillation	D86		
IBP		°C	151.6
5 % Rcvd		°C	168.8
10 % Rcvd		°C	173.6
15 % Rcvd		°C	177.8
20 % Rcvd		°C	181.7
30 % Rcvd		°C	188.9
40 % Rcvd		°C	195.5
50 % Rcvd		°C	202.4
60 % Rcvd		°C	209.7
70 % Rcvd		°C	217.8
80 % Rcvd		°C	227.3
90 % Rcvd		°C	238.7
95 % Rcvd		°C	246.3
FBP		°C	254.3
Residue		%	1.2
Loss		%	0.3
T50-T10		°C	28.8
T90-T10		°C	65.1
Flash Point	D93	°C	44.5
Density/API by Meter (15 °C/60 °F)	D4052	kg/m ³	791.6
Freeze Point (Manual)	D2386	°C	-49
Kinematic Viscosity (100 °C)	D445	mm ² /sec	0.68
Kinematic Viscosity (40 °C)	D445	mm ² /sec	1.28
Kinematic Viscosity (-20 °C)	D445	mm ² /sec	4.16
Naphthalene Content	D1840	vol%	0.77
Copper Strip Corrosion	D130		
Test Temperature		°C	100
Test Duration		hrs	2
Rating		--	1A
Jet Fuel Thermal Oxidation Test	D3241		
Test Temperature		°C	260
ASTM Code		--	1
Maximum Pressure Drop		mm/Hg	0
Ellipsometer		nm	6.06
Total Volume		cm ³	0.000001
Gum Content	D381	mg / 100 mL	2
MSEP	D3948	rating	62
Electrical Conductivity	D2624		
Electrical Conductivity		pS/m	75
Temperature		°C	19.5
Sulfur Content - XRF	D2622	mg/kg	274.74
Lubricity (BOCLE)	D5001	mm	0.553

Table 2. F-24 Chemical & Physical Properties

Test	Method	Units	Sample Code CL19-3497 F-24
Lubricity (HFRR)	D6079		
Major Axis of Scar		mm	0.72
Minor Axis of Scar		mm	0.68
Wear Scar Diameter		mm	0.702
Test Temperature		°C	60
Scar Diameter		microns	702
Cetane Number	D613	--	47.7
Derived Cetane Number (IQT)	D6890		
Ignition Delay		ms	4.16
Derived Cetane Number		--	49.3

Table 3. F-24 Fuel Bulk Modulus

Temperature [°C]	Pressure [psig]	Bulk Modulus [psi]
30.2	0	181,283
64.50	0	141,524
65.96	1035	151,967
65.96	1510	157,643
65.97	2015	163,797
65.97	2516	168,554
65.98	3004	176,113
65.98	3438	181,304
65.98	4031	188,141
65.98	4603	195,232
65.98	5039	198,055
79.00	0	127,454
80.30	1015	136,672
80.30	1497	142,479
80.30	2066	149,742
80.31	2556	155,597
80.31	3002	162,573
80.32	3522	167,229
80.32	4033	173,233
80.33	4508	178,690
80.33	5024	184,701

Table 4. ULSD Chemical & Physical Properties

Test	Method	Units	Sample Code CL19-3551 ULSD
Flash Point	D93	°C	62.5
Water and Sediment	D2709	vol %	<0.005
Distillation	D86		
IBP		°C	174.8
5 % Rcvd		°C	204.7
10 % Rcvd		°C	219.9
15 % Rcvd		°C	229.1
20 % Rcvd		°C	239
30 % Rcvd		°C	255.1
40 % Rcvd		°C	267.8
50 % Rcvd		°C	279.7
60 % Rcvd		°C	291.1
70 % Rcvd		°C	303.5
80 % Rcvd		°C	317.2
90 % Rcvd		°C	335.8
95 % Rcvd		°C	350.4
FBP		°C	357.9
Residue		%	1.3
Loss		%	0.7
T50-T10		°C	59.8
T90-T10		°C	115.9
Kinematic Viscosity (40 °C)	D445	mm ² /sec	3
Ash Content	D482	mass%	<0.001
Total Sulfur Content	D5453	mg/kg	7.69
Copper Strip Corrosion	D130		
Test Temperature		°C	50
Test Duration		hrs	3
Rating		--	1A
Cetane Number	D613	--	54.1
Calculated Cetane Index	D976	--	55.6
Aromatics	D5186		
Total Aromatics		mass%	22.2
MonoAromatics		mass%	18.3
Polynuclear Aromatics		mass%	3.9
Cloud Point	D2500	°C	-5
Cold Filter Plugging Point (CFPP)	D6371	°C	-4
Carbon Residue - 10% Ramsbottom	D524	mass%	0.06
Lubricity (HFRR)	D6079		
Major Axis of Scar		mm	0.49
Minor Axis of Scar		mm	0.4
Wear Scar Diameter		mm	0.449
Test Temperature		°C	60
Scar Diameter		microns	449
Electrical Conductivity	D2624		
Electrical Conductivity		pS/m	45
Temperature		°C	18.7
Lubricity (BOCLE)	D5001	mm	0.486
Derived Cetane Number (IQT)	D6890		
Ignition Delay		ms	3.76
Derived Cetane Number		--	54
Avg. Air Temp		°C	552.9

Table 4. ULSD Chemical & Physical Properties

Test	Method	Units	Sample Code CL19-3551 ULSD
Density/API by Meter (15 °C/60 °F)	D4052	kg/m ³	832.8
Density Curve	D4052_curve		
5°C		g/cm ³	0.8398
15°C		g/cm ³	0.8329
25°C		g/cm ³	0.8259
35°C		g/cm ³	0.8190
45°C		g/cm ³	0.8120
55°C		g/cm ³	0.8050
65°C		g/cm ³	0.7980
75°C		g/cm ³	0.7910
85°C		g/cm ³	0.7840
Net Heat of Combustion	D4809 NET	MJ/kg	43.2950
Carbon Hydrogen	D5291		
Carbon		mass%	86.48
Hydrogen		mass%	13.68

Table 5. ULSD Bulk Modulus

Temperature [°C]	Pressure [psig]	Bulk Modulus [psi]
29.9	0	213,084
64.90	0	171,177
64.99	1022	181,827
64.99	1493	189,803
64.99	2062	199,085
64.99	2486	202,316
64.99	3002	210,859
64.99	3487	214,637
64.99	4042	221,574
64.99	4508	227,521
64.99	5046	233,736
79.90	0	154,052
80.35	998	169,297
80.35	1516	172,982
80.35	2028	179,442
80.34	2559	185,809
80.34	3004	191,280
80.34	3550	198,032
80.34	4014	201,532
80.34	4511	209,704
80.34	5018	215,503

5.0 ENGINE DESCRIPTION

The Caterpillar C7 engine is a 7.2L turbo-charged, after-cooled, direct-injected, inline 6 cylinder engine. The engine evaluated was rated at 330 bhp at a speed of 2400 rpm (using diesel fuel). The C7 engine utilizes a Hydraulically-actuated, Electronically-controlled, Unit Injection (HEUI) fuel injection system. This engine is fielded in the Family of Medium Tactical Vehicles (FMTV), MRAP-All Terrain Vehicles (MATV), and the Stryker family of vehicles. The engine evaluated was serial number FMM16705. A single set of fuel injectors was used during testing, and are identified in Table 6 below by serial number. A replacement injector was used for test activities, listed as 6b below, and is discussed later in this report.

Table 6. Caterpillar C7, Evaluated Injector Serial Numbers

CYL	INJECTOR SN
1	3B1407548406
2	3B1407541998
3	3B114074407B1
4	3B1407538933
5	3B14075377DA
6	3B14075368E2
6b	3B13688456CA

6.0 ENGINE INSTALLATION & TEST CELL

The engine was fully instrumented to measure all pertinent temperatures, pressures and other relevant analog data. The engine was installed and tested in GFLRF Test Cell 08. The following list outlines the general setup of the engine and test cell installation:

- SwRI developed PRISM[®] system was used for data acquisition and control.
- The following controllers were designed into the installation to meet required operating conditions called out in the SOW:
 - Engine speed
 - Throttle output

UNCLASSIFIED

- Coolant out temperature
- Fuel inlet temperature
- Air inlet temperature
- Manifold air temperature

- The engine was coupled with a driveshaft and torsional vibration coupling to a Midwest model 1519 (eddy current) 500 hp wet gap dynamometer.
- Engine speed was controlled through dynamometer actuation, and engine load was controlled through engine throttle operation.
- Coolant temperature was controlled using laboratory process water and a shell and tube heat exchanger. A three way process valve was used to allow coolant to bypass the heat exchanger as required to manipulate engine temperature to desired levels.
- Inlet air was drawn in at ambient conditions through two radiator type cores plumbed prior to the engines turbocharger inlet. The radiator cores were fitted with three way process control valves and used segregated sources of hot engine coolant and chilled laboratory water to control the temperature of the incoming air charge.
- Final intake manifold temperature was controlled through the use of an air to water intercooler and a process control valve which allowed manipulation of water supply to the intercooler core.
- Oil sump temperature was not controlled, and was regulated by the internal engine oil to jacket water oil cooler. Resulting oil temperature was a function of overall coolant temperature and general engine operating conditions (i.e., speed and load).
- Fuel was supplied to the engine using a recirculation tank (or “day tank”) at ambient temperature and pressure conditions. The recirculation tank was connected to the engine fuel supply and return, and maintained at a constant volume through a float mechanism which metered the bulk fuel supply to replenish the tank volume. This recirculation tank make-up fuel flow rate was measured by a Coriolis type flowmeter to determine the engine fuel consumption.
- Fuel temperature was controlled by a series of liquid-to-liquid heat exchangers that supplied required heat transfer to the incoming fuel from a temperature controlled secondary process fluid. This secondary process fluid (ethylene-glycol and water mix) was

UNCLASSIFIED

heated and cooled as needed by an inline circulation heater, and liquid to liquid trim heat exchanger connected to the laboratory chilled water supply. In addition, a liquid to liquid heat exchanger coupled to the high temperature engine coolant was also used in the fuel supply to provide additional heat for the higher temperature Desert Operating Conditions (DOC).

- The engine exhaust was routed to the building's roof top exhaust handling system and discharged outside to the atmosphere. An inline butterfly valve was used to regulate engine exhaust backpressure as required during testing.
- Emissions were directly sampled from an exhaust probe installed between the engine and exhaust system backpressure valve. Raw emissions concentrations were measured using a Horiba MEXA 7200D equipped with its own heated sample line and sample conditioning unit.
- Exhaust smoke was measured by an AVL Smoke Meter Model 4155E.
- Crankcase blow-by gasses were ducted into a containment drum to capture any entrained oil, and then routed to the atmosphere through a vortex shedding flow meter to measure flow rate.
- The engine was lubricated with MIL-PRF-2104L SAE 15W40 engine oil.
- Used oil samples were collected from the engine daily to monitor engine and oil condition.

7.0 RESULTS & DISCUSSION

The following sections discuss results from the C7 test conducted using the F-24 fuel. A summary of all specified testing is listed below:

- Pre-test power curve check with ULSD at ambient conditions
- F-24 pre and post-test power curves at both ambient and DOC (+emissions)
- Pre and post-test fuel maps with F-24 at both ambient and DOC
- 210 hour test duration operated on F-24 at DOC

Table 7 identifies the temperature control specifications for testing based on type of operation specified.

Table 7. Engine Operation Conditions per SOW

Temperature Parameter	Ambient Conditions	Desert-Like Operating Conditions (DOC)
Inlet Air	77 ° +/- 4 °F	120 ° +/- 4 °F
Fuel Inlet	86 ° +/- 4 °F	175 ° +/- 4 °F
Engine Coolant	205 ° +/- 4 °F	218 ° +/- 4 °F
Intake Manifold	127 ° +/- 2 °F	Range Proportional from 118 ° +/- 3 °F (Idle) to 155 ° +/- 3 °F (Full Load)

7.1 PRE-TEST POWER CURVES

Figure 1 shows the pre-test full load torque and power output for the CAT C7 engine evaluated using commercially available ULSD at ambient operating conditions. As demonstrated, the engine produced a peak power of 330 bhp @ 2400 rpm, and a peak torque of 859 ft-lb @ 1400 rpm.

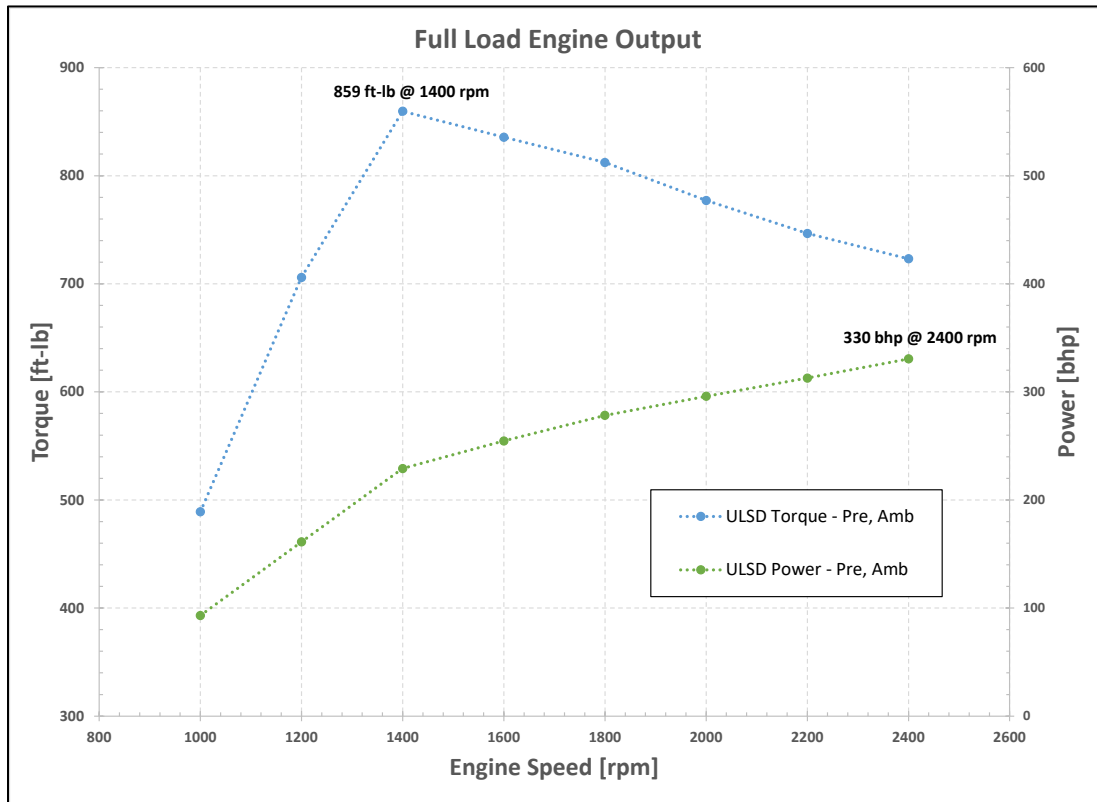


Figure 1. ULSD Pre-Test Output

Figure 2 shows the pre-test full load torque and power output for the CAT C7 engine evaluated using F-24 at both the ambient and the DOC conditions. The engine produced a peak power of 316 bhp @ 2400 rpm, and a peak torque of 815 ft-lb @ 1400 rpm at ambient. Under DOC conditions, the peak power was 300 bhp @ 2400 rpm, and the peak torque was 773 ft-lb @ 1500 rpm. Post-test F-24 power output and its comparison to pre-test output is presented later in the report.

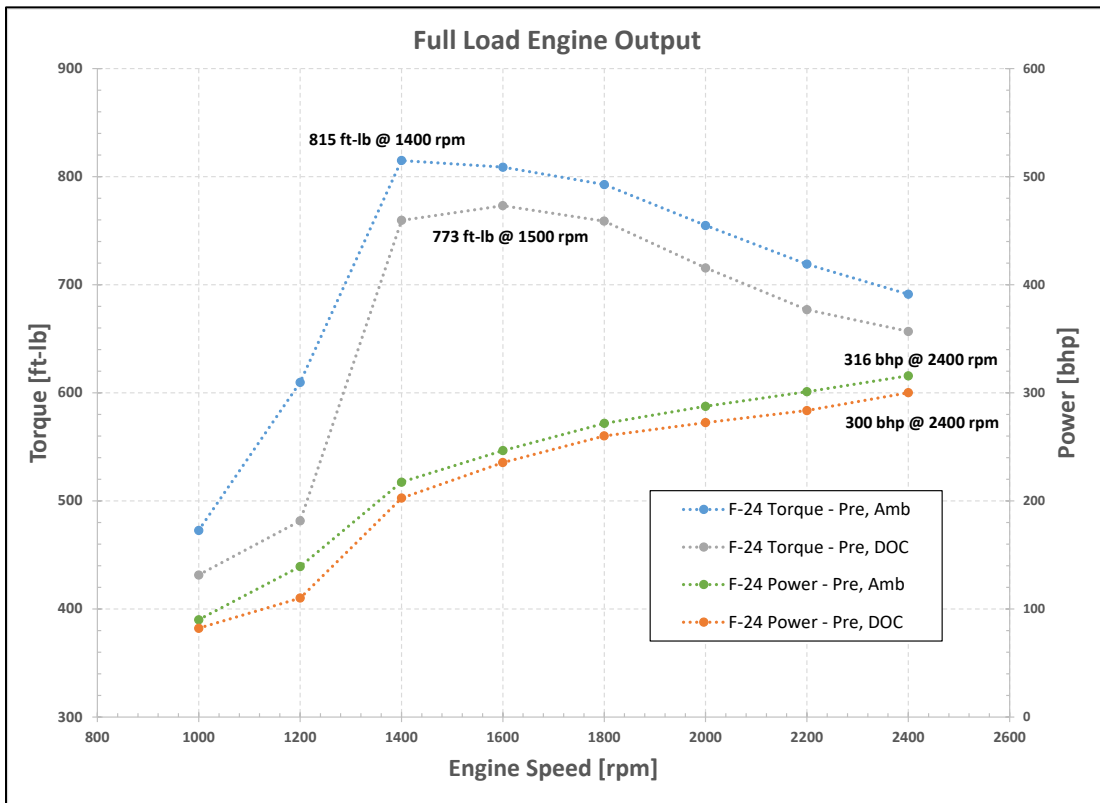


Figure 2. F-24 Pre-Test Output

7.2 PRE-TEST BSFC MAPS

Figure 3 (shown next page) shows the F-24 pre-test BSFC fuel maps for both ambient and DOC. Overall the C7 engine exhibited slightly less efficient operation at DOC compared to ambient operation. The region of minimum BSFC is slightly smaller for the DOC map. Post-test fuel maps and their comparison to pre-test maps are presented later in the report.

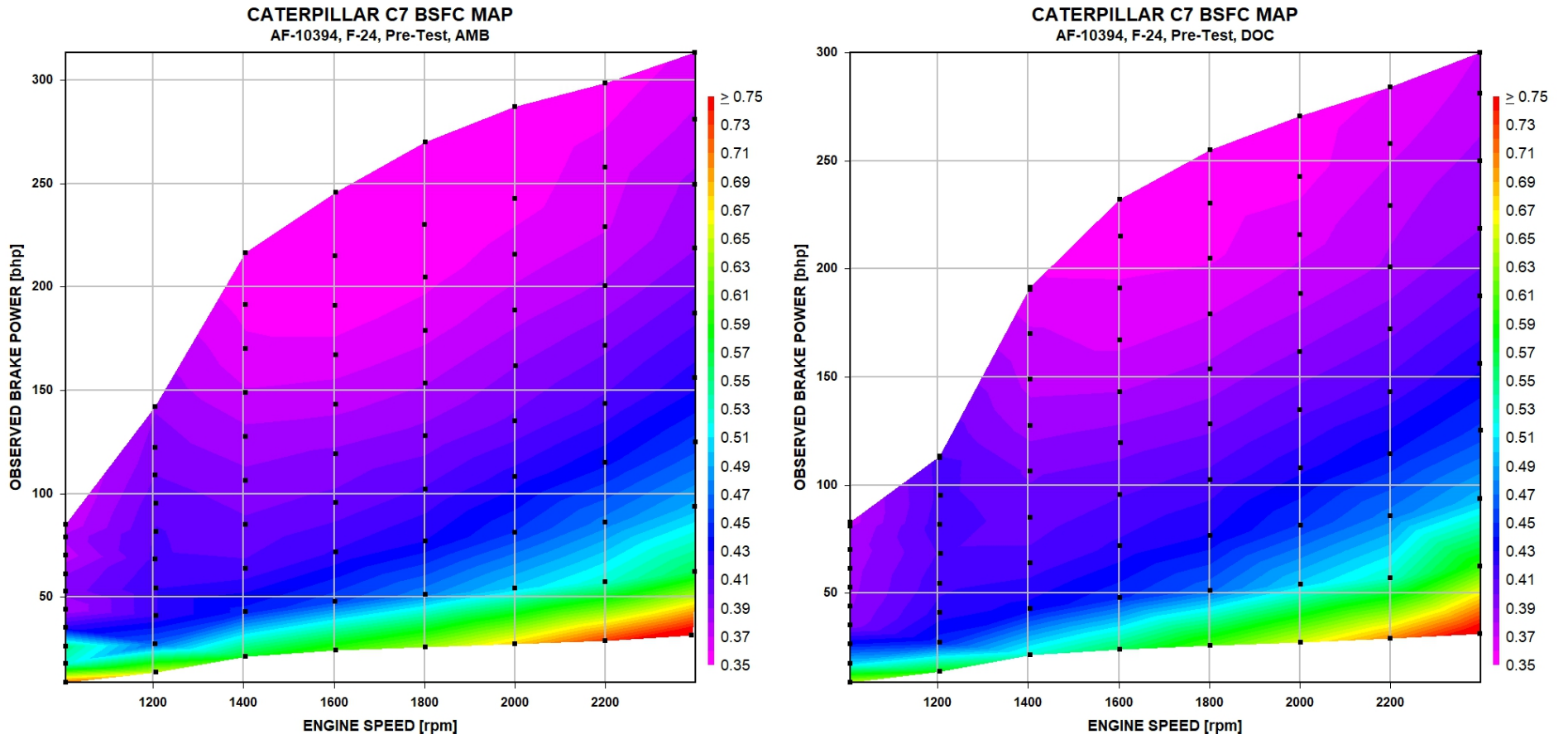


Figure 3. F-24, BSFC Map, Pre-Test, AMB & DOC

7.3 210-HOUR TACTICAL WHEELED VEHICLE CYCLE TEST

The following sections present engine operating summary data over the 210-hour durability test cycle. This includes general operating summary, observed power loss and technical investigation, used oil analysis, oil consumption, and fuel injector and engine photographs.

7.3.1 Overall Operating Summary

Table 8 presents the engine operating condition summary over the 210-hour test duration. Average power level across the test was 287 bhp, with an average brake specific fuel consumption of 0.373 lb/bhp-hr. Green boxes indicate temperatures within tolerance with the red boxes outside the tolerance. The temperatures usually exceeded tolerances on the speed ramps.

Table 8. F-24 210-hour Test Engine Operating Summary

Parameter:	Units:	Rated Conditions (2400 RPM)				Idle Conditions (750 RPM)			
		Average	Std. Dev.	Max	Min	Average	Std. Dev.	Max	Min
Engine Speed	RPM	2400.02	1.13	2404.00	2395.00	749.96	1.75	768.00	724.00
Torque*	ft*lb	628.81	11.56	667.00	580.00	32.29	0.71	34.00	29.00
Fuel Flow	lb/hr	107.31	1.58	113.14	100.40	3.59	0.18	4.76	3.28
Power*	bhp	287.35	5.28	304.90	265.00	4.61	0.10	4.90	4.10
BSFC*	lb/bhp*hr	0.373	0.003	0.389	0.361	0.778	0.042	1.026	0.714
Blow-by	acfm	5.96	0.46	7.10	3.30	1.37	0.20	1.80	0.60
Temperatures:									
Coolant In	°F	204.97	0.50	206.30	201.90	176.78	5.78	195.50	165.00
Coolant Out	°F	218.00	0.21	218.90	217.10	180.69	6.08	200.30	169.20
Oil Galley	°F	240.15	0.33	241.10	236.80	185.01	6.88	206.40	173.50
Oil Sump	°F	253.43	0.48	254.80	248.50	188.14	7.73	212.20	176.60
Fuel In	°F	174.98	0.37	177.10	172.90	163.09	3.12	172.60	155.50
Fuel Out	°F	202.92	0.81	204.50	199.40	163.35	7.77	186.60	150.20
Ambient Air Dry Bulb (Test Cell)	°F	81.35	5.01	92.10	71.20	73.72	5.57	86.90	60.30
Intake Air (before compressor)	°F	116.29	0.62	118.30	115.20	121.98	3.34	125.70	111.10
Intake Air (after compressor)	°F	415.98	1.88	421.50	411.10	127.56	4.26	137.10	115.30
Intake Air (post intercooler)	°F	154.95	3.94	249.80	119.70	117.87	4.15	156.80	109.90
Cylinder 1 Exhaust	°F	1021.24	12.64	1080.90	986.50	263.31	12.85	318.90	245.80
Cylinder 2 Exhaust	°F	1141.48	13.13	1199.00	1085.80	293.77	9.84	358.40	281.30
Cylinder 3 Exhaust	°F	1117.07	12.22	1172.90	1060.20	287.40	8.73	341.60	269.30
Cylinder 4 Exhaust	°F	1110.72	9.04	1169.90	1068.60	285.81	9.63	338.60	269.70
Cylinder 5 Exhaust	°F	1114.01	11.80	1177.60	1079.70	287.61	7.96	319.10	269.30
Cylinder 6 Exhaust	°F	1054.30	13.47	1108.70	994.20	269.75	6.95	301.40	256.30
Exhaust Temperature After Turbo	°F	892.69	12.01	957.60	842.30	296.29	16.26	371.50	280.10
Pressures:									
Oil Galley	psiG	46.19	0.46	49.00	45.60	28.08	1.99	33.00	21.90
Fuel Pressure	psiG	70.32	0.43	71.60	67.70	56.46	1.06	58.10	47.30
Ambient Pressure	psiA	14.34	0.07	14.48	14.18	14.34	0.07	14.47	14.17
Intake Pressure Before Turbo	psiA	13.59	0.08	13.76	13.39	14.31	0.08	14.45	14.11
Intake Restriction	psi	0.75	0.01	0.80	0.64	0.04	0.01	0.06	0.01
Intake Pressure After Turbo	psiG	27.64	0.09	27.92	27.25	0.19	0.03	0.31	0.13
Intake Pressure After Intercooler	psiG	27.02	0.09	27.31	26.62	0.08	0.02	0.18	0.03
Exhaust Manifold Pressure (pre-turbo) Front	psiG	28.39	0.26	30.10	25.00	0.91	0.03	1.00	0.80
Exhaust Manifold Pressure (pre-turbo) Front	psiG	28.69	0.32	30.40	25.20	1.05	0.07	1.20	0.90
Exhaust Back Pressure	psiG	0.25	0.01	0.28	0.09	-0.05	0.01	-0.03	-0.08
Coolant System	psiG	13.30	0.73	15.00	9.20	6.77	1.27	10.20	4.30

* Non-corrected Values

7.3.2 Used Oil Analysis

Used oil samples were collected for analysis over the course of the 210-hour test duration to monitor engine and oil condition during the test. A table summarizing this data is shown in Table 9. No oil changes were conducted during testing. Based on the decreased Total Base Number and the increased Total Acid Number the lubricant charge had reached the end of its useful life by the end of the test. Oil sample and addition amounts are detailed in the following section.

Table 9. Used Oil Analysis

Property	ASTM Test	Test Hours										
		0	21	42	63	84	105	126	147	168	189	210
Viscosity @ 100°C (cSt)	D445 100c	14.9	12.9	12.8	12.7	12.7	12.8	12.8	12.8	12.8	12.9	12.8
Total Base Number (mg KOH/g)	D4739	8.75	7.83	6.67	5.81	5	5.01	4.65	3.88	4.25	4.13	3.54
Total Acid Number (mh KOH/g)	D664	2.5	2.6	2.8	2.8	2.8	1.6	2.5	2.4	2.3	2.3	4.1
Soot		0.0	0.0	0.2	0.3	0.2	0.5	0.2	0.4	0.3	0.4	0.3
Wear Metals (ppm)	D5185											
Al		<1	<1	<1	1	1	1	2	2	2	2	2
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		6	5	6	5	5	4	3	4	6	4	3
Ca		2376	2411	2402	2465	2459	2478	2480	2510	2521	2540	2437
Cr		<1	1	2	2	3	3	3	4	4	4	4
Cu		<1	<1	1	1	2	2	2	3	3	3	5
Fe		4	12	17	22	25	29	33	38	42	47	50
Pb		<1	<1	<1	<1	1	<1	1	1	2	2	2
Mg		277	291	301	304	296	299	298	306	302	308	299
Mn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Mo		2	2	2	2	2	2	2	3	2	3	3
Ni		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
P		1231	1213	1200	1199	1166	1147	1121	1136	1130	1144	1104
Si		5	3	3	3	3	4	4	4	4	4	4
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Sn		<1	<1	<1	1	1	2	2	2	2	2	2
Zn		1327	1353	1372	1376	1331	1367	1369	1376	1393	1436	1362
K		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Sr		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

7.3.3 Oil Additions, Subtractions, and Consumption

Engine oil samples and additions were weighed and recorded to track engine oil consumption. All measurements are shown in Table 10. The total engine oil consumption rate over the 210-hour test was found to be 0.062 lb/hr.

Table 10. C7 F-24 Evaluation Oil Consumption

Test Engine Lubricant Additions, Subtractions, and Consumption					
Lubricant: LO368787, MIL-PRF-2104J 15W40			Project No. 23870.01.301		
Initial Fill: (engine test)					
	Tech	Lubricant + Container Weight, lbs	-	Container Weight, lbs	= Lubricant Weight, lbs
	KE	41.93	-	8.4	= 33.53
filter (wet/dry)		4.67	-	1.23	= 3.44
				Total Initial Fill	= 36.97
Samples:					
	Date	Tech	Sample + Container Weight, lbs	-	Container Weight, lbs = Sample Weight, lbs
0	1/15/19	RG	0.29	-	0.05 = 0.24
21	1/17/19	KE	0.30	-	0.05 = 0.25
42	1/18/19	KE	0.30	-	0.05 = 0.25
63	1/19/19	KE	0.30	-	0.05 = 0.25
84	1/20/19	KE	0.30	-	0.05 = 0.25
105	1/21/19	KE	0.30	-	0.05 = 0.25
126	1/22/19	KE	0.30	-	0.05 = 0.25
147	1/23/19	KE	0.30	-	0.05 = 0.25
168	1/24/19	MR	0.30	-	0.05 = 0.25
189	1/25/19	MR	0.30	-	0.05 = 0.25
210	1/26/19	KE	0.30	-	0.05 = 0.25
				Total Samples	= 2.74
Additions:					
	Date	Tech	Addition + Container Weight, lbs	-	Container Weight, lbs = Addition Weight, lbs
21	1/17/19	KE	0.00	-	0.00 =
42	1/18/19	KE	0.00	-	0.00 =
63	1/19/19	KE	1.90	-	0.10 = 1.8
84	1/20/19	KE	1.20	-	0.10 = 1.1
105	1/21/19	KE	1.30	-	0.10 = 1.2
126	1/22/19	KE	1.80	-	0.10 = 1.7
147	1/23/19	KE	1.90	-	0.10 = 1.8
168	1/24/19	MR	1.70	-	0.10 = 1.6
189	1/25/19	MR	1.50	-	0.10 = 1.4
210	1/26/19	KE	1.80	-	0.10 = 1.7
				Total Additions	= 12.30
210-Hour Drain:*					
	Tech	Lubricant + Container Weight, lbs	-	Container Weight, lbs	= Lubricant Weight, lbs
	KE	34.31	-	1.88	= 32.43
filter (wet/dry)		3.17	-	2.15	= 1.02
				Total 210-Hour Drain	= 33.45
				Total Initial Fill	36.97 [lbs]
				Total Additions	12.30 [lbs]
				Total Samples	2.74 [lbs]
				Total 210-Hour Drain	33.45 [lbs]
				Total 210-Hour OIL CONSUMPTION	13.08 [lbs]
				Oil Consumption Rate (Oil Consumption/Test Hours)	0.062 [lbs/hr]

7.3.4 Post-Test Power Curves

Figure 4 and Figure 5 show the pre and post-test engine power output and torque for the F-24 at ambient and DOC. Peak engine power output loss was measured at 2.5% for the ambient curve, and 1.5% for the DOC curve over the 210-hour test duration.

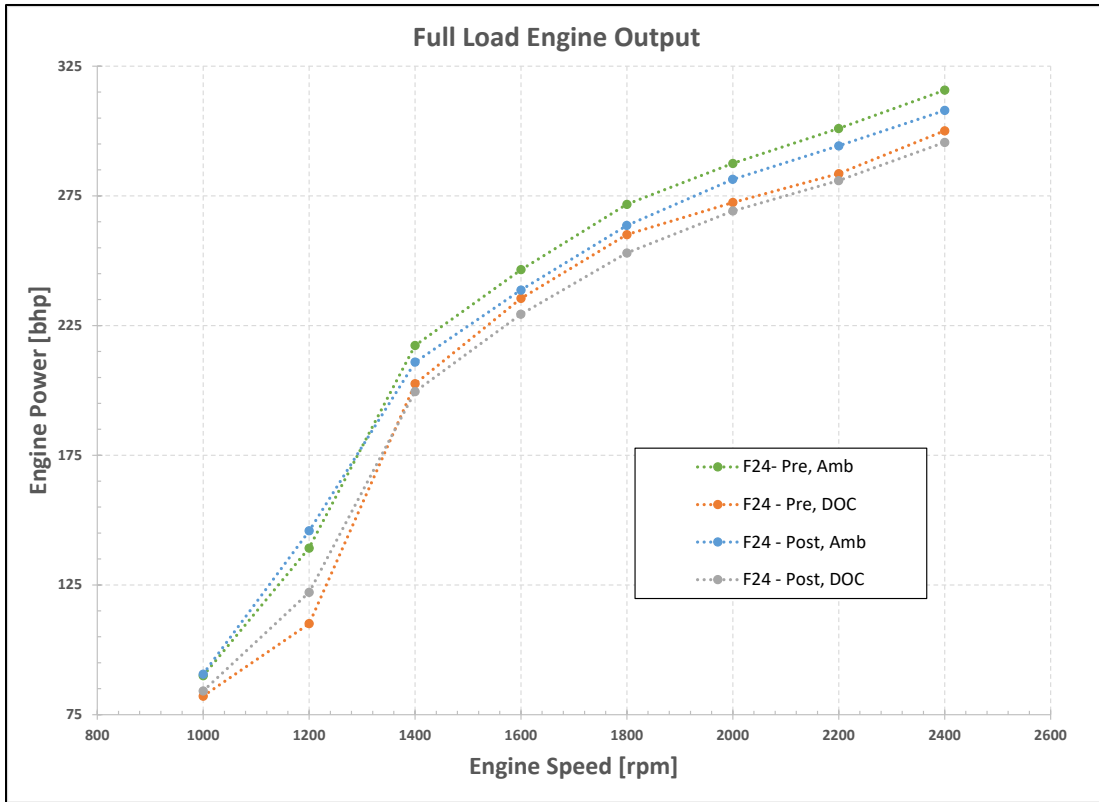


Figure 4. F-24, Pre to Post Power Output, AMB & DOC

For the full load torque curve, the peak torque for the pre and post-test DOC curve occurred slightly later in engine speed than at ambient conditions. The operating area near 1400 rpm has been observed to be a switching point for the engines ECU engine control strategy, and changes in fuel rate and boost levels affect overall output power. For the post-test DOC curve, this mode switching occurred slightly after the 1400 rpm test point, causing the next measured 1600 rpm point to yield actual peak engine torque as opposed to the other curves conducted. This phenomenon was observed in previous testing of the CAT C7, including the preceding tests using the F-24 and ATJ fuel blends in WD 012 [2].

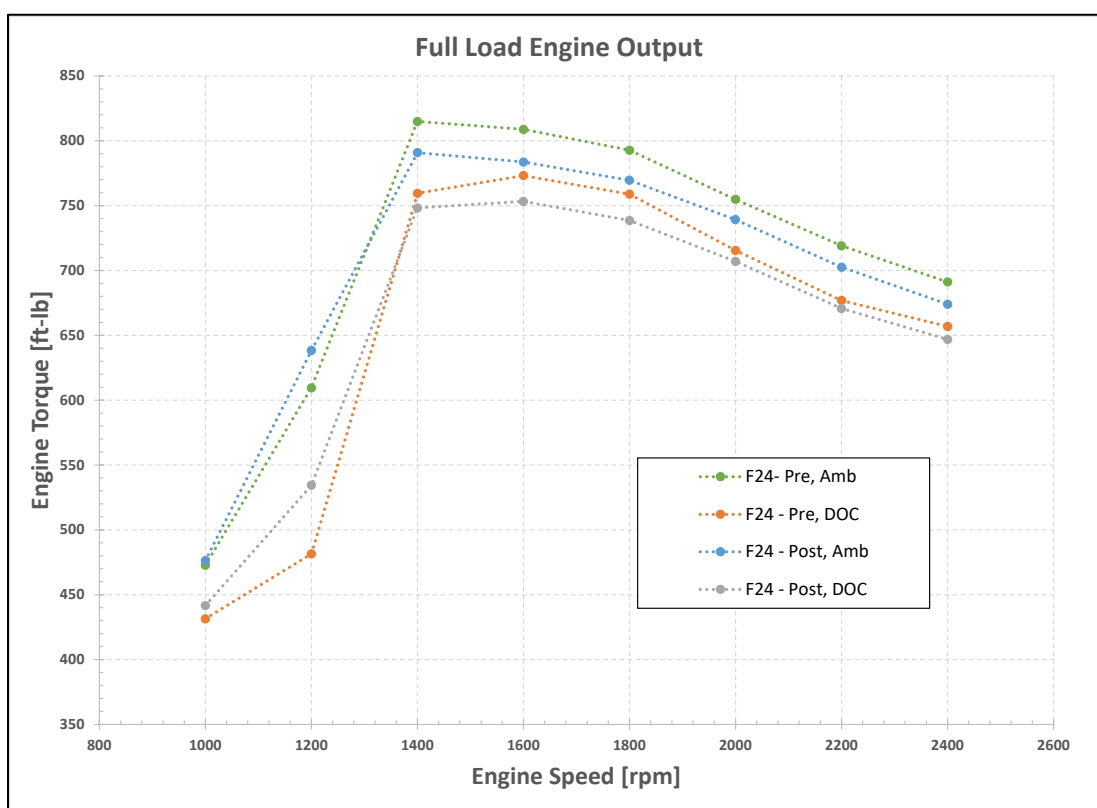


Figure 5. F-24, Pre to Post Torque Output, AMB & DOC

The pre and post-test Brake Specific Fuel Consumption (BSFC) curves for the C7 engine on F-24 at the ambient and DOC are shown in Figure 6. At the ambient conditions the engine overall was slightly more efficient than at DOC. At both sets of operating conditions the C7 engine has slightly higher BSFC after 210 hours of operation with F-24 fuel.

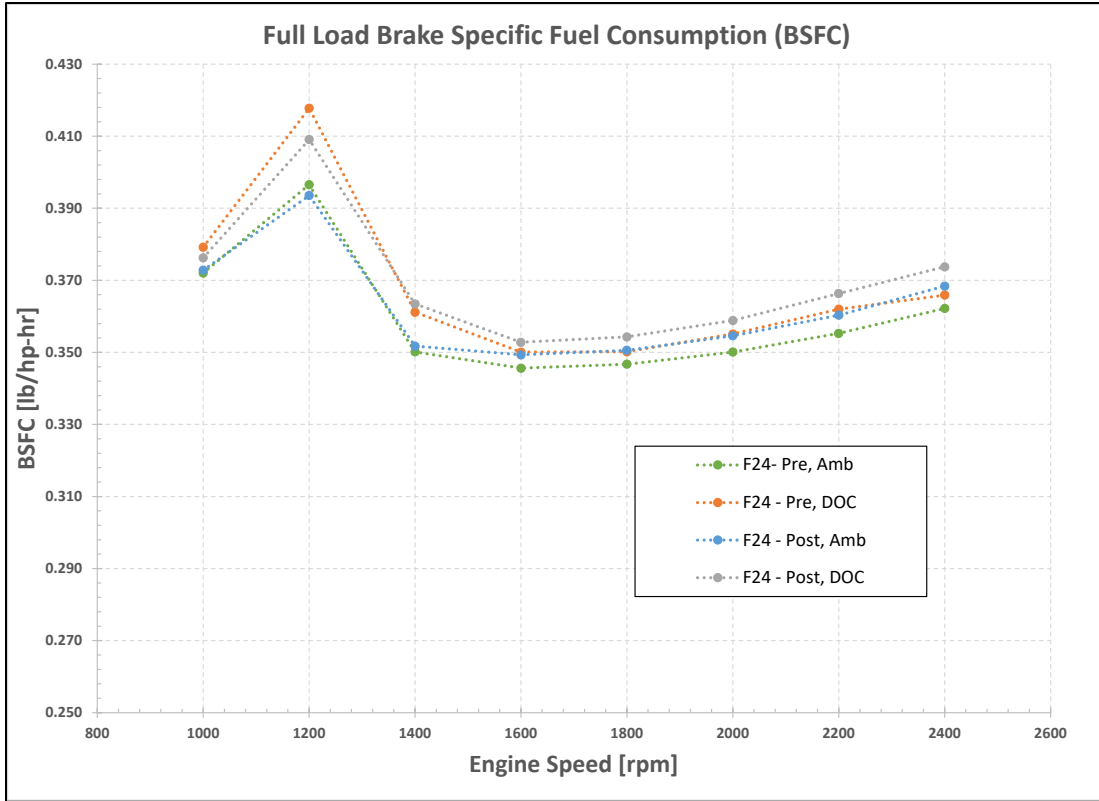


Figure 6. F-24, Pre to Post BSFC, AMB & DOC

During the previous C7 testing on ATJ/F-24 blend, low power due to oil degradation was found during the post-test evaluation of performance [2,3]. The engine oil was then changed to a fresh charge of MIL-PRF-2104L 15W40 and the post-test power curves were repeated. To maintain continuity between testing, this process was duplicated for the F-24 baseline envelope. Figure 7 and Figure 8 show the post-test power curves run using the test oil versus the fresh oil for ambient and DOC conditions, respectively. The recovered power was 1.3% overall for ambient, and 1.3% for DOC, showing nominal power loss due to any oil degradation.

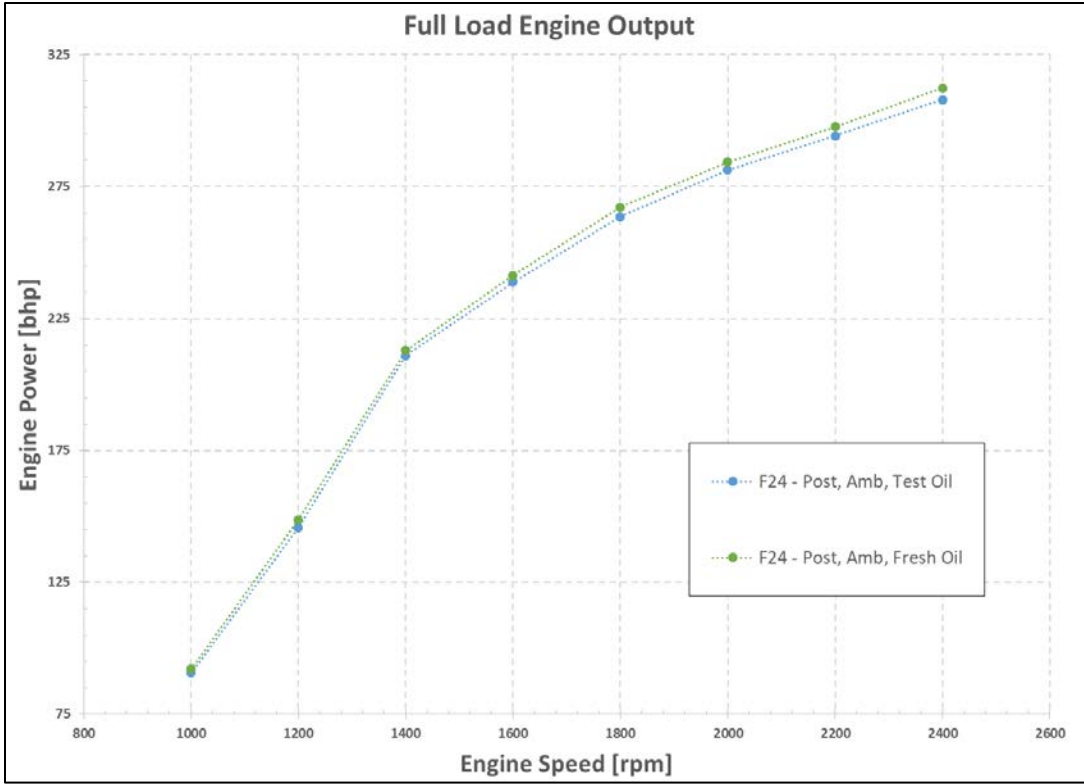


Figure 7. F-24, Post Power Output, Ambient, Test Oil and Fresh Oil

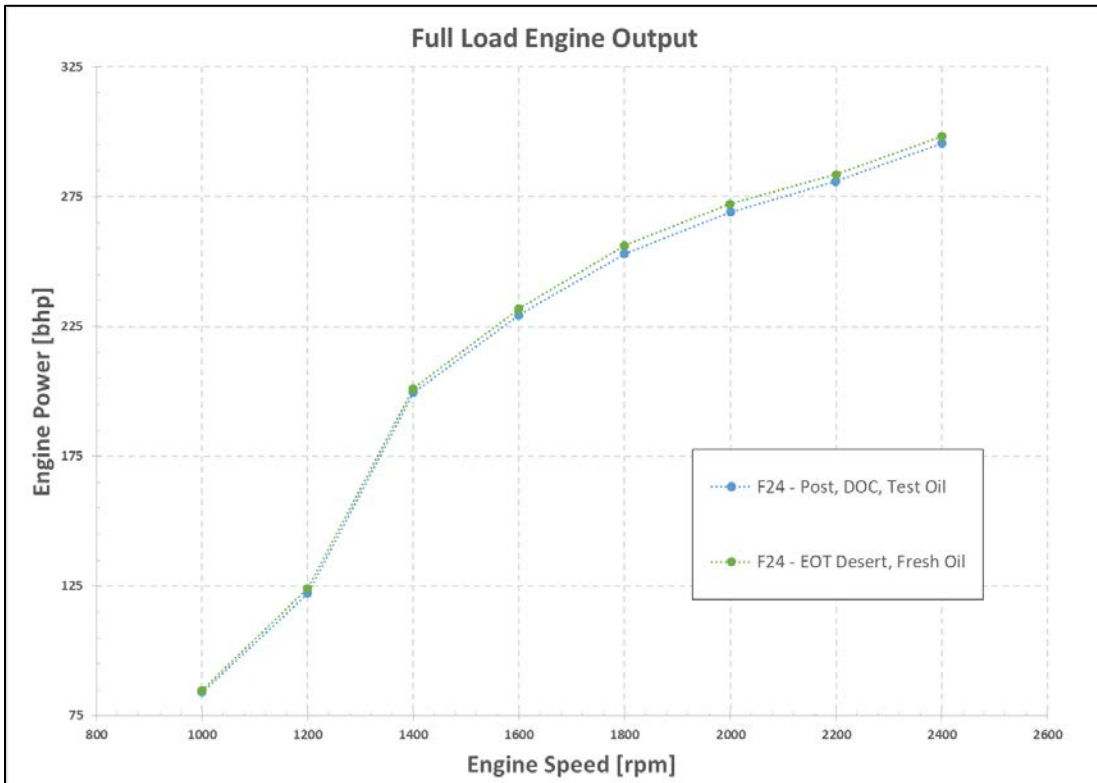


Figure 8. F-24, Post Power Output, DOC, Test Oil and Fresh Oil

7.3.5 Pre & Post-Test Injector and Engine Photos

Figure 9 through Figure 14 show the pre and post-test injector tip photos for all six fuel injectors. The injectors have soot deposits around the holes but the holes are open. Figure 15 shows the pre and post-test photos of the fire deck, and Figure 16 shows the pre and post-test piston crown/combustion chamber photos. Combustion chamber and fire deck deposits appear light. The deposition levels seen are similar to what was documented for the C7 engine using an F-24/ATJ blend [3].

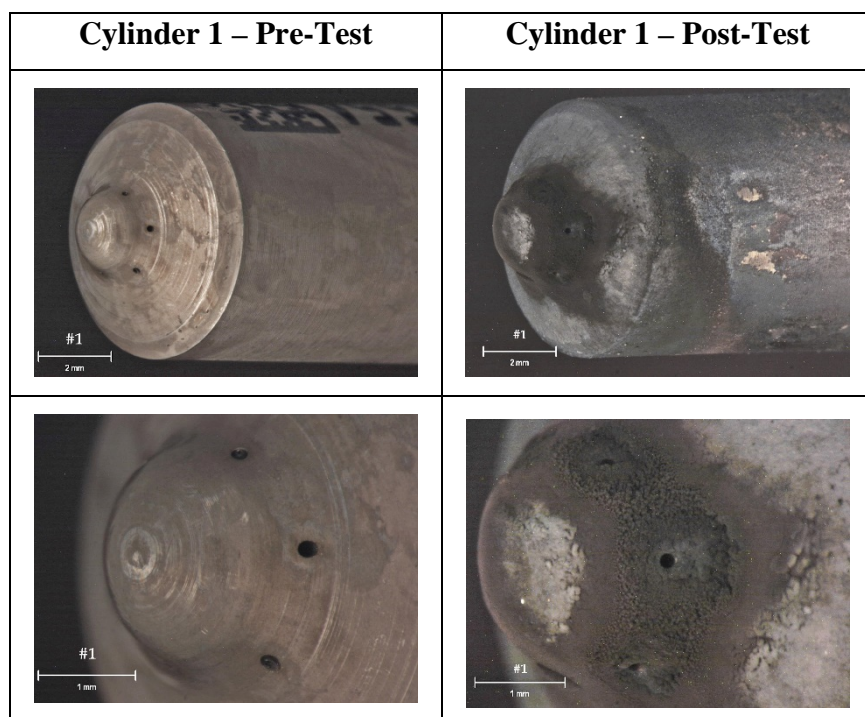


Figure 9. Injector Tip – Cylinder 1

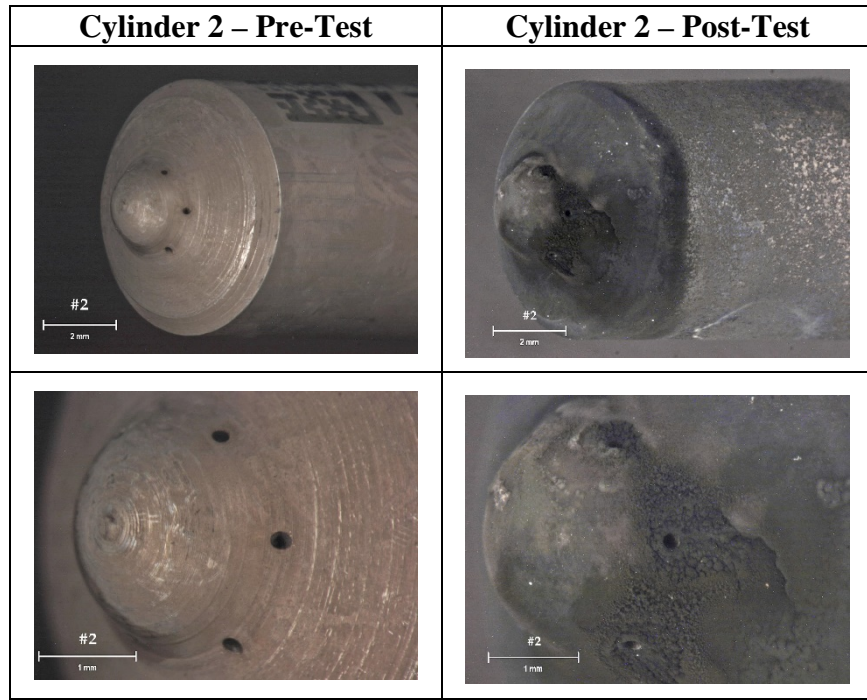


Figure 10. Injector Tip – Cylinder 2

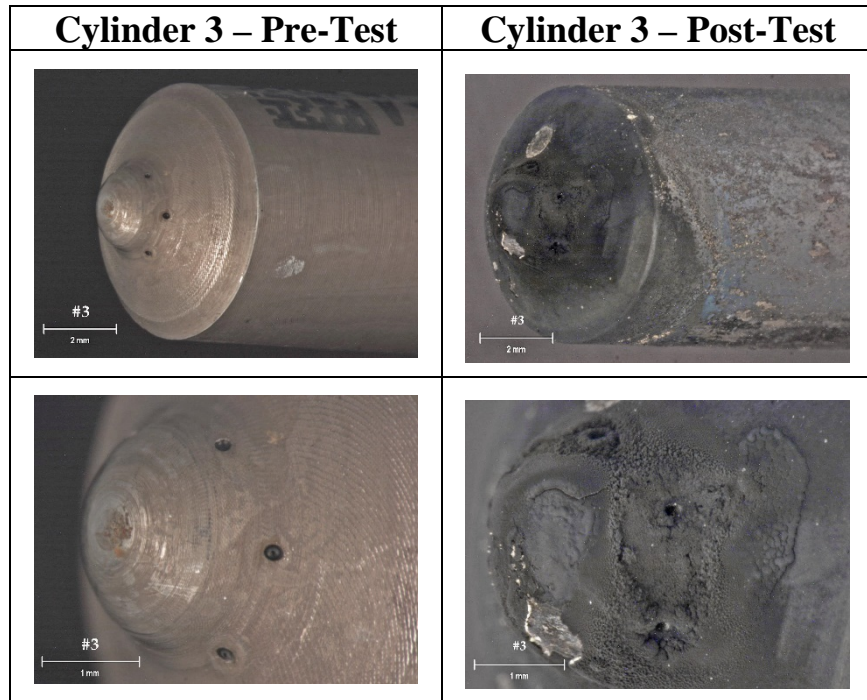


Figure 11. Injector Tip – Cylinder 3

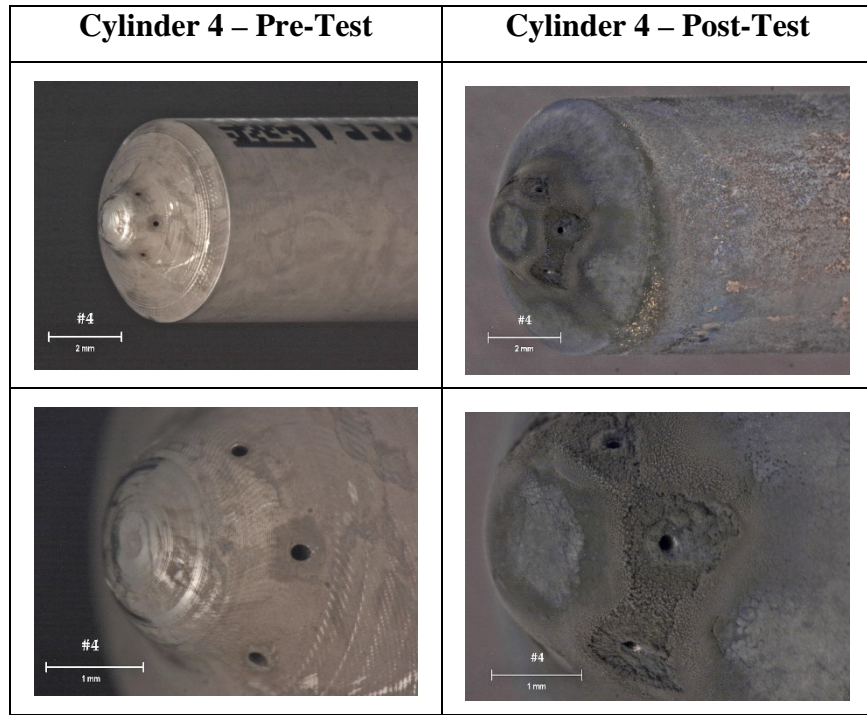


Figure 12. Injector Tip – Cylinder 4

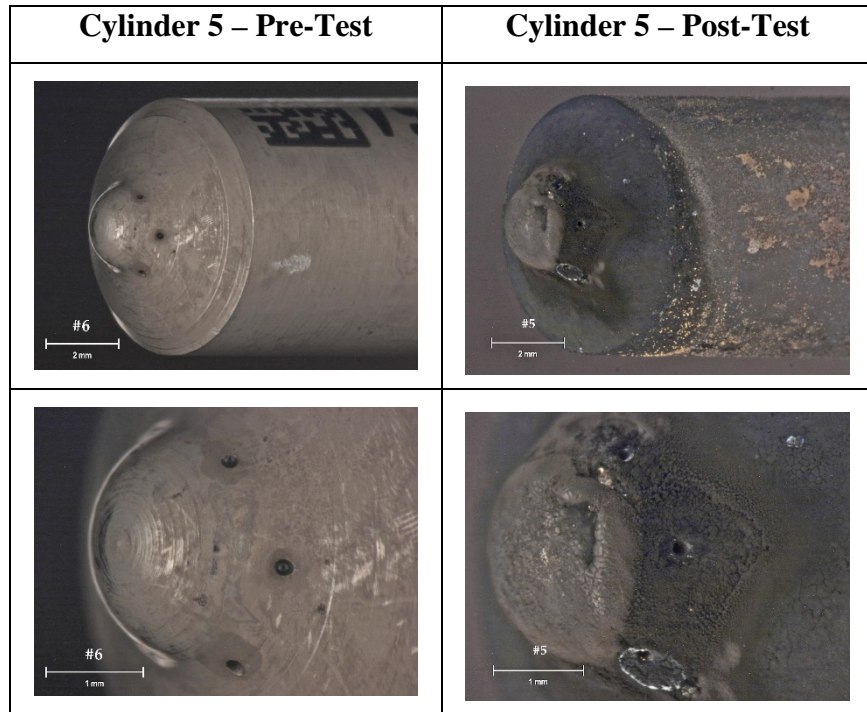


Figure 13. Injector Tip – Cylinder 5

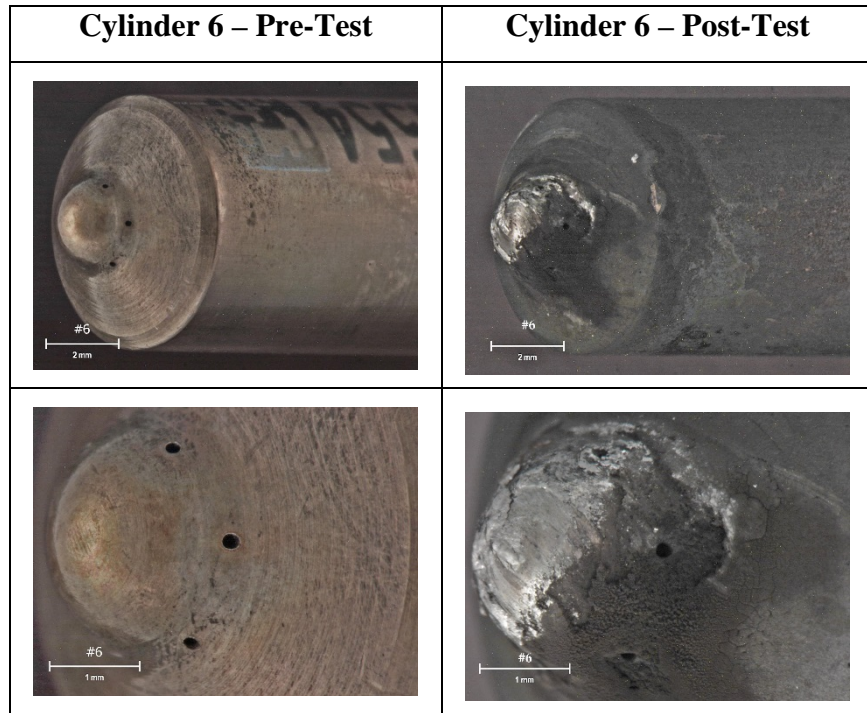


Figure 14. Injector Tip – Cylinder 6













Location	Pre-Test	Post-Test
CYL 1		
CYL 2		
CYL 3		
CYL 4		
CYL 5		
CYL 6		

Figure 15. Fire Deck – ALL






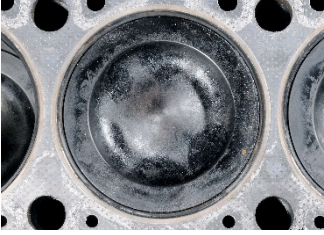

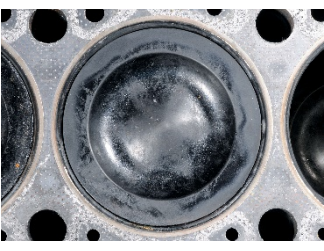




Location	Pre-Test	Post-Test
CYL 1		
CYL 2		
CYL 3		
CYL 4		
CYL 5		
CYL 6		

Figure 16. Piston Crown – ALL

7.3.6 Gaseous Exhaust Emissions

Emissions sampling and smoke number measurements were conducted during the pre and post-test power curves. Emissions and smoke results are shown below in Figure 17 through Figure 22. For the more critical emissions (carbon monoxide (CO), oxides of nitrogen (NO_x), and unburned hydrocarbons (UHC)), small changes were noticed between the pre-test F-24 at ambient and the F-24 at DOC curves. For CO, the F-24 at DOC shows a consistent reduction compared to the F-24 at ambient. The opposite is seen with NO_x, where the F-24 at DOC for pre-test conditions was slightly increased. Directionally this tends to make sense, as NO_x is typically a result of higher combustion temperatures, and the oxidation of CO to carbon dioxide (CO₂) is also affected by gas temperatures. For pre-test unburned hydrocarbons (UHC), both the F-24 at ambient and F-24 at DOC blend response was very low, and difference between their reported magnitude is small based on the measurement calibration range and repeatability of the emissions measurement equipment. The UHC emissions improve over the test duration.

For the F-24 at ambient pre and post-test comparison, CO response increases slightly across the test duration. Post-test NO_x concentrations did show a decrease which suggests a lower overall bulk combustion temperature than during pre-test ambient power curves. Again for UHC the measured response is fairly low, with the exception of an increase at the lower engine speeds below peak torque, where combustion is air limited.

For the F-24 at DOC pre and post-test comparison, CO response increases slightly across the test duration and is lower than the ambient response. NO_x concentrations during post-test did show a decrease over the test duration which suggests a lower overall bulk combustion temperature than during pre-test power curves for the DOC. The DOC NO_x response was slightly higher than the ambient condition response. Again for UHC the measured response is fairly low, with the exception of an increase at the lower engine speeds below peak torque, where combustion is air limited. At higher speeds combustion time decreases and UHC rises. The UHC is lower at the DOC than the ambient conditions.

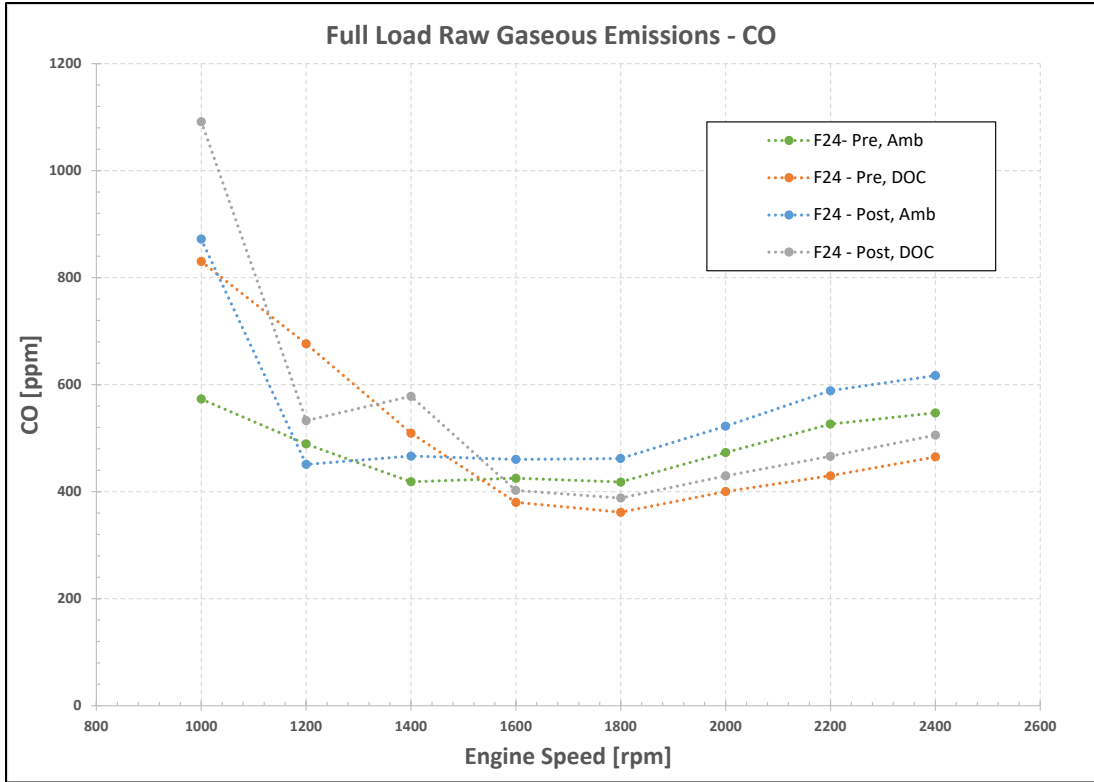


Figure 17. F-24, Pre to Post CO, AMB & DOC

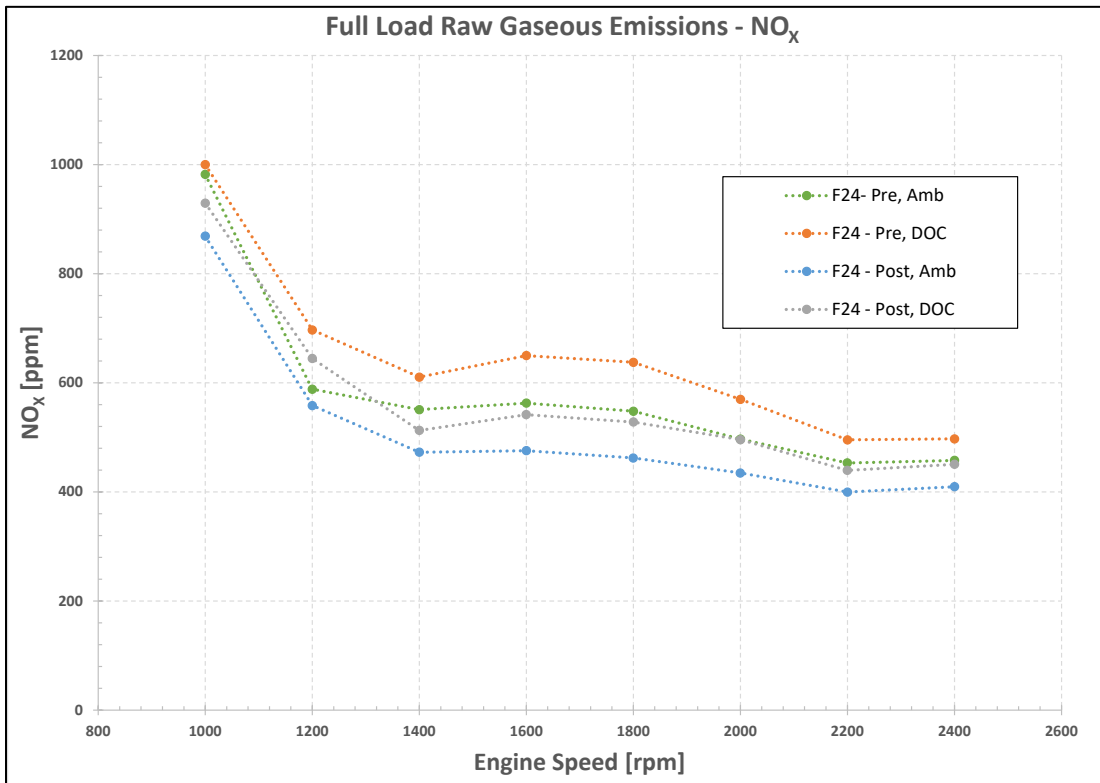


Figure 18. F-24, Pre to Post NO_x, AMB & DOC

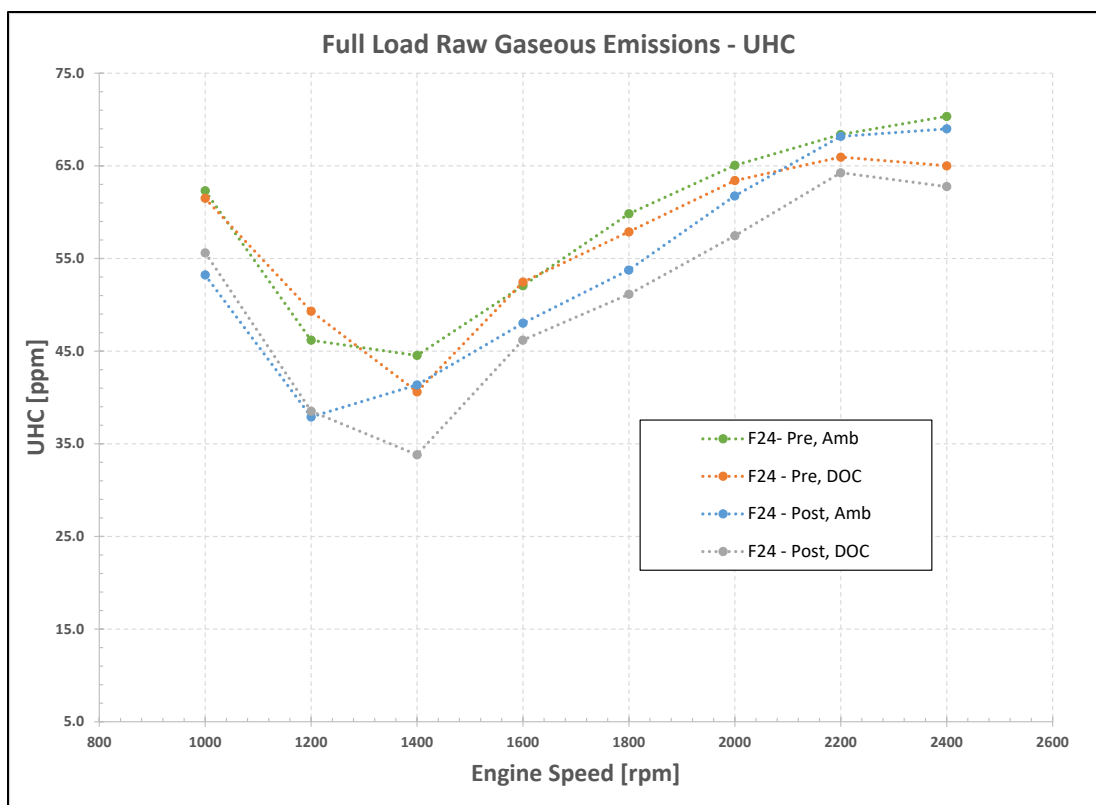


Figure 19. F-24, Pre to Post UHC, AMB & DOC

The exhaust CO₂ emissions are consistent from pre to post-test and at either operating condition for the C7 engine operating on F-24 fuel.

Exhaust Filter Smoke Number (FSN) measurements in Figure 21 showed a consistent increase with the F-24 at ambient operating conditions over the test duration. With F-24 at DOC the FSN in Figure 22 revealed a slight decrease over the test duration. Both operating conditions generated smoke numbers well below 1 at all engine speeds. Below peak torque, as the engine air flow reduces, both operating conditions trended towards slightly higher smoke numbers.

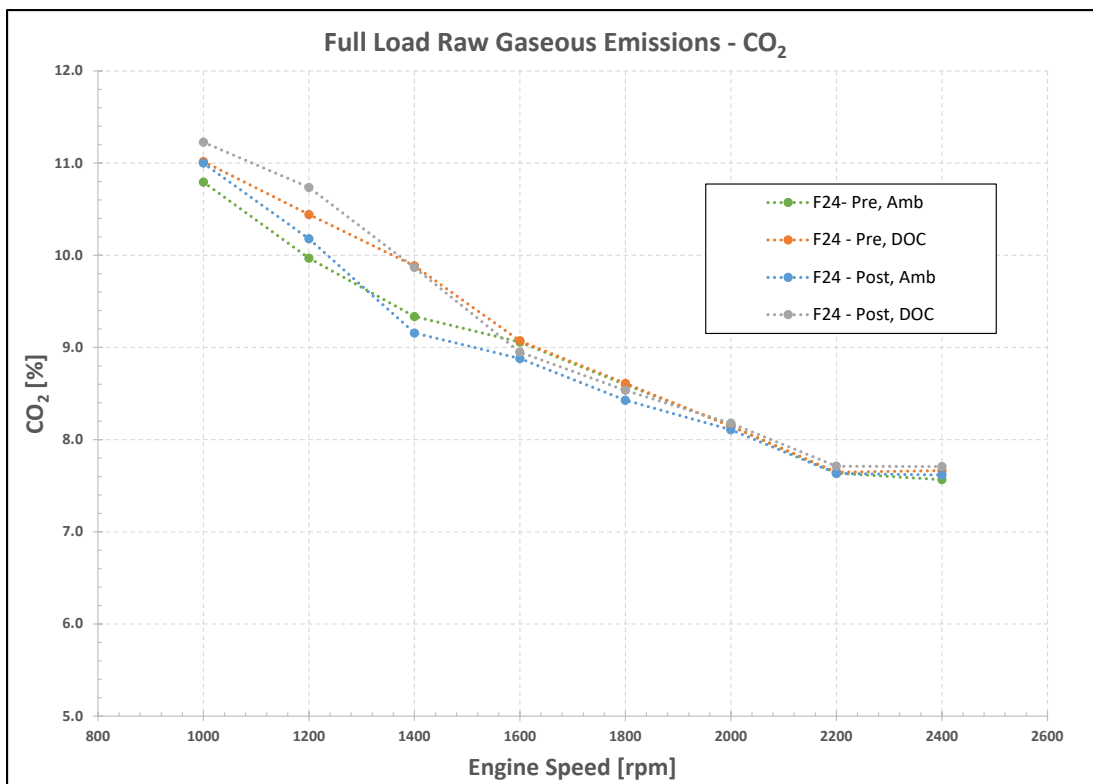


Figure 20. F-24, Pre to Post CO₂, AMB & DOC

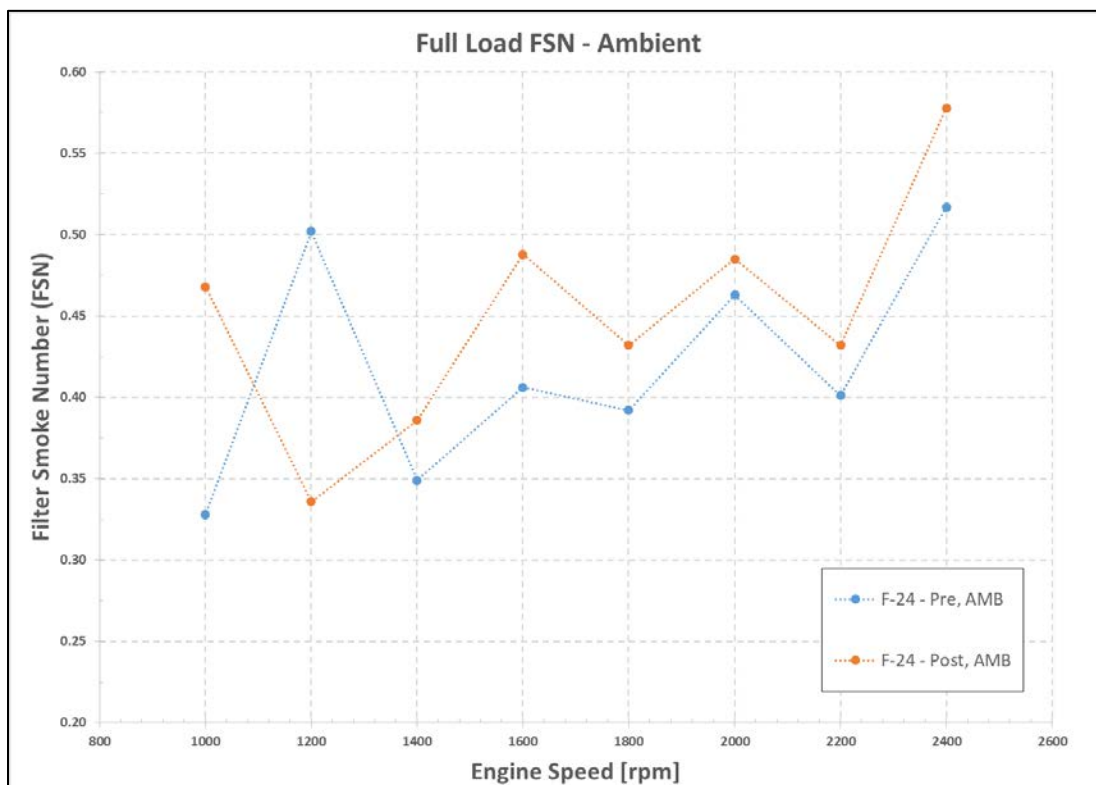


Figure 21. F-24, Pre to Post-Smoke, AMB

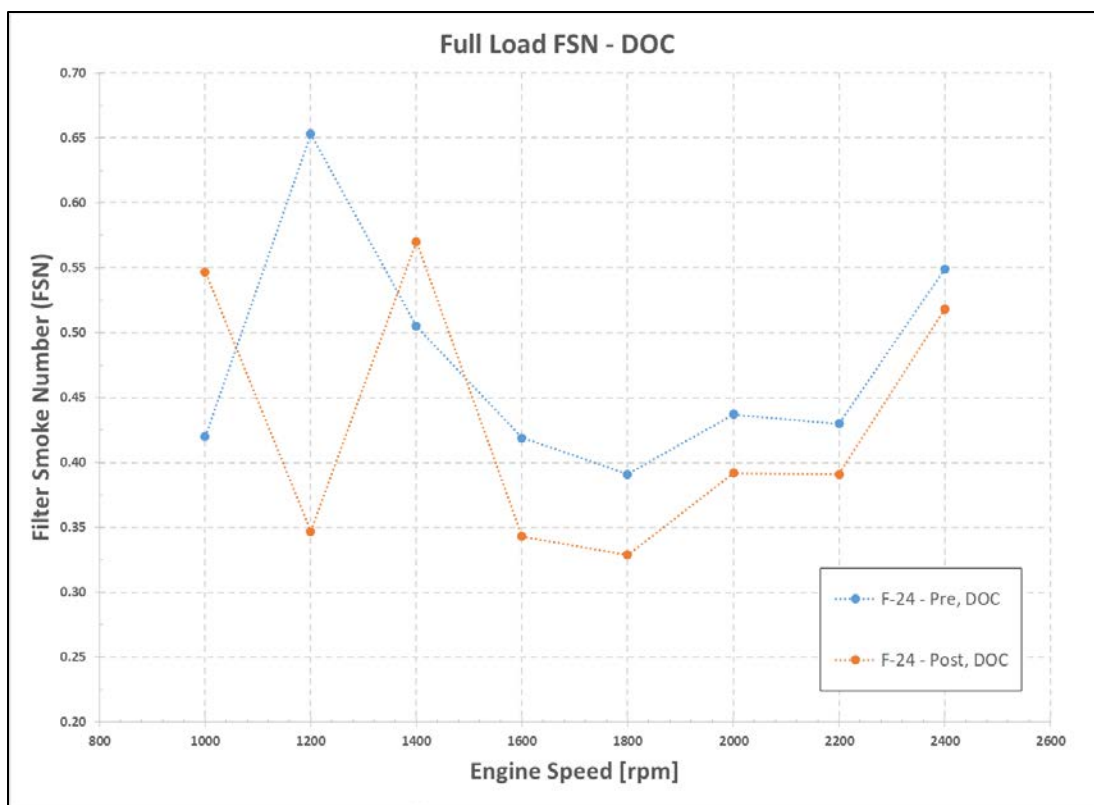


Figure 22. F-24, Pre to Post-Smoke, DOC

7.4 PRE & POST-TEST BSFC MAPS

Post-test BSFC fuel maps were conducted to compare to pre-test maps and document change in engine efficiency. During the first attempt to run the post-test fuel map at ambient conditions, the engine exhibited low power and intermittent torque instability. Upon further investigation, the diagnostic software (CAT Electronic Technician) showed the actual injection pressure was measuring lower than the commanded injection pressure as measured by the HEUI actuation pressure. Based on the exhaust port temperature traces, injector #6 was thought to be suspect. Injector #6 was replaced with a remanufactured injector, and the fuel map was re-run. However, power was still low during wide open throttle suggesting there was not an injector issue. The commanded injection pressure was low due to the lubricant side pressure being low, possibly due to the oxidation of the lubricant during testing that compromised the HEUI pump. Subsequently, the HEUI hydraulic lubricant pump was replaced. Power was recovered and both the ambient and DOC fuel maps were then run.

For both the ambient and DOC fuel maps (shown in Figure 23 and Figure 24), some minor decreases were observed in BSFC between pre-test and post-test maps. At ambient conditions the area of minimum BSFC increased slightly over the test duration with F-24. The region of minimum BSFC also increased marginally at the DOC over the test duration. The ambient conditions overall had broader regions of minimum BSFC.

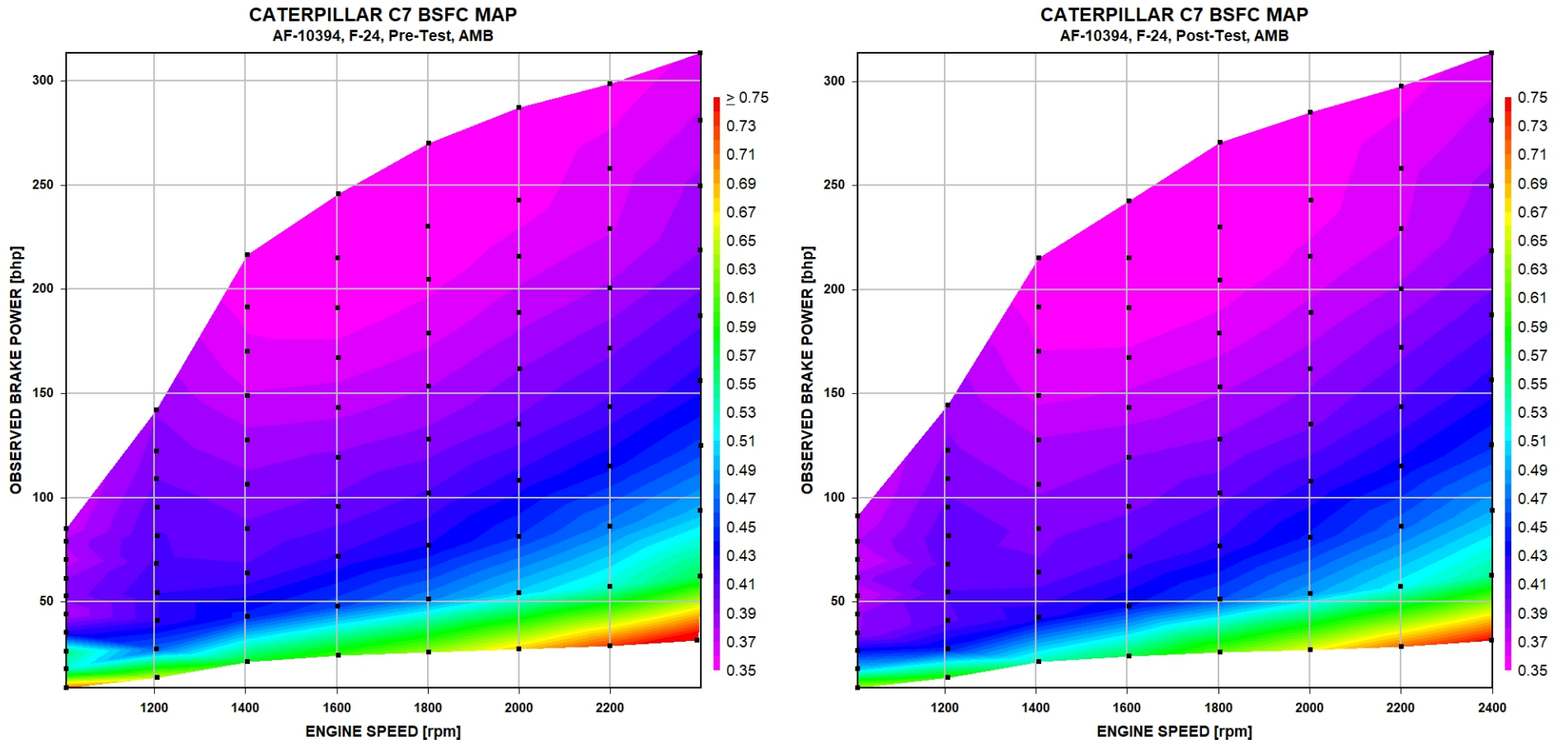


Figure 23. F-24, BSFC Map, AMB, Pre to Post-Test

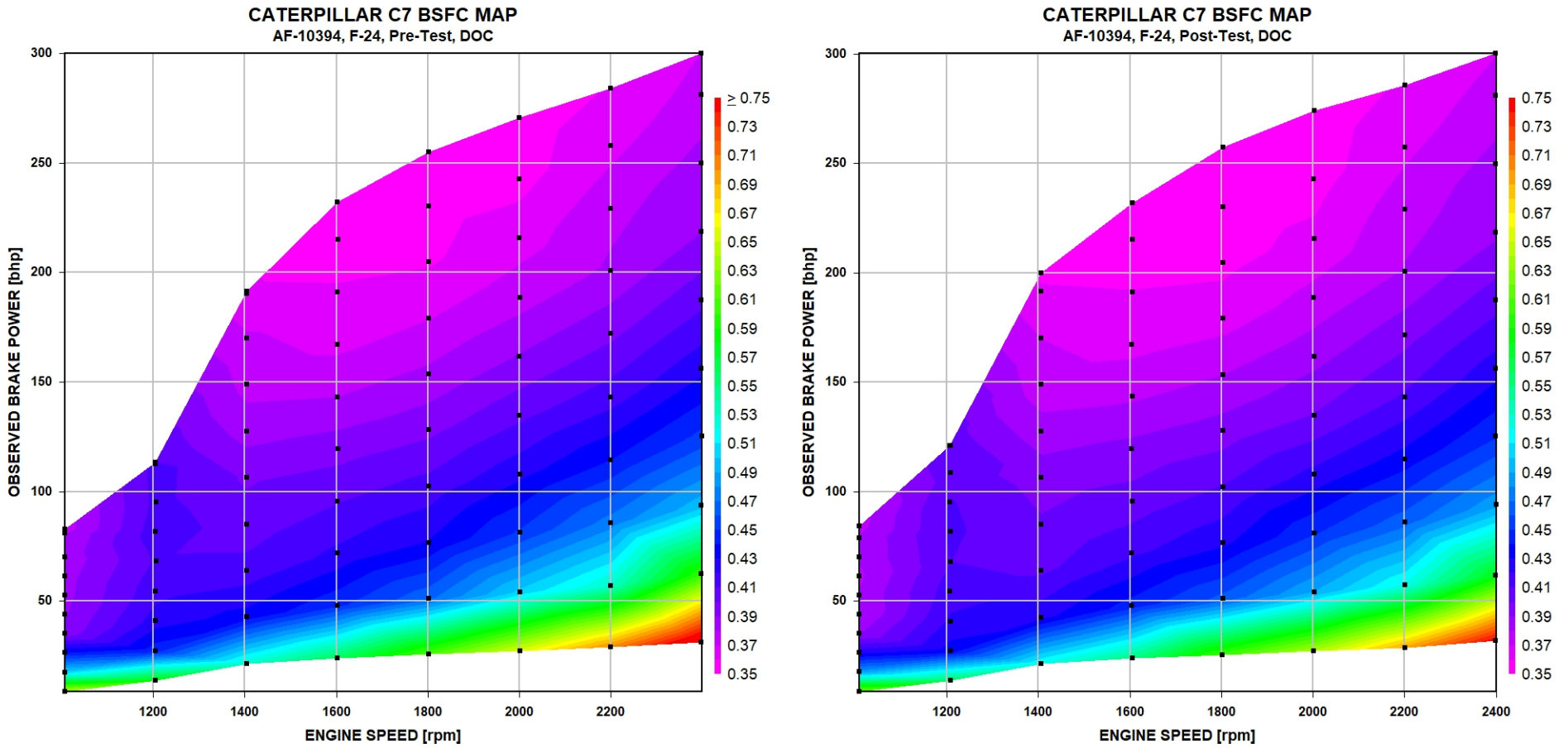


Figure 24. F-24, BSFC Map, DOC, Pre to Post-Test

7.5 POST-TEST FUEL INJECTOR FLOW MEASUREMENTS

To determine the changes in injector performance as a result of the 210-hour test on F-24, the C7 injectors were returned to Caterpillar for flow checks, with the exception of injector #6. Injector #6 was replaced post-test with a re-manufactured injector and as such, was not able to be flow checked via their equipment. According to data provided by Caterpillar, the following faults were identified upon testing:

- Serial 3B1407548406, CYL 1 – MFLT,OS_FLT – backpressure fault
- Serial 3B1407541998, CYL 2 – MD-, main delivery low
- Serial 3B14074407B1, CYL 3 – MD-, main delivery low
- Serial 3B1407538933, CYL 4 – MD-, main delivery low
- Serial 3B14075377DA, CYL 5 – MD-, main delivery low

Because of these faults, the injectors were unable to be flow tested further. Data provided by Caterpillar is included in Table 11. Of note is the data indicates that the injection volume was low but the engine did not display low power. Furthermore the BSFC maps only showed subtle post-test variations after 210 hours of operation on F-24. The upper and lower seat leakage are for the lubricant drive actuator control valve. Possibly the lubricant degradation during testing may have affected the HEUI actuator.

Table 11. Caterpillar HEUI Fuel Injector Test Parameters

Row	LOCATION_ID	FINAL_TEST_DATE	PRODUCT_I D_SHORT	SERIAL_NO	FAIL_DESCRIPTION	BUILD_NO	TP_MAIN_DELI VERY_1	TP_MAIN_ TIMING_1	UPPER_SEAT _LEAK	LOWER_SEAT _LEAK	TP_MAIN_DELIVERY _STD_1	TP_MAIN_TIMING _STD_1
1	M3051B	6/14/2018 2:17	3879428	3B14074407B1		89	73.28	1.128	1735.996	1693.92	0.42	0.004
	M3051A	4/10/2019 16:32	3879428	3B14074407B1	TP1_MD-	89	54.547	1.112	1596.244	898.416	0.2	0.004
2	M3051B	6/14/2018 15:06	3879428	3B14075377DA		1299	75.93	1.141	1905.367	1780.227	0.38	0.003
	M3051A	4/10/2019 16:34	3879428	3B14075377DA	TP1_MD-	1299	60.007	1.088	1705.822	1030.67	0.33	0.005
3	M3170A	6/14/2018 15:14	3879428	3B1407538933		1304	74.353	1.142	1766.963	1544.549	0.28	0.005
	M3051A	4/10/2019 16:38	3879428	3B1407538933	TP1_MD-	1304	54.137	1.135	2317.965	1352.393	0.22	0.003
4	M3051B	6/15/2018 0:15	3879428	3B1407541998		1342	75.3	1.175	1767.82	1497.572	0.4	0.004
	M3051A	4/10/2019 16:36	3879428	3B1407541998	TP1_MD-	1342	62.247	1.153	1562.234	1027.428	0.21	0.003
5	M3166B	6/15/2018 0:57	3879428	3B1407548406		1393	75.724	1.137	1849.518	2020.477	0.44	0.004
	M3051A	4/10/2019 16:40	3879428	3B1407548406	MFLT_OS_FLT, - Backpressure Fault	1393	0	0	1156.299	542.141	0	0

7.6 POST-TEST FUEL INJECTOR TEARDOWN

After the flow checks the injectors were returned to SwRI where they were disassembled for internal inspection. A new unused injector was also disassembled to provide a point of comparison of internal condition. Figure 25 shows a HEUI fuel injector, with the lower outer housing separated to access the barrel assembly (which contains the fuel wetted section of the injector).

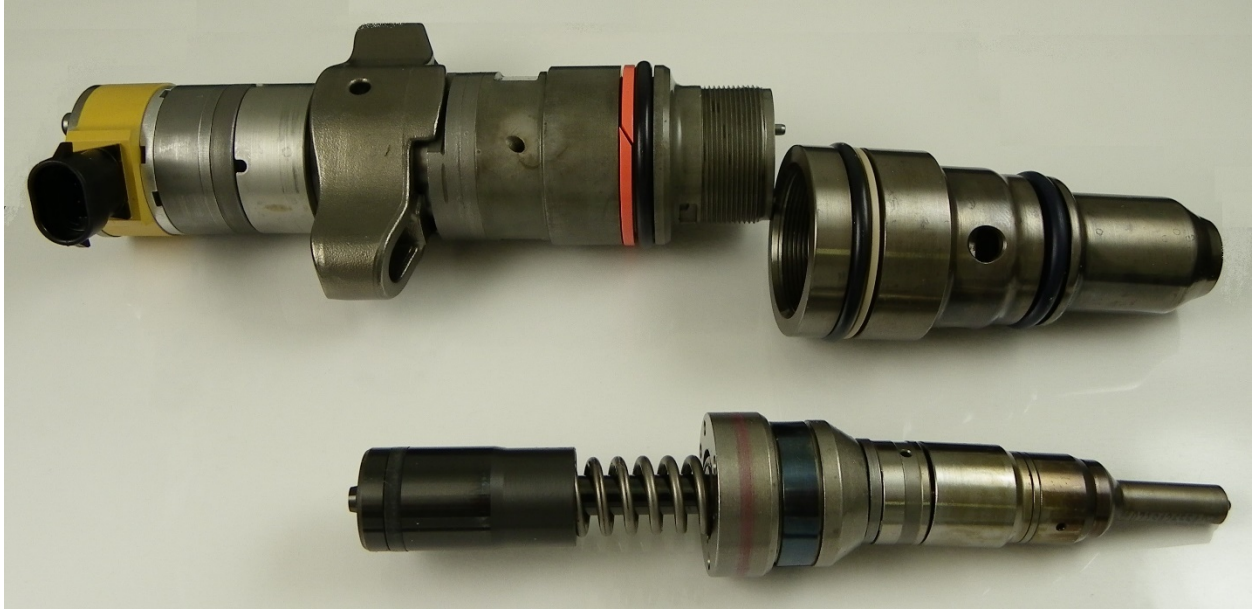


Figure 25. Caterpillar C7 HEUI Injector – Barrel Assembly Removal

Figure 26 (next page) shows an exploded view of the barrel assembly. Everything above the top of the intensifier piston (A) is in the oil wetted section of the injector. The solenoid only controls the timing and duration of the oil actuation pressure to the intensifier piston. Components below the intensifier piston and plunger are fuel wetted.

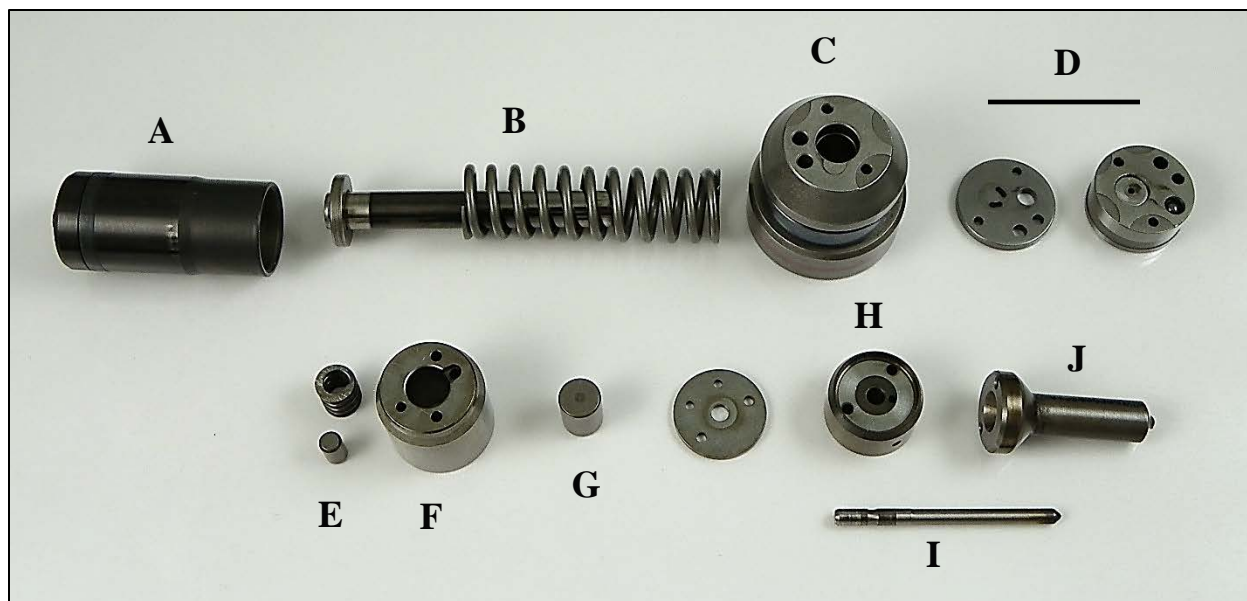


Figure 26. C7 HEUI Injector Barrel Assembly Exploded View

The HEUI injector uses high pressure oil acting on the upper surface of the intensifier piston to provide the force to depress the plunger (B) in the barrel (C), pressurizing fuel for injection. The metering section of the injector (D) contains passages and valves that control and route the fuel throughout the injector. The metering section contains a small check ball and stop plate that control fuel movement. The check ball controls the fuel inlet, opening to allow fuel to enter the barrel as the plunger retracts after an injection event, and closes when the plunger descends down the barrel to allow the increase in fuel pressure for injection. The stop plate (or check plate) opens to let the pressurized fuel flow from the barrel down to the nozzle, and then closes back when the needle seats. The plate acts as a damper to prevent fuel pushed up from the needle from holding the check ball closed and prevent barrel refilling upon end of injection (both the check ball and stop plate are moved by fuel pressure only). The stop pin (E) limits the total upward travel of the injector needle during an injection event, while the spring (E) provides the seat pressure for the needle to shut off fuel flow once injection pressure is removed from the needle's lower taper. The lift spacer (G) physically rides on top of the needle, while both it and the stop pin and spring (E) are housed in the spacer sleeve (F). Lastly the needle (I) rides in the bore of the guide housing (H) and nozzle (J). The nozzle has an angular fuel passage that allows the high pressure fuel from the barrel assembly to pass down to the lower portion of the needle and act on the tapered surface of the

needle to provide lift. Once sufficient fuel pressure is achieved on this surface to overcome the seat pressure provided by the spring, the needle lifts and injection occurs. Injection stops once this pressure drops below the seat pressure provided by the spring.

Noted on the lubricant wetted intensifier piston of several of the fuel injectors was some wear on the intensifier piston that is shown in Figure 27 along with a new piston. Prior C7 work with an alternative fuel revealed light polishing of the intensifier pistons in the same region of the piston [3].



Figure 27. C7 HEUI Injector Plunger (CYL#5 shown on left, NEW shown on right)

During inspection, attention was given to the fuel wetted components that tended to show wear markings when compared to those from the new unused injector. Overall wear appeared to be typical of a used injector. As previously discussed, none of the injectors exhibited any operational problems during the F-24 fuel testing that would indicate a failure of internal components. The conditions of these F-24 injectors compare to prior efforts with alternative or other standard military fuels. All of the following photos below show internal components from CYL#4 versus those from the new unused injector. Photos of the selected components for all other injectors can be found in APPENDIX A.

The first component shown in detail is the plunger (Figure 28). The exterior surface of the plunger tended to show some wear/polish on the diamond-like carbon (DLC) coating used to protect the plunger surface where it interfaces with the barrel. This type of polish is expected and typical. No

scoring or material transfer was noted. Any physical damage to this component would cause immediate injector malfunction.



Figure 28. C7 HEUI Injector Plunger (CYL#4 shown left, NEW shown right)

The stop plate (or check plate), Figure 29 tended to show some markings on its upper surface where it contacted the separating plate of the metering housing when lifted off of its seat. It is unlikely that wear here would cause a complete failure in function, but it could potentially hinder the ability of the plate to move freely, affecting injector performance/fuel metering.

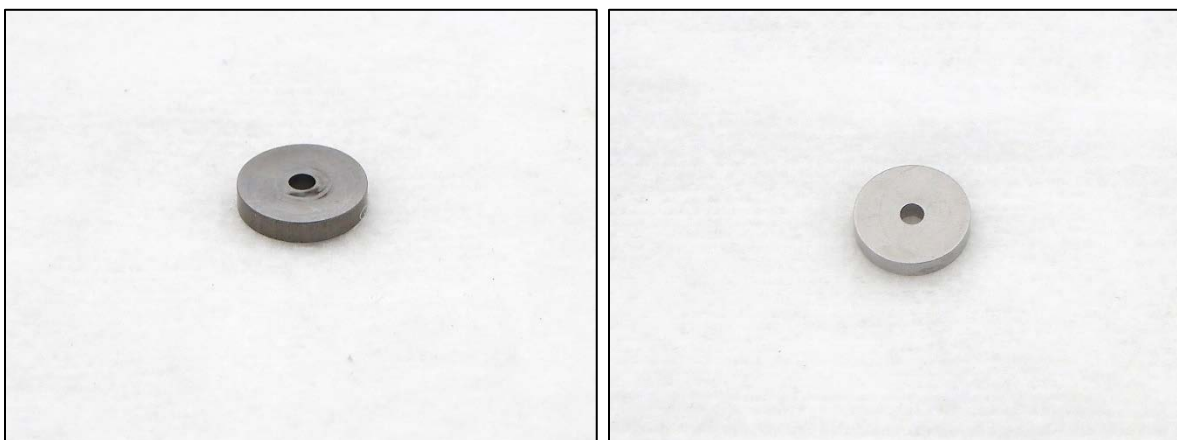


Figure 29. C7 HEUI Injector Stop Plate (CYL#4 shown left, NEW shown right)

The needle lift spacer (Figure 30) is in direct contact against the top surface of the needle and is loaded at spring pressure. A small contact spot can be noted on the spacer where it rides on the needle. If excessive wear occurred here, the needle spring preload would be reduced, resulting in

decreased opening pressure of the injector and changing its fuel delivery characteristics. Although visible, actual wear at this interface was limited.

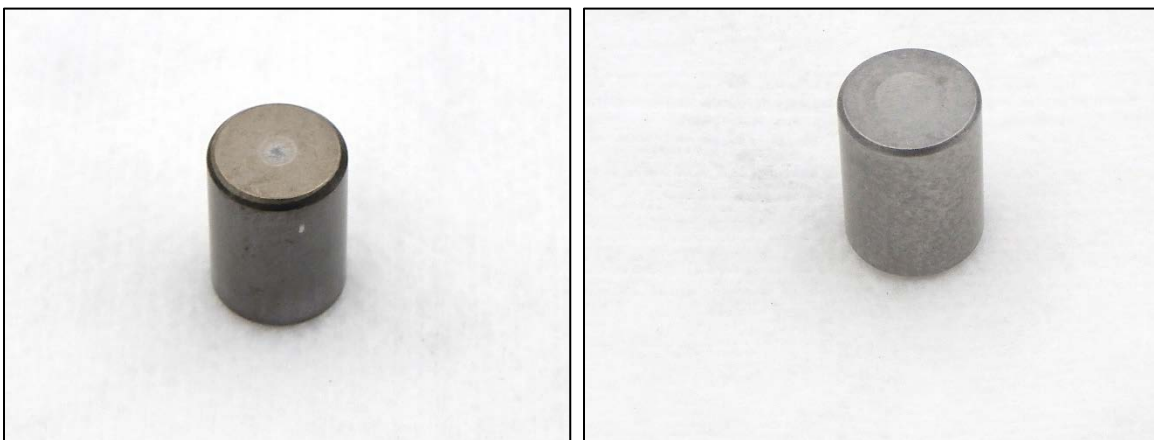


Figure 30. C7 HEUI Injector Lift Spacer (CYL#4 shown left, NEW shown right)

Lastly the injector needle itself (Figure 31), which moves up and down during injection in the nozzle housing and guide housing, tended to show some light markings at its upper end where it rides in the guide housing. Any wear occurring here could impact needle lift, and ultimately make the injector non-functional. There is light fuel deposition near the tip.



Figure 31. C7 HEUI Injector Needle (CYL#4 shown left, NEW shown right)

Overall no major concerns were noted during the internal inspection of the fuel wetted components of the fuel injectors. Although the Caterpillar testing showed injector issues, the component conditions do not seem distressed. However, based on the engine performance, fuel maps, and the

observed condition of internal components, there does not appear to be a major concern of injector compatibility from the use of F-24 fuel.

8.0 CONCLUSIONS

All test results collected support the use of F-24 fuel in the C7 engine. Once the cause of the engine power output loss during the 210 hours was attributed to engine oil condition and corrected, post-test measurement of engine performance showed little degradation (less than 3%) from the pre-test condition as a result of the 210-hour operation on the F-24 fuel. Post-test fuel injector flow ratings suggest the actuator side of the fuel injector may have been affected by the lubricant degradation. Post-test fuel injector internal component inspection did not identify any major changes in performance or undue wear, and post-test inspection of the injector tips, fire deck, and pistons did not reveal any unusual or unexpected engine deposits.

9.0 RECOMMENDATIONS

It is recommended that a similar F-24 test be conducted at ambient conditions with the minimum lubricity additive concentration in the future to provide a baseline comparison for alternative fuel use in the C7 engine. It is also recommended to investigate potential power loss issues with the C7 engine and HEUI injection system due to degradation of the engine lubricant. This phenomenon has not been noted in past work using the C7 engine, and may suggest some performance limitation of the current MIL-PRF-2104L oil specification.

10.0 REFERENCES

1. Development of Military Fuel/Lubricant/Engine Compatibility Test, CRC Report 406, January 1967
2. Brandt, Adam C., Frame, Edwin A., Yost, Douglas M., "CATERPILLAR C7 & GEP 6.5L(T) FUEL SYSTEM DURABILTIY USING 25% ATJ FUEL BLEND," Interim Report TFLRF No. 474, February 2015
3. Brandt, Adam C., Frame, Edwin A., "CATERPILLAR C7 FUEL SYSTEM DURABILTIY USING 30% ATJ FUEL BLEND," Interim Report TFLRF No. 487, September 2017

UNCLASSIFIED

APPENDIX A.
C7 FUEL INJECTOR COMPONENT PHOTOGRAPHS

UNCLASSIFIED

Intensifier Piston - Injector 1



Intensifier Piston - Injector 4



Intensifier Piston - Injector 2



Intensifier Piston - Injector 5



Intensifier Piston - Injector 3



Intensifier Piston - Injector 6



Plunger - Injector 1



Plunger - Injector 4



Plunger - Injector 2



Plunger - Injector 5



Plunger - Injector 3



Plunger - Injector 6



Stop Plate - Injector 1



Stop Plate - Injector 4



Stop Plate - Injector 2



Stop Plate - Injector 5



Stop Plate - Injector 3



Stop Plate - Injector 6



Needle Spacer - Injector 1



Needle Spacer - Injector 4



Needle Spacer - Injector 2



Needle Spacer - Injector 5



Needle Spacer - Injector 3



Needle Spacer - Injector 6



Needle - Injector 1



Needle - Injector 4



Needle - Injector 2



Needle - Injector 5



Needle - Injector 3



Needle - Injector 6

