CATERPILLAR C7 FUEL SYSTEM DURABILITY USING 30% ATJ FUEL BLEND

INTERIM REPORT
TFLRF No. 487

by
Adam C. Brandt
Edwin A. Frame

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

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

Contract No. W56HZV15C0030

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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 a second investigation into the use of a 30% ATJ blended fuel in the Caterpillar (CAT) C7 engine. Testing was conducted following an accelerated 210hr Tactical Wheeled Vehicle cycle to determine impact on engine performance, combustion, fuel system durability, raw gas emissions, and combustion related deposits. Overall performance degradation as a result of using the ATJ blend over the 210hr test duration was approximately 3% for the both the ATJ blend and F-24 post-test powercurves. End of test power levels and emissions between the ATJ blend and F-24 were essentially identical. Post-test inspection of the fuel injector tips, combustion chambers, and fire deck did not yield any abnormal deposit generation, and post-test fuel injector flows checks and internal component inspection suggested that the ATJ blend fuel did not negatively affect the performance or durability of the C7 engine fuel system.

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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. This report covers a second investigation into the use of an ATJ blended 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, 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 ATJ component was limited to 30% volume of the total blend, and blended with standard F-24. The ATJ was limited to maintain a desired minimum 40 cetane number in the final blend to ensure satisfactory operation in a compression ignition engine. The entire fuel blend was additized according to AFLP-3747 NATO F-24 fuel specification, with additive concentrations sufficient for the total volume (target concentrations: 24g/m^3 CI/LI, 1g/m^3 STADIS, 0.09% FSII). Testing was conducted following an accelerated 210hr Tactical Wheeled Vehicle cycle to determine ATJ blend impact on engine performance, combustion, fuel system durability, raw gas emissions, and combustion related deposits. Overall performance degradation as a result of using the ATJ blend over the 210hr test duration was approximately 3% for the both the ATJ blend and F-24 post-test powercurves. Consistent with pre-test checks, end of test power levels between the ATJ blend and F-24 were essentially identical. Post-test inspection of the fuel injector tips, combustion chambers, and fire deck did not yield any abnormal deposit generation, and post-test fuel injector flows checks and internal component inspection suggested that the ATJ blend fuel did not negatively affect the performance or durability of the C7 engine fuel system.

In general, all results support the use of the ATJ blend fuel in the C7 engine. It is recommended that a similar F-24 test be conducted in the future to provide a baseline comparison for alternative fuel use in this engine.

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 of SEP 2016 to SEP 2017 under Contract No. W56HZV15C0030. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the TARDEC contracting officer's technical representative. Ms. Patsy Muzzell of TARDEC served as project technical monitor.

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

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ACRONYMS AND ABBREVIATIONS

ATJ – alcohol to jet
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
FTIR - Fourier-transform infrared spectroscopy
HC – hydrocarbon
HEUI – hydraulically actuated, electronically controlled, unit injector
hp – horsepower
hr/hrs – hour/hours
JP8 – jet propulsion 8
L - liter
lbft – pound feet torque
MATV – MRAP All Terrain Vehicle
MRAP – Mine Resistant Ambush Protected
NOX – nitrogen oxides
O2 – oxygen
rpm – revolution per minute
SOW – scope of work
SwRI – Southwest Research Institute
TARDEC – Tank Automotive Research, Development, and Engineering Center
TFLRF – TARDEC Fuels and Lubricants Research Facility
TWV – tactical wheeled vehicle
TWVC – tactical wheeled vehicle cycle
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 second investigation into the use of an ATJ blended 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 U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF), located at Southwest Research Institute (SwRI), San Antonio TX.

2.0 OBJECTIVE

The objective of this testing was to determine the compatibility of ATJ blended fuels for use in the CAT C7 engine. Testing was conducted to determine impact on engine performance, combustion, fuel system durability, combustion related deposits, and raw exhaust gas emissions. Based on the contract scope of work (SOW), the ATJ blending stock was limited to a maximum of 30% (by volume) to maintain a desired minimum cetane number of 40 to ensure proper compression ignition engine operation. All testing was conducted at the maximum effective treat rate of corrosion inhibitor/lubricity improver (CI/LI).

3.0 APPROACH

An engine dynamometer test stand was used to evaluate the ATJ blend in the C7 engine. Durability testing was preceded by full load engine powercurves on both the ATJ blend fuel and standard F24 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 with the ATJ blend fuel 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 210hr 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 210hr 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 210hr 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 210hr test was completed, post-test powercurves were completed again using the ATJ blend fuel and standard F24. Post-test BSFC fuel maps were also conducted using the ATJ blend fuel to document the change in engine efficiency over the test cycle.

4.0 FUEL PROPERTIES

The ATJ blend stock was provided by the U.S. Army TARDEC, and was blended with commercially available Jet-A fuel sourced by TFLRF at a volumetric ratio of 30% ATJ 70% F-24. The fuel blend was additized consistent to AFLP-3747 NATO F-24 fuel specifications. All additive concentrations blended sufficient for the total blended volume (target concentrations: 24g/m^3 CI/LI, 1g/m^3 STADIS, 0.09% FSII). Blending of the ATJ and F-24 occurred in bulk on-site at TFLRF. Commercially available ultra-low sulfur diesel (ULSD) and standard F-24 were also 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 with respect to standard military fuels. Table 2 presents the chemical and physical properties of the tested F-24 (AF-9623) and 30% ATJ blend (AF-9625). Table 3 presents the chemical and physical properties of the USLD in accordance with ASTM D975.

Table 2. 30% ATJ Blend & Neat F-24 Chemical & Physical Properties

Test	ASTM Method	Units	SwRI Code AF-9625 Sample Code CL16-0368 30% ATJ Blend	SwRI Code AF-9623 Sample Code CL16-0369 F-24
Saybolt Color	**D156**	--	26	22
Acid Number	**D3242**	mg KOH / g	0.006	0.006
Chemical Composition	**D1319**			
Aromatics		vol %	12.9	18.7
Olefins		vol %	0.6	0.6
Saturates		vol %	86.5	80.7
Sulfur Content - XRF	**D2622**	ppm	850.22	1202.49
Sulfur Mercaptan	**D3227**	mass%	0.0	0.0
Doctor Test	**D4952**	--	Sweet	Sweet

Table 2. 30% ATJ Blend & Neat F-24 Chemical & Physical Properties (CONT)

Test	ASTM Method	Units	SwRI Code AF-9625 Sample Code CL16-0368 30% ATJ Blend	SwRI Code AF-9623 Sample Code CL16-0369 F-24
Distillation	**D86**			
IBP		°C	170.3	168.8
5% Rcvd		°C	178.6	178.3
10% Rcvd		°C	179.2	181.3
15% Rcvd		°C	181.8	184.2
20% Rcvd		°C	183.8	187.3
30% Rcvd		°C	187.6	192.7
40% Rcvd		°C	191.6	198.2
50% Rcvd		°C	196.3	203.7
60% Rcvd		°C	202.0	209.6
70% Rcvd		°C	210.6	217.1
80% Rcvd		°C	222.7	227.0
90% Rcvd		°C	237.9	240.1
95% Rcvd		°C	249.2	251.2
FBP		°C	262.5	262.8
Residue		%	0.8	0.8
Loss		%	0.8	1.3
T50-T10		°C	17.1	22.4
T90-T10		°C	58.7	58.8
Flash Point by Tag Closed Cup Tester	**D56**	°C	51	52
Density 15°C	**D4052**	kg/m^3	784.4	795.2
Freeze Point (Manual)	**D2386**	°C	-56.0	-55.0
Net Heat of Combustion	**D4809 NET**	BTU/lb	18692.0	18546.0
Hydrogen Content (NMR)	**D3701**	mass %	14.36	13.99
Smoke Point	**D1322**	mm	26.8	24.7
Naphthalene Content	**D1840**	vol%	1.20	0.89
Calculated Cetane Index	**D976**	--	49.3	48.0
Copper Strip Corrosion	**D130**			
Test Temperature		°C	1A	1A
Test Duration		hrs	100	100
Rating		--	2.0	2.0

Table 2. 30% ATJ Blend & Neat F-24 Chemical & Physical Properties (CONT)

Test	ASTM Method	Units	SwRI Code AF-9625 Sample Code CL16-0368 30% ATJ Blend	SwRI Code AF-9623 Sample Code CL16-0369 F-24
JFTOT	**D3241**			
Test Temperature		°C	260	260
ASTM Code		rating	1	1
Maximum Pressure Drop		mmHg	0	0
Ellipsometer		nm	5.207	4.144
Total Volume		cm^3	1.0000E-06	1.0000E-06
Test Temperature		°C	325.0	325.0
ASTM Code		rating	4P	2.0
Maximum Pressure Drop		mmHg	0.0	0.0
Ellipsometer		nm	247.575	61.854
Total Volume		cm^3	--	7.00E-06
Gum Content	**D381**	mg / 100 mL	2	1
Particulate Contamination in Aviation Fuels	**D5452**			
Total Contamination		mg/L	4.40	4.60
Total Volume Used		mL	1000	1000
Water Reaction	**D1094**			
Volume Change of Aqueous Layer		mL	1.0	1.0
Interface Condition		rating	1B	1B
Separation		--	2	2
MSEP	**D3948**	rating	62	67
Fuel System Icing Inhibitor (FSII) Content	**D5006**			
Test Temperature		°C	20.5	20.5
FSII Content		vol %	0.14	0.14
Electrical Conductivity	**D2624**			
Electrical Conductivity		pS/m	0	453
Temperature		°C	20.8	19.9
Derived Cetane Number (IQT)	**D6890 (AL)**			
Ignition Delay		ms	5.013	4.324
Derived Cetane Number		--	41.68	47.62

Table 2. 30% ATJ Blend & Neat F-24 Chemical & Physical Properties (CONT)

Test	ASTM Method	Units	SwRI Code AF-9625 Sample Code CL16-0368 30% ATJ Blend	SwRI Code AF-9623 Sample Code CL16-0369 F-24
Kinematic Viscosity	**D445**			
Test Temperature		°C	100	100
Viscosity		mm²/s	0.69	0.67
Test Temperature		°C	40	40
Viscosity		mm²/s	1.32	1.28
Test Temperature		°C	-20	-20
Viscosity		mm²/s	4.352	4.215
Lubricity (BOCLE)	**D5001**	mm	0.560	0.563
Hydrocarbon Types by Mass Spec.	**D2425**			
Paraffins		mass %	60.8	52.8
Monocycloparaffins		mass %	23.9	25.7
Dicycloparaffins		mass %	0.0	0.0
Tricycloparaffins		mass %	0.0	0.0
Total Napthenes		mass%	23.9	25.7
TOTAL SATURATES		mass %	84.7	78.5
Alkylbenzenes		mass %	10.3	14.3
Indans/Tetralins		mass %	3.4	4.8
Indenes		mass %	0.2	0.4
Naphthalenes		mass %	0.3	0.4
Alkyl Naphthalenes		mass %	0.9	1.3
Acenaphthenes		mass %	0.1	0.1
Acenaphthylenes		mass %	0.1	0.1
Tricycl- Aromatics		mass %	0.0	0.0
Total Polynuclear Aromatics (PNAs)		mass %	1.4	1.9
TOTAL AROMATICS		mass %	15.3	21.4
Karl Fischer Water Content	**D6304**	ppm	54	59

Table 2. 30% ATJ Blend & Neat F-24 Chemical & Physical Properties (CONT)

Test	ASTM Method	Units	SwRI Code AF-9625 Sample Code CL16-0368 30% ATJ Blend	SwRI Code AF-9623 Sample Code CL16-0369 F-24
Elemental Analysis	**D7111**			
Al		ppb	<100	<100
Ba		ppb	<100	<100
Ca		ppb	585	379
Cr		ppb	<100	<100
Co		ppb	578	353
Cu		ppb	<100	<100
Fe		ppb	<100	<100
Pb		ppb	<100	<100
Li		ppb	<100	<100
Mg		ppb	154	<100
Mn		ppb	<100	<100
Mo		ppb	<100	<100
Ni		ppb	<100	<100
Pd		ppb	<100	<100
P		ppb	<1,000	<1,000
Pt		ppb	<100	<100
K		ppb	<1,000	<1,000
Si		ppb	<100	<100
Ag		ppb	<100	<100
Na		ppb	<1,000	<1,000
Sr		ppb	<100	<100
Sn		ppb	<100	<100
Ti		ppb	<100	<100
V		ppb	<100	<100
Zn		ppb	<100	<100
Nitrogen Content	**D4629**	mg/kg	<1.0	<1.0
Carbon Hydrogen	**D5291**			
Carbon		mass%	84.56	85.16
Hydrogen		mass%	14.28	13.98
Cetane Number	**D613**	--	40.8	49.4
Lubricity (HFRR)	**D6079**			
Test Temperature		°C	60	60
Wear Scar Diameter		µm	759	760
Micro Separation (MSEP)	**D7224**	--	86	81

Table 3. ULSD Chemical & Physical Properties

Test	ASTM Method	Units	SwRI ID RDF-5780 Sample Code CL17-0435 ULSD
Flash Point	**D93**	°C	58.5
Water and Sediment	**D2709**		
Sample Description		--	--
Total Contaminant		vol %	<0.005
Distillation	**D86**		
IBP		°C	182.6
5 % Rcvd		°C	205.1
10 % Rcvd		°C	217.0
15 % Rcvd		°C	225.9
20 % Rcvd		°C	233.9
30 % Rcvd		°C	348.3
40 % Rcvd		°C	261.8
50 % Rcvd		°C	272.9
60 % Rcvd		°C	284.0
70 % Rcvd		°C	294.9
80 % Rcvd		°C	306.6
90 % Rcvd		°C	322.1
95 % Rcvd		°C	335.0
FBP		°C	345.8
Residue		%	1.0
Loss		%	0.5
T50-T10		°C	55.9
T90-T10		°C	105.1
Kinematic Viscosity	**D445**		
Test Temperature		°C	80
Viscosity		mm²/s	1.44
Test Temperature		°C	40
Viscosity		mm²/s	2.75
Test Temperature		°C	-20
Viscosity		mm²/s	Sample froze during soak time
Ash Content	**D482**	mass %	<0.001
Total Sulfur Content	**D5453**	mg/kg	6.30
Copper Strip Corrosion	**D130**		
Test Temperature		°C	50
Test Duration		hrs	3.0
Rating		--	1A

Table 3. ULSD Chemical & Physical Properties (CONT)

Test	ASTM Method	Units	SwRI ID RDF-5780 Sample Code CL17-0435 ULSD
Cetane Number	**D613**	--	54.1
Calculated Cetane Index	**D976**	--	55.0
Chemical Composition	**D1319**		
Aromatics		vol %	20.7
Olefins		vol %	0.9
Saturates		vol %	78.4
Cloud Point	**D2500**	°C	-11.3
Carbon Residue - 10% Ramsbottom	**D524**	mass%	0.06
Lubricity (HFRR)	**D6079**		
Test Temperature		°C	60
Wear Scar Diameter		µm	460
Electrical Conductivity	**D2624**		
Electrical Conductivity		pS/m	66
Temperature		°C	16.2
Lubricity (BOCLE)	**D5001**	mm	0.497
Net Heat of Combustion	**D4809**	MJ/kg	43.22
Density 15 °C	**D4052**	kg/m^3	830.8
Derived Cetane Number (IQT)	**D6890**		
Ignition Delay		ms	3.89
Derived Cetane Number		--	52.4
Carbon Hydrogen	**D5291**		
Carbon		mass%	86.42
Hydrogen		mass%	13.79

5.0 ENGINE DESCRIPTION

The Caterpillar C7 engine is a 7.2L turbo-charged, aftercooled, direct-injected, inline 6 cylinder engine. The engine evaluated was rated a 330bhp at a speed of 2400rpm (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 SN:FM16705. A single set of fuel injectors were used during testing, and are identified below by serial number:

Table 4. Caterpillar C7, Evaluated Injector Serial Numbers

CYL	INJECTOR SN
1	3B1189326569
2	3B118932627C
3	3B1189333256
4	3B118933442F
5	3B118932504D
6	3B1189327067

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 TFLRF 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
  - 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) 500hp 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 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 DOC operating conditions.

- 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 FTIR Gas Analyzer 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-2104J 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 ATJ blended fuel. A summary of all specified testing is listed below:

- Pre-test powercurve check with ULSD at ambient conditions
- F-24 pre and post-test powercurves at both ambient and DOC (+emissions)
- ATJ blend pre and post-test powercurves at both ambient and DOC (+emissions)
- Pre and post-test fuel maps with ATJ blend at both ambient and DOC
- 210hr test duration operated on ATJ blend at DOC

Table 5 identifies the temperature control specifications for testing based on type of operation specified.

Table 5. 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 Powercurves

Figure 1 shows the pre-test full load power and torque output for the C7 engine using commercially available ULSD at ambient operating conditions. The engine produced a peak power of 328bhp @ 2400rpm, and a peak torque of 840lbft @ 1400rpm, which is within 1% of the specified rating of 330hp.

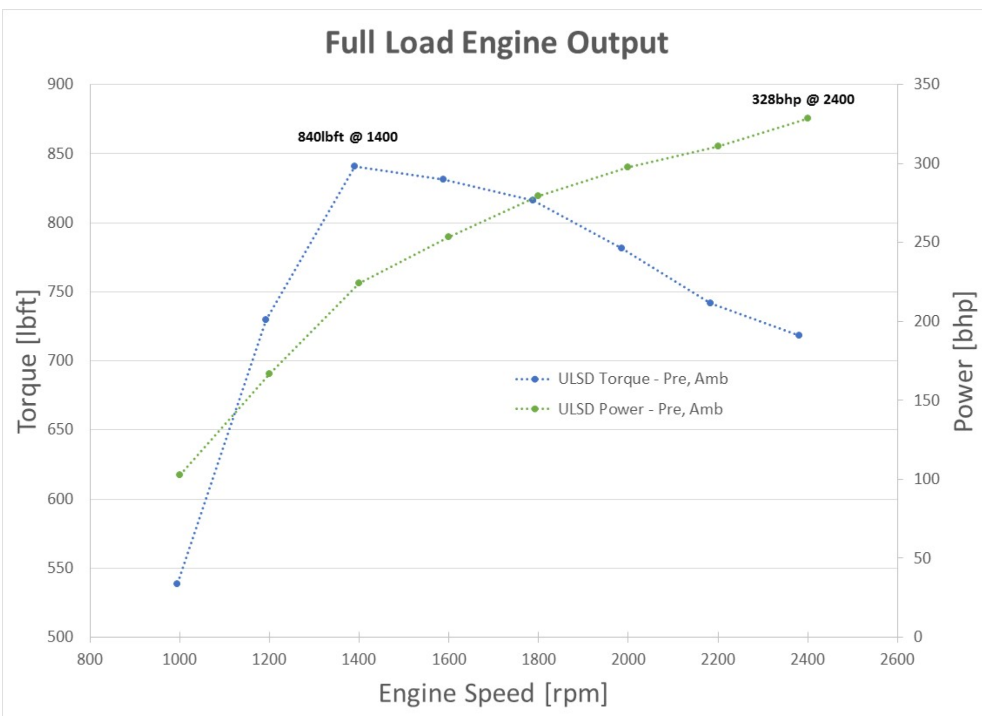


Figure 1. ULSD Pre-Test Output

Figure 2 shows the pre-test full load torque and power output using F24 at ambient and DOC. The engine produced a peak power of 313bhp and 300bhp @ 2400rpm, and a peak torque of 798lbft and 740lbft @ 1400rpm (values presented for ambient and DOC respectively). Post-test F24 power output (and its comparison to pre-test output) is presented later in the report.

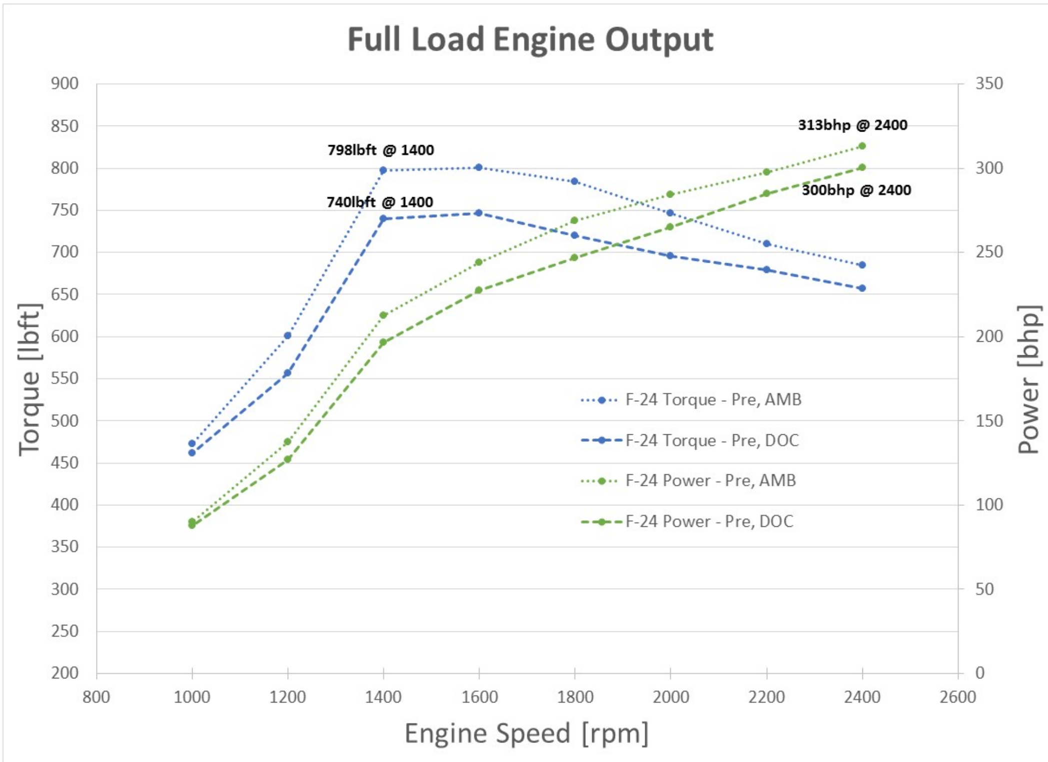


Figure 2. F-24 Pre-Test Output

Figure 3 shows the pre-test full load torque and power output for the 30% ATJ blend at ambient and DOC. The engine produced a peak power of 312bhp and 302bhp @ 2400rpm, and a peak torque of 795lbft and 742lbft @ 1400rpm (values presented for ambient and DOC respectively). This demonstrated that the 30% ATJ blend produces comparable power output levels to that of F24 in the C7 engine. Post-test 30% ATJ blend power output (and its comparison to pre-test output) is presented later in the report.

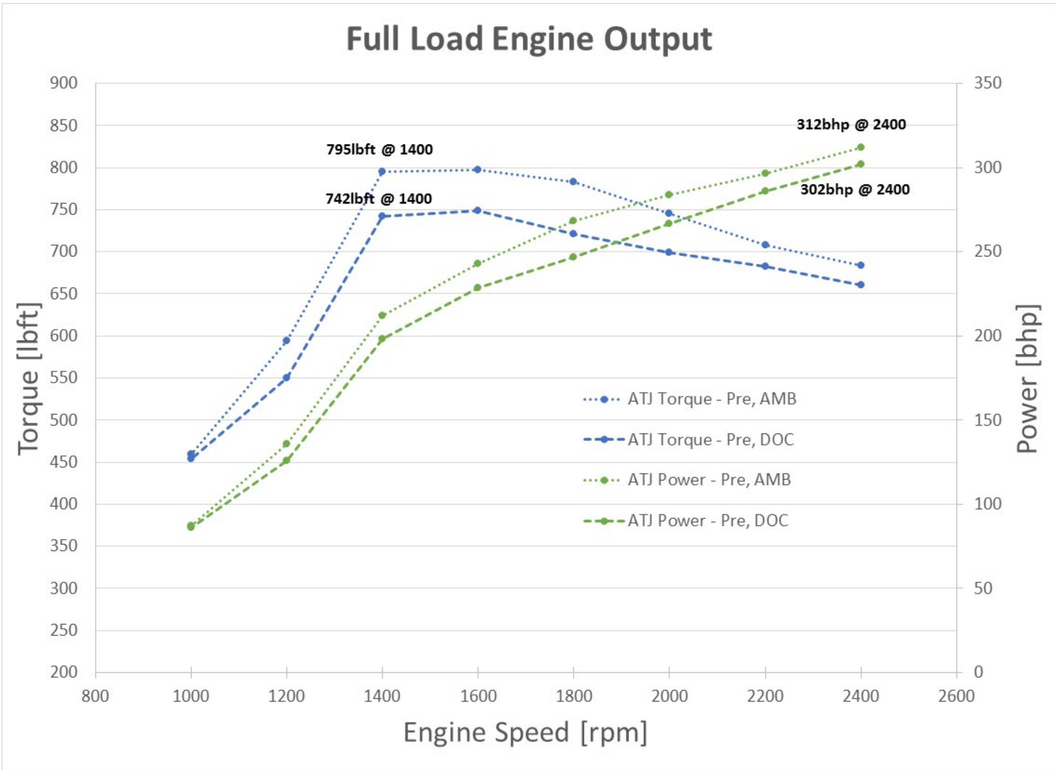


Figure 3. 30% ATJ Blend Pre-Test Output

7.2 PRE-TEST BSFC MAPS

Figure 4 (shown next page) shows the pre-test BSFC fuel maps for the 30% ATJ blend at both ambient and DOC. Overall the C7 engine exhibited slightly less efficient operation at DOC compared to ambient operation. Post-test fuel maps (and their comparison to pre-test maps) is presented later in the report.

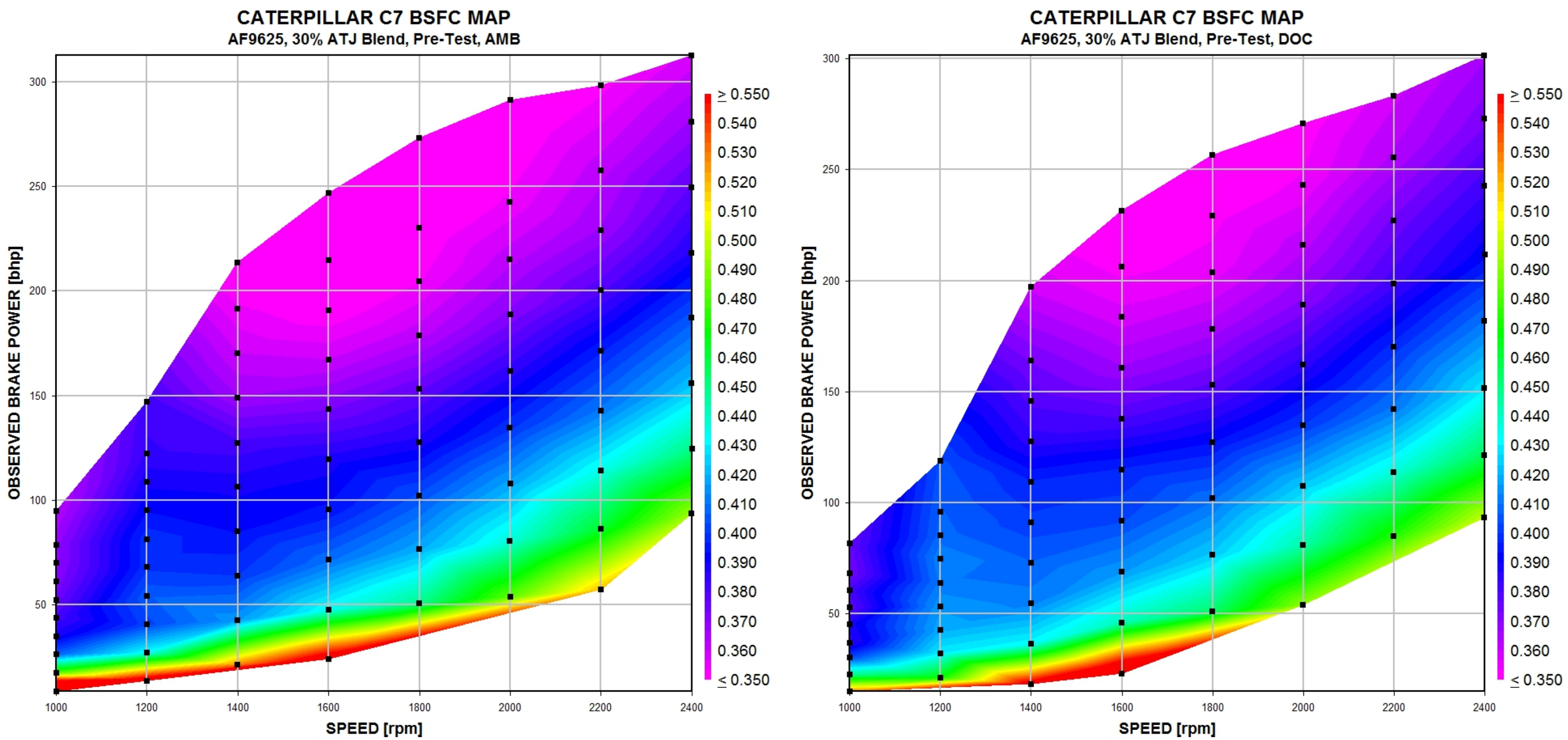


Figure 4. ATJ Blend, BSFC Map, Pre Test, AMB & DOC

7.3 210HR TACTICAL WHEELED VEHICLE CYCLE TEST

The following sections present engine operating summary data for the 30% ATJ blend evaluation over the 210hr 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 6 (shown next page) presents the engine operating condition summary for the 30% ATJ blend over the 210hr test duration. Data from test hours 42 through 75 was excluded from this table, as operation during that time was conducted at lower ambient-like temperatures to troubleshoot observed engine power output. For all remaining test hours, the specified critical DOC control parameters for coolant out, fuel in, intake air, and manifold air temp are shown to be on target. Average power level across the test was 276 bhp, with an average brake specific fuel consumption of 0.371 lb/bhp-hr.

Table 6. 30% ATJ Blend 210hr Test Engine Operating Summary

		Rated Conditions (3400 RPM)				Idle Conditions (900 RPM)			
Perameter:	**Units:**	**Average**	**Std. Dev.**	**Max**	**Min**	**Average**	**Std. Dev.**	**Max**	**Min**
Engine Speed	RPM	2399.96	0.98	2404.00	2397.00	699.40	0.80	707.00	696.00
Torque*	ft*lb	605.12	24.94	682.00	564.00	26.63	0.82	28.00	24.00
Fuel Flow	lb/hr	102.53	3.51	116.09	97.31	3.86	1.79	11.52	2.00
Power*	bhp	276.52	11.39	311.80	257.90	3.54	0.10	3.80	3.30
BSFC*	lb/bhp*hr	0.371	0.003	0.390	0.356	-	-	-	-
Blow-by	acfm	7.38	0.31	8.20	6.10	0.51	0.30	1.50	0.00
Temperatures:									
Coolant In	°F	206.48	0.63	208.50	204.30	178.03	11.93	208.20	155.30
Coolant Out	°F	218.00	0.37	219.30	216.50	181.23	12.25	211.80	158.50
Oil Gallery	°F	239.69	0.61	241.50	235.20	185.37	12.61	216.00	162.30
Oil Sump	°F	251.55	0.89	253.70	244.70	188.09	13.20	219.70	164.30
Fuel In	°F	175.04	0.43	177.80	173.80	159.00	8.98	178.40	136.70
Fuel Out	°F	198.37	0.56	199.90	195.20	128.11	9.03	153.60	106.00
Ambient Air Dry Bulb (Test Cell)	°F	105.85	9.47	121.00	82.20	92.92	6.22	107.00	73.10
Intake Air (before compressor)	°F	120.06	0.63	123.60	116.50	118.91	6.50	134.20	103.00
Intake Air (after compressor)	°F	412.29	4.18	475.00	403.60	122.19	4.85	136.70	111.70
Intake Air (post intercooler)	°F	155.00	0.37	156.70	149.30	99.23	10.06	134.70	78.60
Cylinder 1 Exhaust	°F	974.53	37.68	1081.10	918.50	240.46	16.97	319.80	219.20
Cylinder 2 Exhaust	°F	1123.18	20.71	1203.60	1084.30	275.77	12.58	328.50	256.40
Cylinder 3 Exhaust	°F	1088.62	29.56	1172.50	1015.70	254.81	14.23	319.00	234.80
Cylinder 4 Exhaust	°F	1044.60	27.80	1153.00	1015.70	259.52	10.84	306.70	244.70
Cylinder 5 Exhaust	°F	1054.94	30.17	1160.80	1020.30	257.56	10.16	299.90	242.40
Cylinder 6 Exhaust	°F	1020.27	33.37	1134.00	978.10	246.20	11.00	291.40	227.20
Exhaust Temperature After Turbo	°F	851.85	24.05	934.40	814.60	256.09	15.47	324.30	237.80
Pressures:									
Oil Galley	psiG	47.69	0.60	50.00	46.50	27.10	3.41	35.00	19.40
Fuel Pressure	psiG	67.85	0.46	69.20	66.10	49.15	1.85	53.60	39.80
Ambient Pressure	psiA	14.31	0.08	14.46	14.16	14.31	0.08	14.46	14.16
Intake Pressure Before Turbo	psiA	13.59	0.09	13.77	13.43	14.26	0.08	14.42	14.11
Intake Restriction	psi	0.72	0.03	0.86	0.68	-	-	-	-
Intake Pressure After Turbo	psiG	27.88	0.20	28.21	26.01	0.08	0.03	0.21	0.02
Intake Pressure After Intercooler	psiG	26.99	0.20	27.29	25.20	0.12	0.03	0.23	0.05
Exhaust Manifold Pressure (pre-turbo) Front	psiG	27.09	0.48	30.30	26.20	0.62	0.06	0.80	0.50
Exhaust Manifold Pressure (pre-turbo) Front	psiG	27.30	0.69	31.70	26.40	0.95	0.06	1.10	0.70
Exhaust Back Pressure	psiG	0.25	0.01	0.30	0.11	-	-	-	-
Coolant System	psiG	14.03	1.00	16.20	9.30	5.14	1.96	9.90	1.00

* Non-corrected Values

Note: Data reported excludes data during test hours 42 through 75, which were operated at reduced temperatures to troubleshoot observed power loss

7.3.2 Observed Power Loss, Technical Investigation, & Power Recovery

Over the course of the 210hr test duration, a steady degradation in engine power output was noted during rated speed and load steps. This appeared to be similar in nature to the issue observed in the previous ATJ blend qualification attempt using a different C7 engine [2], but the rate of power loss was much less severe. To diagnose the issue, a Caterpillar Electronic Technician (CAT ET) tool was used to communicate with the engines electronic control module (ECM) to retrieve pending and active fault codes, and review critical engine parameters, but did not report any active fault codes relevant to the observed power loss, and all reported sensor readings were found to be in line with actual measurements being taken by the dyno stands data acquisition system.

Consideration was given to the possibility of the elevated DOC temperatures causing a low level fueling de-rate without triggering a fault code, in which the engine ECU would attempt to try and lower the engine operating temp by reducing fueling. To test this theory, the engines coolant out temperature setpoint was reduced to the more typical ambient operating setpoint of 205 °F for approximately 33 hours starting at the 42hr test point. The fuel temperature and air temperature set points were not reduced, as the ECU does not have direct feedback on those processes, thus couldn't adjust fueling based on their levels. The post intercooler intake manifold air temperature was also not reduced, as it was not considered to be excessive. Over the 33hrs operating at a lower coolant temp, the same power degradation trend in engine power was observed. Since the coolant temperature was not identified as a contributor to the power loss, the testing was returned to the higher 218 °F DOC specification.

Further investigation into the engine controller using the CAT ET tool identified ECU reported parameters for "commanded" and "actual" fueling rates. It was expected that if "actual" fueling matched the "commanded" fuel rate, any problems present in the engine would not be a result of the engine controller or ECU, and be attributed to a mechanical system. These parameters were then routinely monitored to see if they changed along with the observed power loss, or if the reported "actual" fueling rate deviated from the "commanded" rate. Over the remainder of the test no changes in these reported "actual" or "commanded" fueling rate were identified. This means that from the engine/ECU perspective, the engine was consistently fueling at the requested maximum rate for its rated power output. However in actuality, test cell data acquisition measured reducing fuel consumption correlating with the engines power degradation. This implied that the power reduction was a result of some other mechanical influence, or actual wear in the fuel injection system. Since no other causes or faults were identified, testing was continued to complete the scheduled 210hr test duration. Figure 5 (shown next page) shows a plot of engine power, fuel consumption, and measured fuel inlet and coolant out temperatures over the 210hr test duration for the rated speed and load step of the test profile. As shown, the engine power and fuel consumption trended similarly across the test duration. EOT output power reduced to approximately 262hp on the ATJ blend, a 13% loss in output from SOT DOC powercurve.

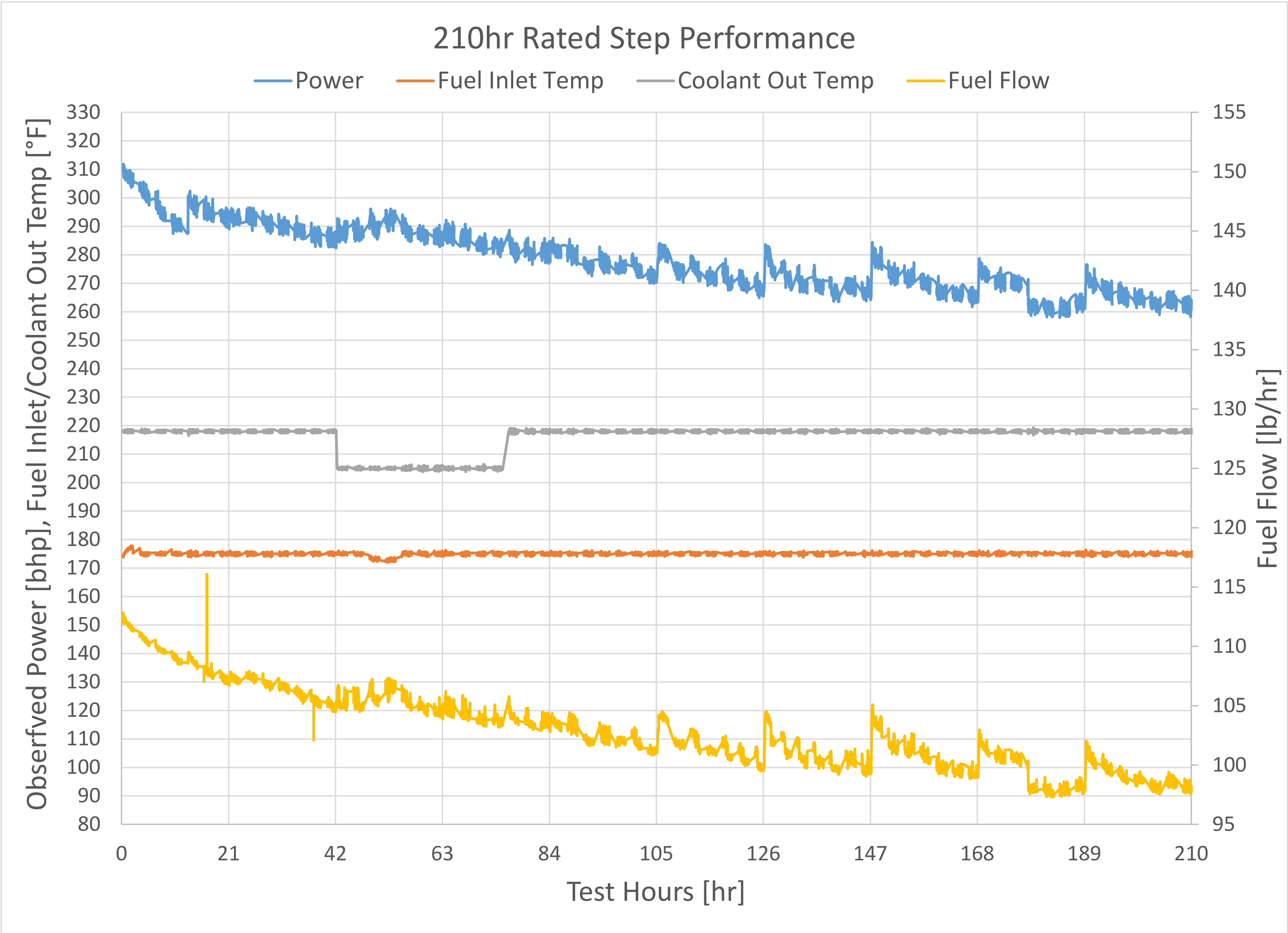


Figure 5. 210hr Test Duration Observed Power Loss

After the 210hr test cycle was completed, post-test powercurves were initiated. The 210hr test duration completed on a Friday evening, and the engine sat shutdown for two days over the weekend prior to starting the first post-test powercurve check. Starting with the ATJ blend, the EOT full load engine power output on the ATJ blend at DOC was completed and observed to recover to approximately 273hp. This was now only a 9.4% loss in output from the SOT DOC curve, as opposed to the 13% loss observed at the end of the 210hr test duration. Some minor power recovery after an engine sits off for an extended amount of time following a long duration test cycle has been noted in the past, and is generally attributed to an absence of heat soak from previous high load test conditions, but the observed recovery for the post-test ATJ curves seemed higher than expected. The following day the engine and test cell fuel lines were flushed to F-24, and upon completion of its curve output power measured at 281hp, only a 6.4% loss from the SOT DOC F24 curve. This caused additional concern in the stability of engine output, as all pre-test powercurves showed the F-24 and ATJ fuel blend producing nearly identical output power levels. Based on this deviation in power between the post-test F-24 and ATJ blend, and the varied engine output recorded with each passing day, further investigation into the cause was conducted.

The HEUI fuel injection system ultimately came under question. Wear of the fuel wetted components in the injector was unlikely, as output power wouldn't improve with time if actual fuel related wear in the injectors was the culprit. However the C7 engine, which uses HEUI, utilizes the engines oil as a hydraulic fluid in the injectors to control and operate the injection system. This makes the fuel system potentially sensitive to engine oil condition. Specifically, this style of fuel system is known to be sensitive to engine oil aeration, as aeration effects the bulk modulus of the oil and its ability to function as a hydraulic fluid. Over the course of the 210hr test, some oil degradation in the MIL-PRF-2104H 15W40 was observed, but oil condition was still considered to be acceptable (though at the end of its useful life). It was theorized that the condition of the used oil, and/or accumulated aeration from the long durations at high engine speed with short engine off soak times could have been a contributor to the changes in engine output. To test this theory, the engine oil was changed to a fresh charge of MIL-PRF-2104H 15W40, and all post-test powercurves were repeated. Immediately the engine power recovered for both the F-24 and ATJ blend fuels, and the two fuels again aligned in output power, consistent with how they behaved during pre-test curves. This confirmed that some aspect of the engines post-test oil condition was driving the observed power loss, and the ATJ fuel blend itself was not the cause of undue or excessive wear of the fuel injection system. Table 7 shows a summary of the engine power output measured during this investigation. All remaining post-test power information in this report represents the recovered power after the oil change was completed.

Table 7. Engine Power Loss Summary

Caterpillar C7 Engine, 2400 RPM, Rated Power [bhp]							
Fuel, Temp Condition	PRE TEST	@End of 210hr duration	*loss*	@Original Post Test Powercurves (no oil change)	*loss*	@Final Post Test Powercuves (post oil change)	*loss*
ULSD, AMB	328.3	-					
F24, AMB	313.1	-		293.2	*6.4%*	303.9	*3.0%*
F24, DOC	300.2	-		281.0	*6.4%*	292.6	*2.5%*
ATJ/F24 Blend, AMB	312.0	-		281.8	*9.7%*	303.5	*2.7%*
ATJ/F24 Blend, DOC	301.8	262.2	*13.1%*	273.3	*9.4%*	292.8	*3.0%*

NOTE: All reported % power loss values are calculated against their respective pre-test power levels at the specified operating conditions (i.e. temperature)

7.3.3 Used Oil Analysis

Used oil samples were collected for analysis over the course of the 210hr test duration to monitor engine and oil condition during the test. A table summarizing this data is shown in Table 8. No oil changes were conducted over the 210hr test duration prior to the EOT oil change that occurred to correct engine power levels. Although near the end of its usable life at the 210hr sample, the used oil still maintained some reserve base number, with no elevation in soot or viscosity, and did not have high accumulations of wear metals suggesting the oil should have been condemned.

Table 8. Used Oil Analysis

Property	ASTM Test	Test Hours										
		0	21	42	63	84	105	126	147	168	189	210
Viscosity @ 100°C (cSt)	D445	15.4	13.4	13.2	13.1	13.0	13.1	13.0	13.1	13.1	13.2	13.2
Total Base Number (mg KOH/g)	D4739	8.9	7.2	6.5	6.2	5.9	5.7	5.1	5.4	4.5	4.5	4.7
Total Acid Number (mg KOH/g)	D664	2.8	2.4	2.6	2.6	2.9	2.8	3.1	2.8	2.9	3.4	3.1
Soot	Soot	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
Wear Metals (ppm)	D5185											
Al		<1	1	1	2	2	2	2	2	2	3	3
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		2	2	1	<1	<1	1	<1	<1	<1	<1	<1
Ca		2468	2469	2504	2499	2524	2544	2570	2577	2580	2573	2564
Cr		<1	<1	1	2	2	3	3	3	4	4	4
Cu		<1	<1	2	2	2	4	5	6	6	7	9
Fe		3	18	30	35	39	46	53	58	60	61	62
Pb		<1	1	<1	1	2	<1	1	<1	2	3	3
Mg		300	299	304	309	314	320	317	324	325	322	323
Mn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Mo		<1	<1	<1	1	<1	<1	<1	<1	<1	<1	<1
Ni		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
P		1284	1260	1238	1222	1228	1215	1191	1180	1169	1160	1154
Si		8	4	4	4	4	5	5	5	5	5	5
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		<5	<5	<5	6	6	5	<5	6	<5	7	14
Sn		<1	<1	<1	<1	<1	<1	1	2	2	2	2
Zn		1438	1432	1430	1431	1428	1442	1441	1455	1458	1463	1453
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

7.3.4 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 9. The total engine oil consumption rate over the 210hr test was calculated as 0.086 lb/hr.

Table 9. C7 ATJ Evaluation Oil Consumption

Test Engine Lubricant Additions, Subtractions, and Consumption

Lubricant: LO319411, MIL-PRF-2104J 15W40 — Project No. 22375.01.201

Initial Fill: (engine test)

	Tech	Lubricant + Container Weight, lbs	-	Container Weight,lbs	=	Lubricant Weight, lbs
	MG	unspecified	-	unspecified	=	35.51
filter (wet/dry)			-		=	3.62
				Total Initial Fill	=	39.13

Samples:

	Date	Tech	Sample + Container Weight, lbs	-	Container Weight,lbs	=	Sample Weight, lbs
0	1/30/17	KE	0.31	-	0.05	=	0.26
21	1/31/17	CV	0.30	-	0.06	=	0.24
42	2/1/17	DV	0.30	-	0.06	=	0.24
63	2/2/17	DV	0.31	-	0.06	=	0.25
84	2/3/17	DV	0.31	-	0.06	=	0.25
105	2/4/17	REG	0.29	-	0.05	=	0.24
126	2/5/17	REG	0.32	-	0.06	=	0.26
147	2/6/17	CV	0.29	-	0.06	=	0.23
168	2/7/17	CV	0.30	-	0.06	=	0.24
189	2/8/17	CV	0.31	-	0.06	=	0.25
210	2/9/17	CV	0.3	-	0.06	=	0.24
					Total Samples	=	2.7

Additions:

	Date	Tech	Addition + Container Weight, lbs	-	Container Weight,lbs	=	Addition Weight, lbs
21	1/31/17	CV	0.00	-	0.00	=	
42	2/1/17	CV	4.40	-	2.85	=	1.55
63	2/2/17	CV	4.97	-	2.49	=	2.48
84	2/3/17	CV	5.25	-	3.67	=	1.58
105	2/4/17	REG	3.67	-	2.59	=	1.08
126	2/5/17	REG	2.59	-	1.59	=	1.00
147	2/6/17	CV	5.11	-	2.95	=	2.16
168	2/7/17	CV	5.68	-	2.98	=	2.70
189	2/8/17	CV	5.17	-	2.69	=	2.48
210	2/9/17	CV	3.18	-	1.01	=	2.17
					Total Additions	=	17.20

210-Hour Drain:*

	Tech	Lubricant + Container Weight, lbs	-	Container Weight,lbs	=	Lubricant Weight, lbs
	KE	37.44	-	2.72	=	34.72
filter (wet/dry)		3	-	2.13	=	0.87
				Total 210-Hour Drain	=	35.59

Total Initial Fill	39.13	[lbs]
Total Additions	17.20	[lbs]
Total Samples	2.7	[lbs]
Total 210-Hour Drain	35.59	[lbs]
Total 210-Hour OIL CONSUMPTION	18.04	[lbs]
Oil Consumption Rate (Oil Consumption/Test Hours)	0.086	[lbs/hr]

7.3.5 Post Test Power Curves

As previously discussed, all post-test powercurves reported below represent engine power output AFTER the oil charge had been changed in the engine. Figure 6 and Figure 7 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 3.0% for the ambient curve, and 2.5% for the DOC curve over the 210hr test duration.

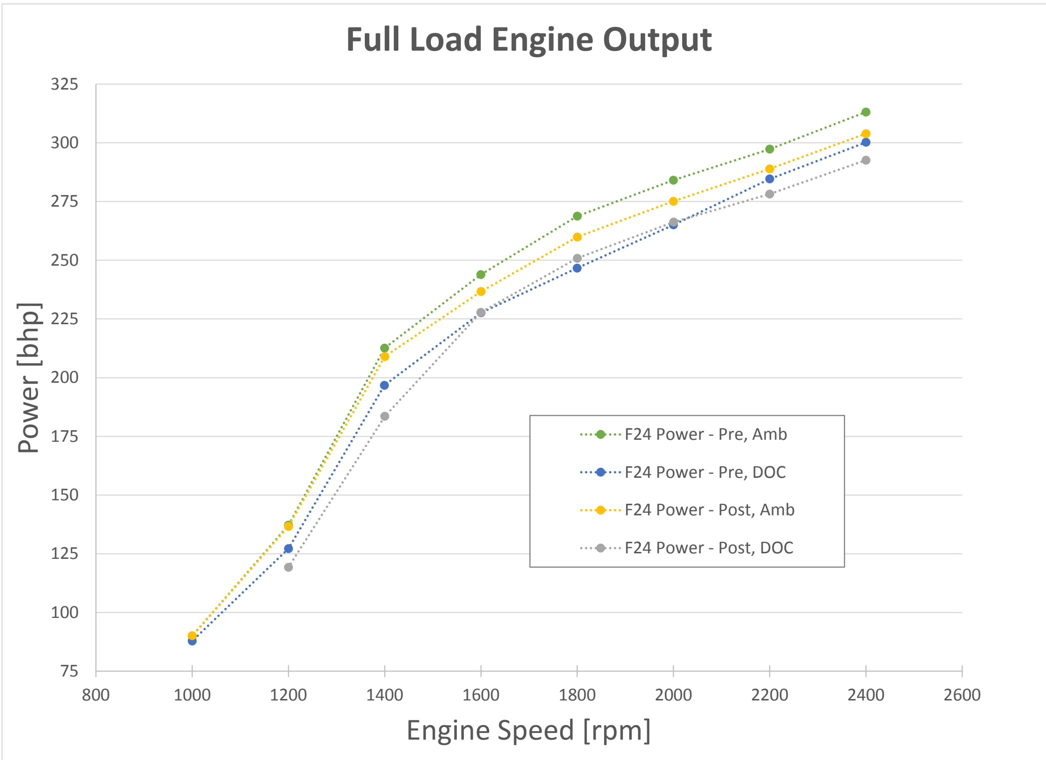


Figure 6. F-24, Pre to Post Power Output, AMB & DOC

For the full load torque curve, the peak torque for the post-test DOC curve occurred slightly later in engine speed then the other curves. The operating area near 1400rpm has been observed to be a switching point for the engines ECU engine control strategy, and changes in fuel rate and boost levels effect overall output power. For the post-test DOC curve, this mode switching occurred slightly after 1400rpm test point, causing the next measured 1600rpm point to yield actual peak engine torque as opposed to the other curves conducted. The exact conditions that dictate the ECU's mode changes are unknown, but this phenomenon has been observed in the C7 engine in other testing. It is expected that if the engine speed target for the post-test DOC curve would have been slightly above 1400rpm, the overall torque curve would look much more similar to the pre-test curve.

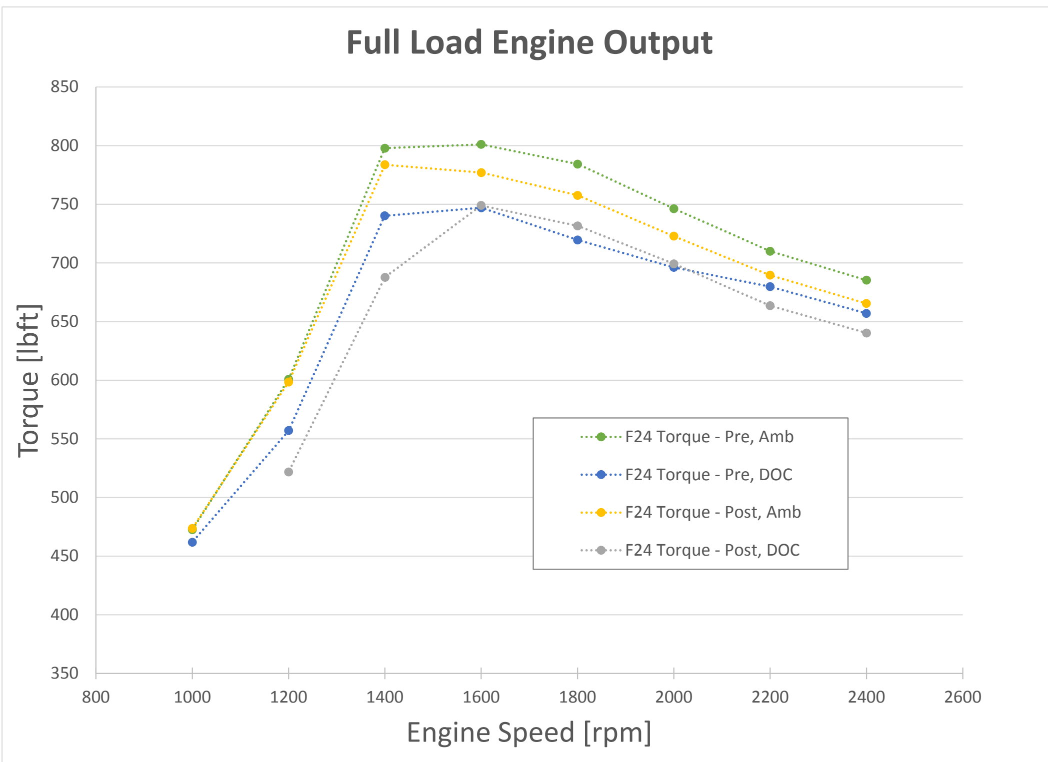


Figure 7. F-24, Pre to Post Torque Output, AMB & DOC

Figure 8 and Figure 9 show the pre and post-test engine power output and torque for the ATJ blend at ambient and DOC. Similar to the F-24 losses, peak engine power output loss for the ATJ blend was measured at 2.7% for the ambient curve, and 3% for the DOC curve over the 210hr test duration.

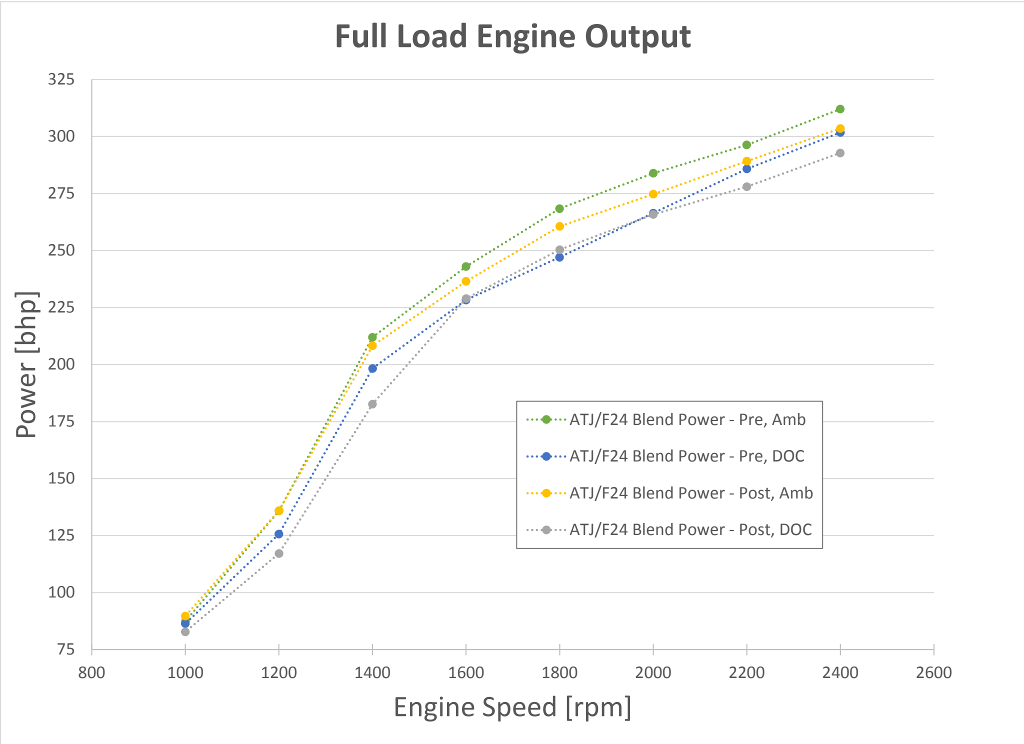


Figure 8. ATJ Blend, Pre to Post Power Output, AMB & DOC

Identical to the F24 post-test DOC curve, the peak torque for the post-test DOC curve on the ATJ blend occurred slightly later in engine speed. As expected, the ATJ blend trended in line with the powercurves completed with F-24.

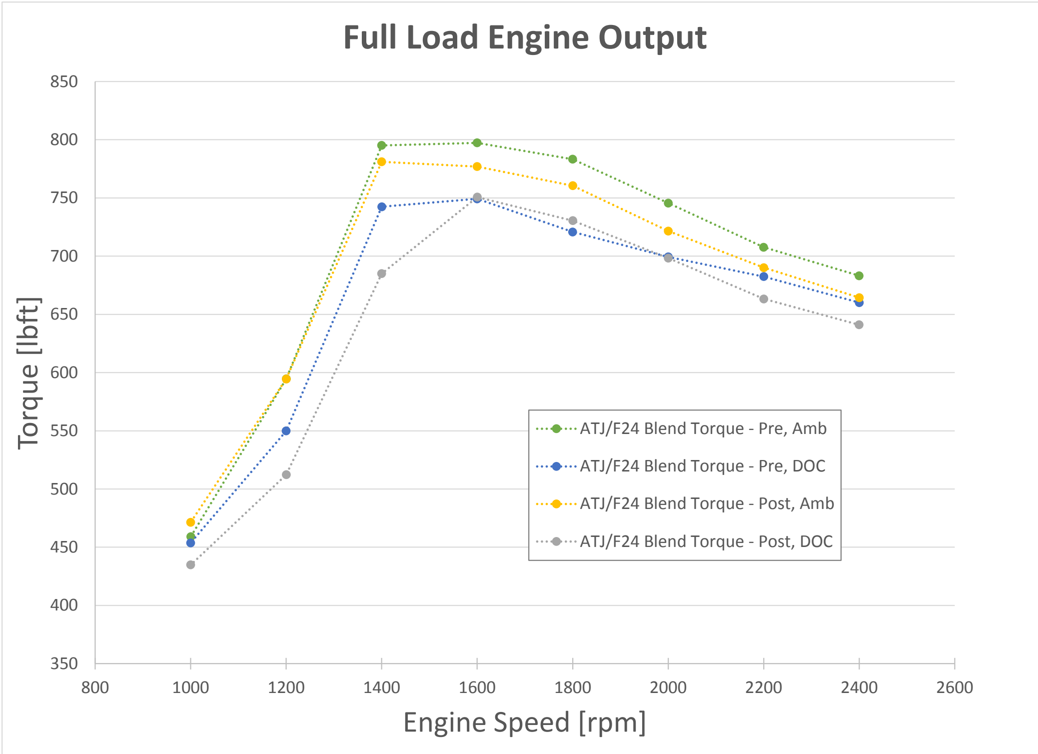


Figure 9. ATJ Blend, Pre to Post Torque Output, AMB & DOC

7.3.6 Pre & Post Test Injector and Engine Photos

Figure 10 through Figure 15 show the pre and post-test injector tip photos for all six fuel injectors, Figure 16 shows the pre and post-test photos of the fire deck, and Figure 17 shows the pre and post-test piston crown/combustion chamber photos. Overall deposit levels for all components appeared to be typical in nature. Without baseline test data using diesel or F-24 for comparison, no further detailed analysis is possible.

Cylinder 1 – Pre Test	Cylinder 1 – Post Test

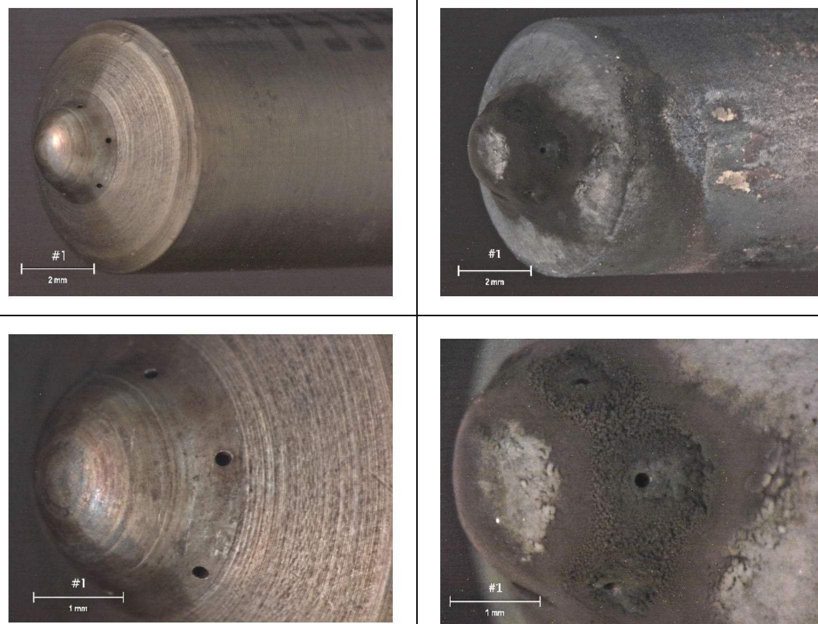


Figure 10. Injector Tip – Cylinder 1

Cylinder 2 – Pre Test	Cylinder 2 – Post Test

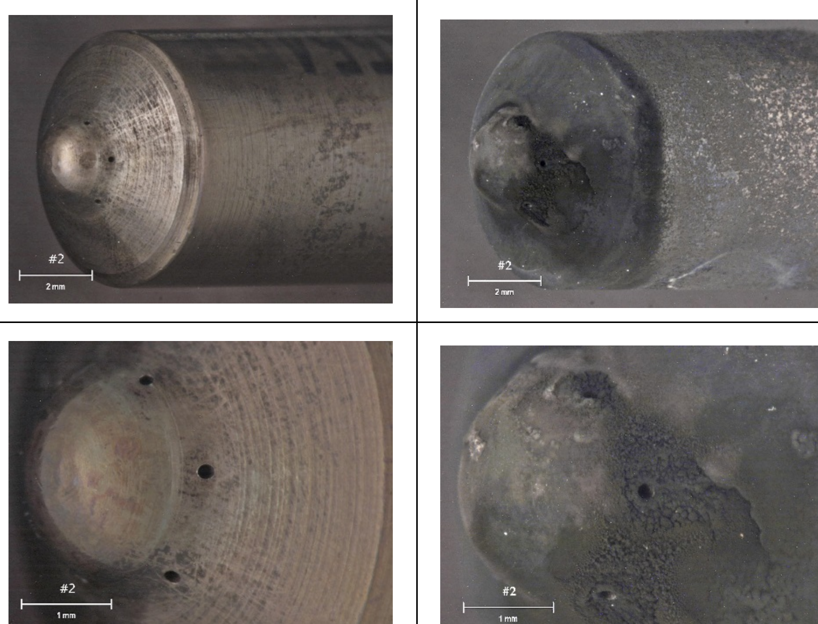


Figure 11. Injector Tip – Cylinder 2

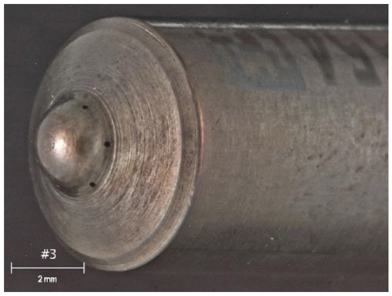
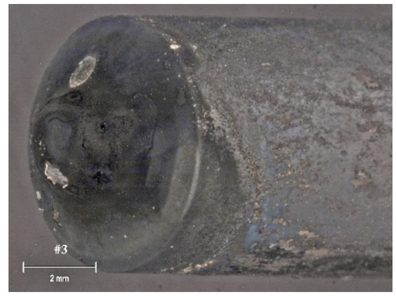
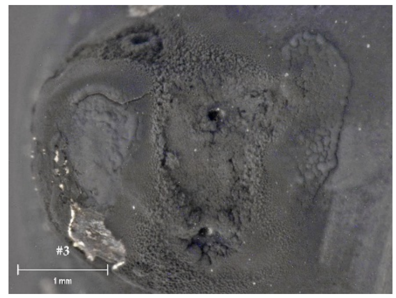
Cylinder 3 – Pre Test	Cylinder 3 – Post Test
	
	

Figure 12. Injector Tip – Cylinder 3

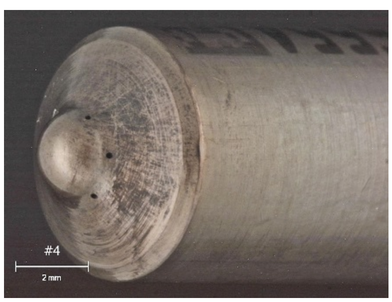
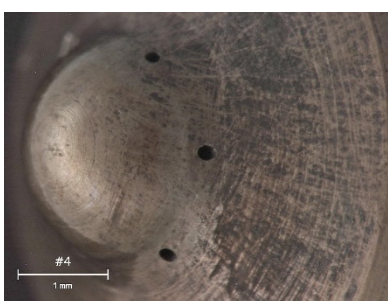
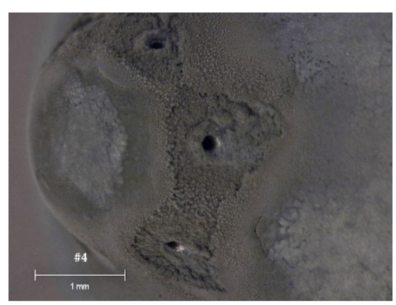
Cylinder 4 – Pre Test	Cylinder 4 – Post Test
	
	

Figure 13. Injector Tip – Cylinder 4

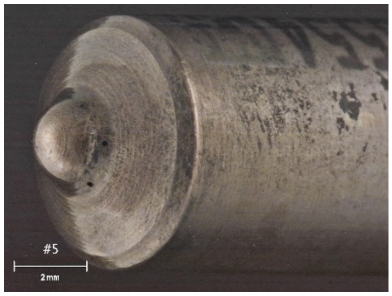
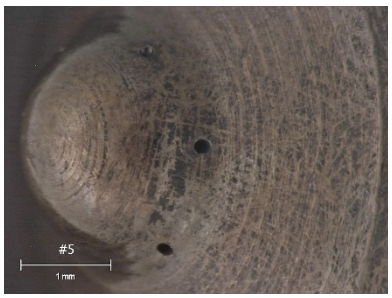
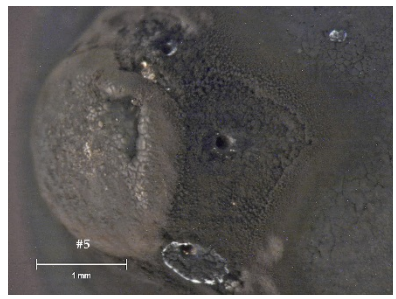
Cylinder 5 – Pre Test	Cylinder 5 – Post Test
	
	

Figure 14. Injector Tip – Cylinder 5

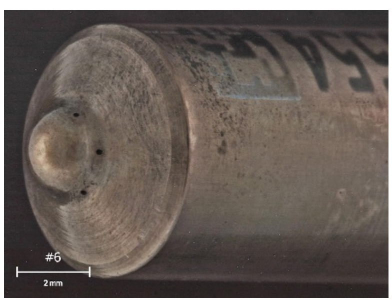
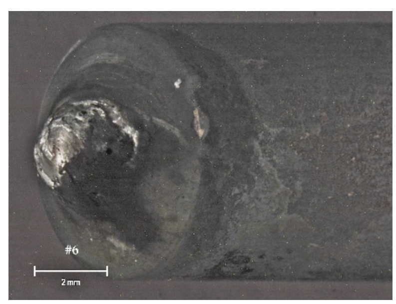
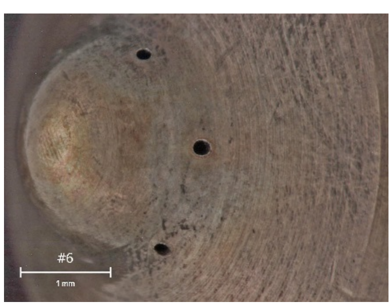
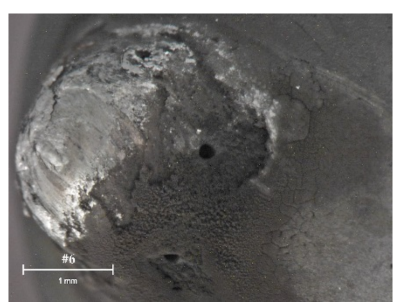
Cylinder 6 – Pre Test	Cylinder 6 – Post Test
	
	

Figure 15. Injector Tip – Cylinder 6

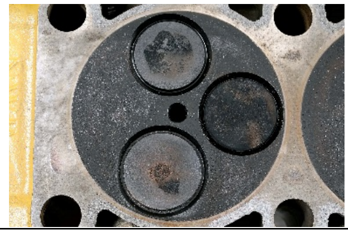
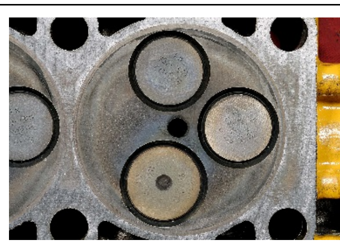
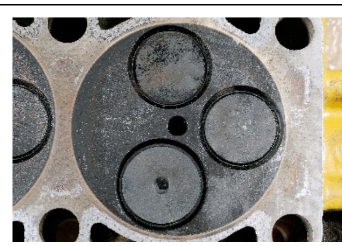
Location	Pre Test	Post Test
CYL 1		
CYL 2		
CYL 3		
CYL 4		
CYL 5		
CYL 6		

Figure 16. Fire Deck – ALL

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

Figure 17. Piston Crown – ALL

7.3.7 Gaseous Exhaust Emissions

Emissions sampling was conducted during the pre and post-test ATJ blend and F-24 powercurves. Due to inoperability of TFLRF's normal Horiba engine exhaust gas analyzer equipment, emissions sampling was attempted through FTIR spectral analysis of the engines exhaust gases during the powercurves. Data was collected for each of the powercurves conducted, but upon post-test analysis, overall trends and measurements exhibited some unexplained phenomenon, and ultimately the results were called into question. Due to lack of confidence in the collected data, emissions results are not included in this report and considered incomplete for this evaluation.

7.4 PRE & POST-TEST BSFC MAPS

Post-test BSFC fuel maps for the ATJ blend were conducted to compare to pre-test maps and document change in engine efficiency. For both the ambient and DOC fuel maps (shown Figure 18 and Figure 19), some minor decreases were observed in BSFC between pre-test and post-test maps. This demonstrates a slight reduction in efficiency of the engine, and coincides with the actual engine output power loss observed across the test duration.

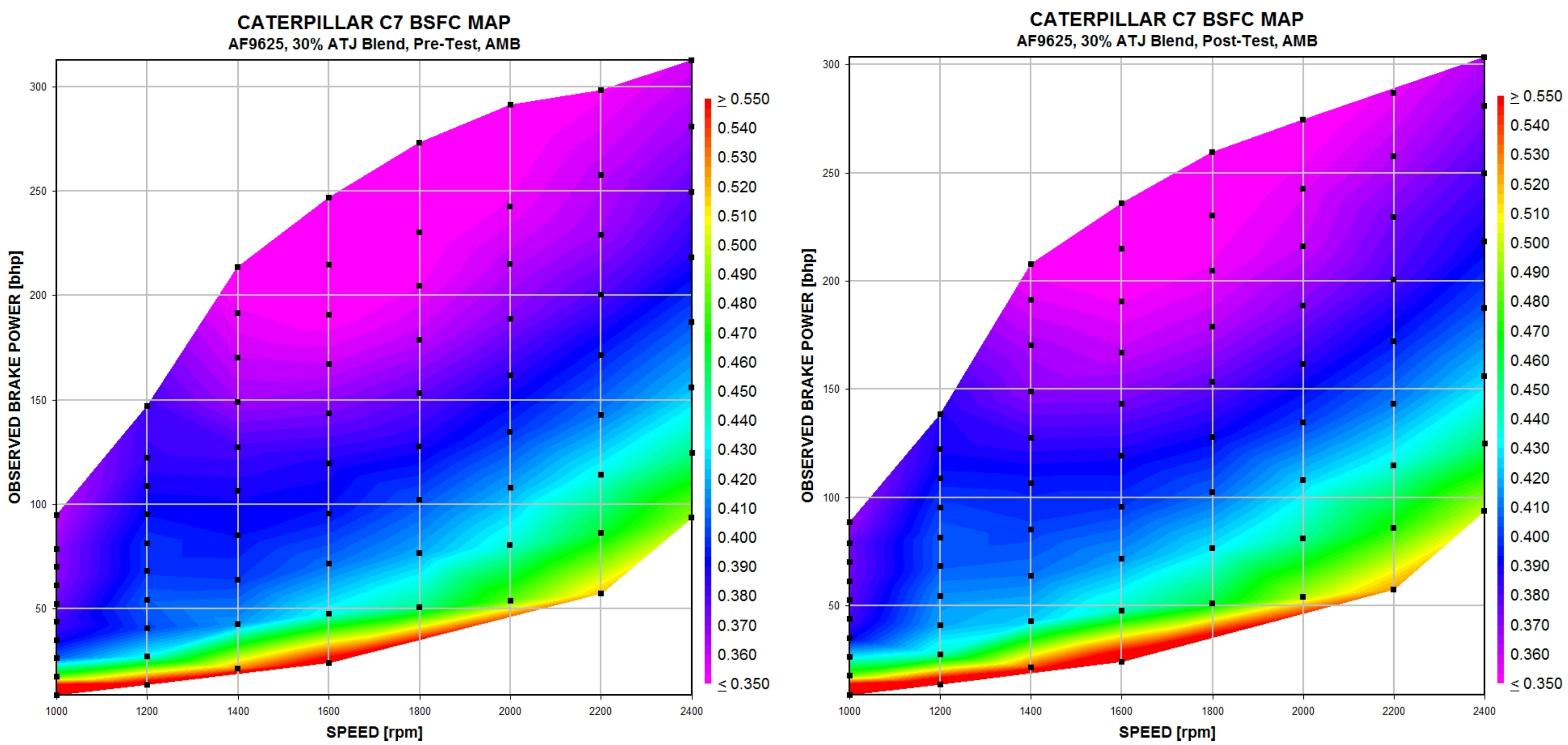


Figure 18. ATJ Blend, BSFC Map, AMB, Pre to Post Test

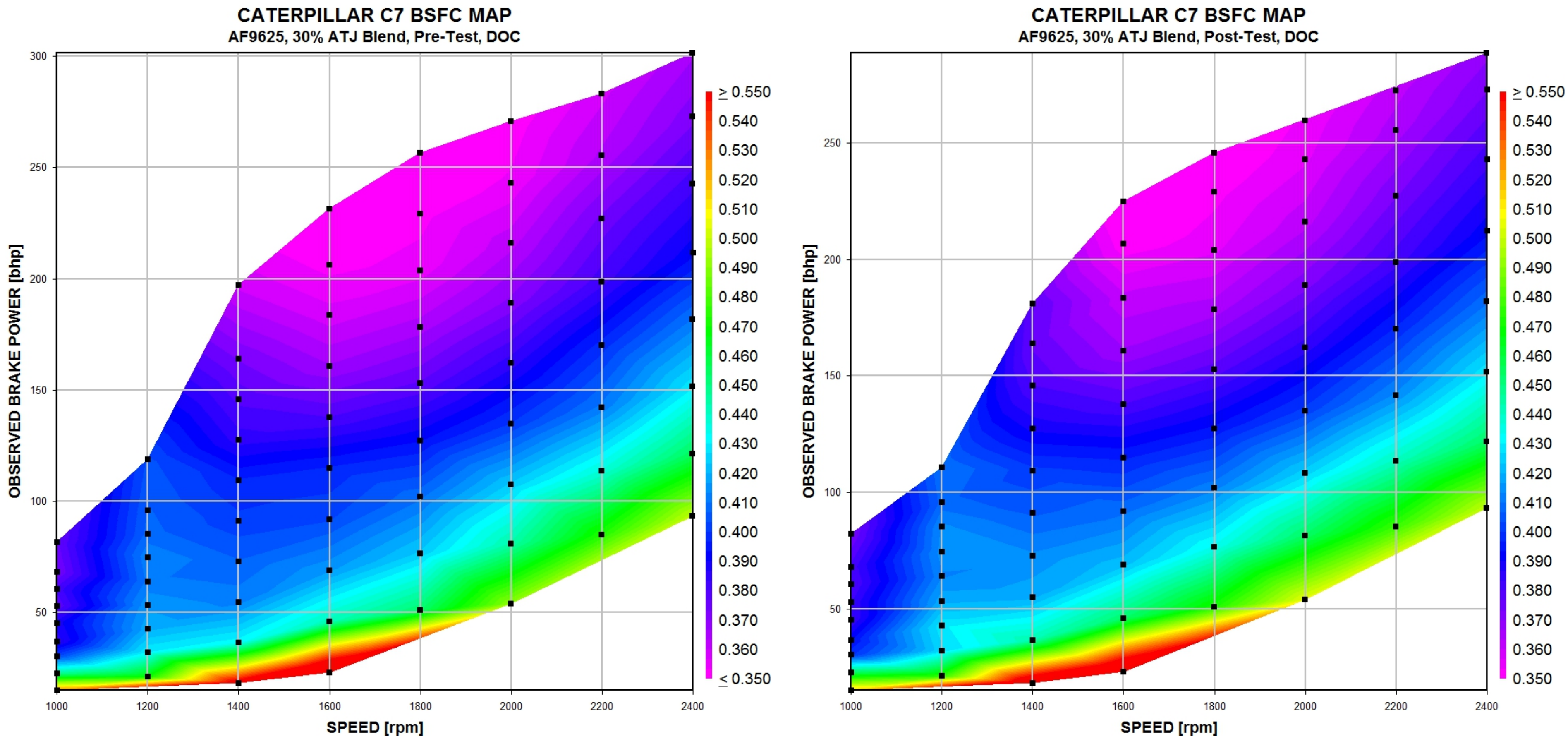


Figure 19. ATJ Blend, BSFC Map, DOC, Pre to Post Test

7.5 POST TEST FUEL INJECTOR FLOW MEASUREMENTS

To determine changes in injector performance as a result of the ATJ blend testing, the C7 injectors were returned to Caterpillar for flow checks. This allowed current end of test condition to be compared back to end of line data created for each injector at the completion of manufacturing. It was recommended by personnel at Caterpillar to use the ETrim test points to compare the injectors. The ETrim points are those used to develop the injector TRIM codes, which are used by the engines ECU to fine tune the electronic control of the injector to achieve desired performance and emissions characteristics. All data provided by Caterpillar for the ETrim points is shown in Table 10. The delivery values shown in the table are expressed as cc/1000 strokes, but the timing value units are uncertain. When closely reviewing the data, some instances of increased and decreased fuel delivery and timing are noted across all of the injectors. Small changes in injector flow characteristics is often typical in diesel injectors after being in service. According to the data provided by Caterpillar, the only faults identified in the ETrim test points were noted as:

- Serial 3B118933442F, CYL 4 – ET6, main delivery high
- Serial 3B118932504D, CYL 5 – ET4, main delivery and timing standard deviation high

It is unknown how these two faults would ultimately effect affect real world operation, or how they might compare to typical injector changes expected after being in service. Considering all other injectors showed acceptable performance and no fault identification, and no discernable engine performance variations as a result of the fuel system were noted during the post-test engine dyno tests, it is not expected that the use of the ATJ blend is problematic in this type injector. Considering all results gathered, the condition of the engine oil appears to be a much larger influence injector function than any impact from the ATJ blend.

Table 10. ATJ Post Test HEUI Injector Flow Checks

	SERIAL	LOC	ET POINT 1 MAIN DELIVERY	ET POINT 1 MAIN TIMING	ET POINT 2 MAIN DELIVERY	ET POINT 2 MAIN TIMING	ET POINT 3 PILOT DELIVERY	ET POINT 3 PILOT TIMING	ET POINT 3 MAIN DELIVERY	ET POINT 3 MAIN TIMING	ET POINT 4 PILOT DELIVERY	ET POINT 4 PILOT TIMING	ET POINT 4 MAIN DELIVERY	ET POINT 4 MAIN TIMING
POST TEST	3B1189326569	1	34.69	1.40	27.69	0.64	12.62	1.16	143.75	1.31	14.71	1.17	97.96	0.69
	3B118932627C	2	33.74	1.48	27.68	0.66	12.90	1.16	137.80	1.32	14.60	1.18	91.19	0.73
	3B1189333256	3	32.83	1.45	24.91	0.65	11.51	1.16	129.46	1.33	13.80	1.15	86.68	0.72
	3B118933442F	4	34.27	1.48	28.53	0.62	11.73	1.18	140.66	1.36	14.22	1.19	89.09	0.81
	3B118932504D	5	35.29	1.42	28.57	0.60	12.19	1.16	139.73	1.33	15.09	1.17	89.35	0.79
	3B1189327067	6	34.28	1.49	27.13	0.68	10.86	1.21	134.79	1.41	14.49	1.21	90.84	0.76
END OF LINE	3B1189326569	1	32.33	1.55	27.26	0.67	12.21	1.22	140.64	1.42	14.92	1.22	90.00	0.85
	3B118932627C	2	30.95	1.53	24.37	0.73	11.96	1.25	136.89	1.41	14.61	1.26	92.55	0.77
	3B1189333256	3	33.63	1.49	27.65	0.66	12.52	1.24	138.47	1.42	15.48	1.24	94.10	0.74
	3B118933442F	4	32.44	1.56	27.06	0.65	12.79	1.22	139.83	1.40	15.82	1.22	95.18	0.73
	3B118932504D	5	31.88	1.53	25.87	0.72	11.77	1.23	134.94	1.44	15.30	1.22	91.59	0.78
	3B1189327067	6	31.99	1.57	26.02	0.70	11.86	1.23	135.24	1.42	15.01	1.25	92.09	0.77

	SERIAL	LOC	ET POINT 5 MAIN DELIVERY	ET POINT 5 MAIN TIMING	ET POINT 6 PILOT DELIVERY	ET POINT 6 PILOT TIMING	ET POINT 6 MAIN DELIVERY	ET POINT 6 MAIN TIMING
POST TEST	3B1189326569	1	125.90	0.75	15.91	1.00	95.59	0.65
	3B118932627C	2	121.50	0.77	15.28	1.02	89.50	0.71
	3B1189333256	3	116.29	0.71	14.61	0.99	95.99	0.54
	3B118933442F	4	133.21	0.69	14.54	1.02	110.43	0.56
	3B118932504D	5	127.54	0.68	14.69	1.02	104.62	0.58
	3B1189327067	6	118.82	0.78	13.37	1.06	89.38	0.70
END OF LINE	3B1189326569	1	134.05	0.70	16.37	1.06	100.80	0.62
	3B118932627C	2	120.12	0.88	15.82	1.10	91.81	0.72
	3B1189333256	3	123.86	0.82	16.80	1.07	83.47	0.79
	3B118933442F	4	125.30	0.82	17.00	1.05	89.75	0.73
	3B118932504D	5	122.23	0.81	16.34	1.06	93.51	0.67
	3B1189327067	6	120.81	0.85	15.54	1.08	90.39	0.72

7.6 POST TEST FUEL INJECTOR TEARDOWN

After the flow checks the injectors were returned to TFLRF where they were disassembled for internal inspection. A new unused injector was also disassembled to provide a point of comparison of internal condition. Figure 20 shows the post-test ATJ blend CYL#1 injector, with the lower outer housing separated to access the barrel assembly (which contains the fuel wetted section of the injector).

Figure 20. Caterpillar C7 HEUI Injector – Barrel Assembly Removal

Figure 21 (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, while everything below is fuel wetted.

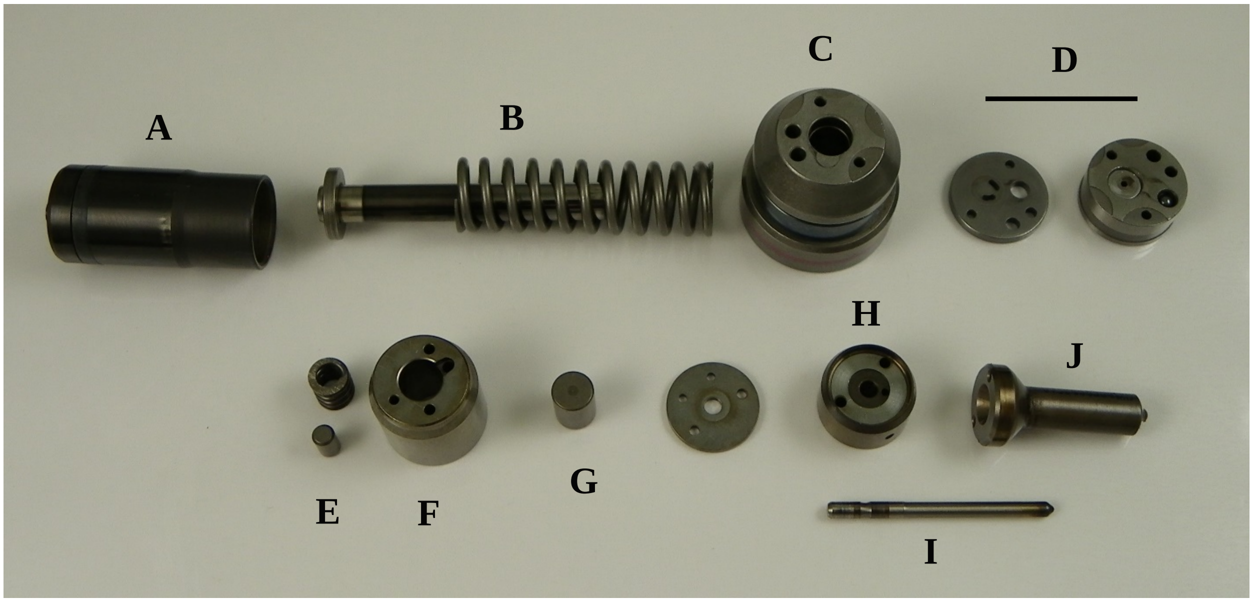


Figure 21. C7 HEUI Injector Barrel Assembly Exploded View

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) pressuring 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 needles 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.

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 in nature of a used injector. As previously discussed, none of the injectors exhibited any operational problems during the ATJ blend test that would indicate a failure of internal components. However, since there are no baseline F24 injectors to compare against, there is no definitive way to establish if wear observed would be considered out of line or excessive compared to diesel or other standard military fuels. All of the following photos below show internal components from CYL#1 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 22). 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 to be typical. No scoring or material transfer was noted. Any physical damage to this component would be expected to cause immediate injector malfunction.

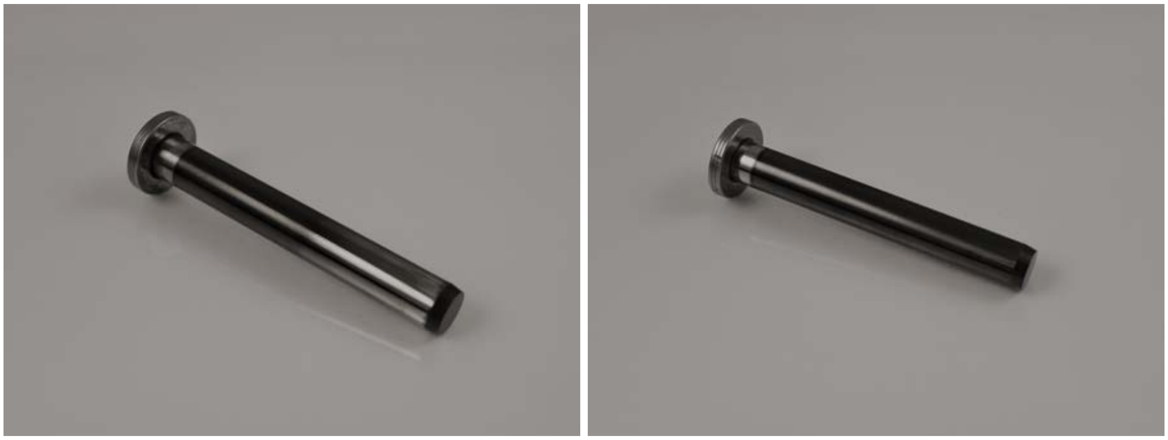


Figure 22. C7 HEUI Injector Plunger (CYL#1 shown left, NEW shown right)

The stop plate (or check plate) 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 could potentially hinder the ability of the plate to move freely effecting injector performance/fuel metering.

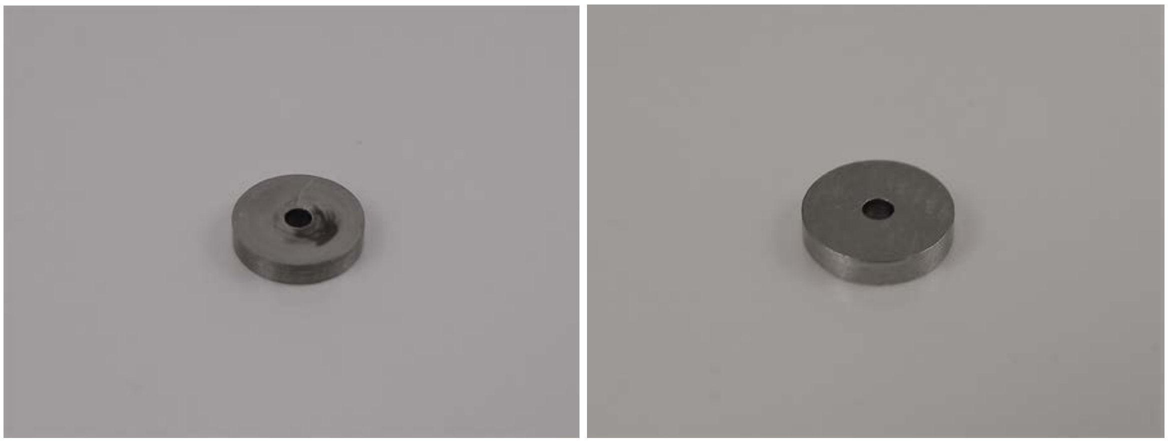


Figure 23. C7 HEUI Injector Stop Plate (CYL#1 shown left, NEW shown right)

The needle lift spacer (Figure 24) 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 reduce resulting in decreased opening pressure of the injector changing its fuel delivery characteristics. Although visible, actual wear at this interface was limited.

Figure 24. C7 HEUI Injector Lift Spacer (CYL#1 shown left, NEW shown right)

Lastly the injector needle itself (Figure 25), which moves up and down during injection in the nozzle housing and guide housing, tended to show some 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.

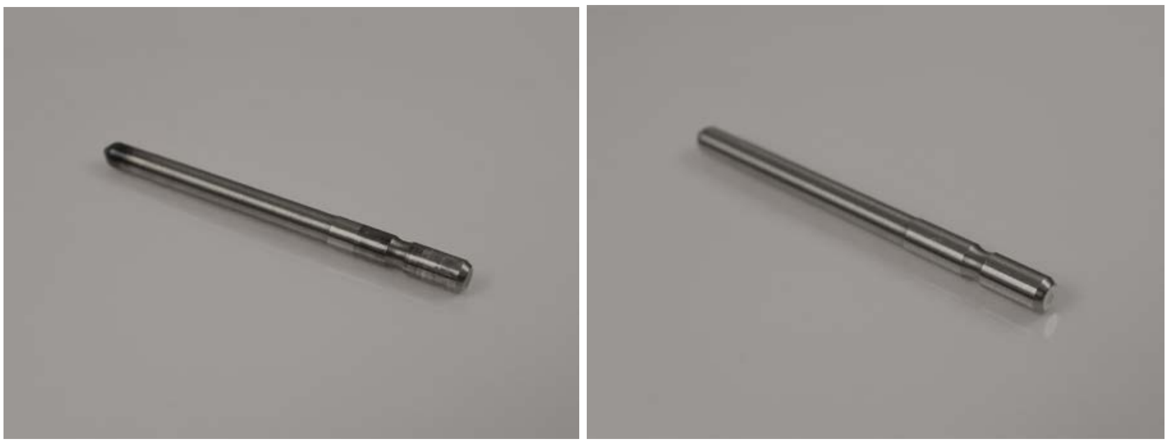


Figure 25. C7 HEUI Injector Needle (CYL#1 shown left, NEW shown right)

Overall no major concerns were noted during the internal inspection of the fuel injectors. Without a baseline F24 test to compare against, definitive analysis of condition cannot be made. However, based on the engine performance and the observed condition of internal components, there does not appear to be a major concern of injector compatibility from the use of ATJ blend fuel.

8.0 CONCLUSIONS

All test results collected support the use of 30% ATJ blend fuel in the C7 engine. Once the cause of the engine power output loss during the 210hrs was attributed to engine oil condition and corrected, post-test measurement of engine performance showed little degradation (less than 5%) from the pre-test condition as a result of the 210hr operation on the ATJ blend. Engine output power level was essentially identical between the F24 and ATJ fuel blend at both pre and post-test evaluations, suggesting that the ATJ blend can be used as a drop in replacement for the F24 fuel, while delivering nearly identical power levels. Post-test fuel injector flow ratings and 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 RECOMENDATIONS

It is recommended that a similar F24 test be conducted 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-2104H 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

APPENDIX A.

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 2

Plunger - Injector 3

Plunger - Injector 4

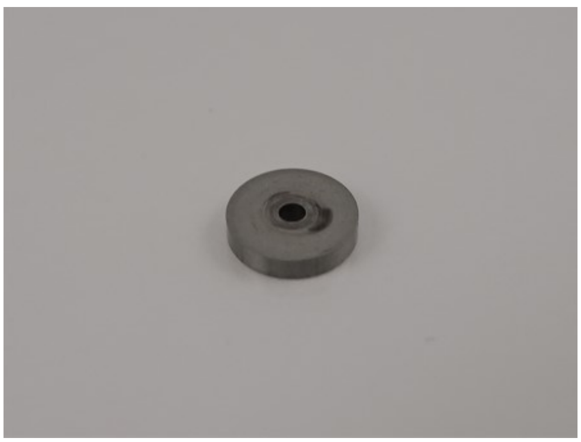
Plunger - Injector 5

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 2

Needle Spacer - Injector 3

Needle Spacer - Injector 4

Needle Spacer - Injector 5

Needle Spacer - Injector 6

Needle - Injector 1

Needle - Injector 4

Needle - Injector 2

Needle - Injector 5

Needle - Injector 3

Needle - Injector 6