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RAPID RESPONSE RESEARCH AND DEVELOPMENT (R&D) FOR THE AEROSPACE SYSTEMS DIRECTORATE

Delivery Order 0021: Engineering Research and Technical Analyses of Advanced Airbreathing Propulsion Fuels

Subtask: Engine and Pump Studies Utilizing JP-8 and Alcohol-to-Jet (ATJ) Blends

Douglas M. Yost, Adam C. Brandt, and Gregory A.T. Hansen

Southwest Research Institute (SwRI®)

AUGUST 2014
Interim Report

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14. ABSTRACT

This report contains the results of engine and pump studies carried out on Alcohol-to-Jet (ATJ) and JP-8 blends. Performance and endurance testing was performed using a Ford 6.7L high pressure common rail (HPCR) diesel engine. Wear testing was performed on rotary fuel injection pumps at various temperatures. A cetane sensitivity study was performed on the Ford 6.7L engine using fuels having cetane values between 30 and 51. A cold temperature study with high and low cetane fuels was also performed on a GEP 6.5L Turbo Diesel Engine.

15. SUBJECT TERMS

alternative fuels, pump, engine, HPCR, ATJ, cetane, JP-8

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Preface

This report was prepared for the Universal Technology Corporation (UTC), 1270 North Fairfield Road, Dayton, Ohio, 45432-2600 under Sub Contract Number 12-S590-0021-02-C1 (Contract Number FA8650-08-D-2806 Task Order 0021, SwRI task numbers 4, 5, and 6a) for the Air Force Research Laboratory's Fuels & Energy Branch (AFRL/RQTF). Ms. Michele Puterbaugh (UTC) was the Task Order Program Manager for this effort. Ms. Amanda Welch (UTC) was the Task Order Assistant Program Manager for this effort. Mr. James Klein, (Subcontractor, Klein Consulting LLC), was the technical leader in support of Dr. James T. Edwards, Government Task Order Program Manager and Technical Point of Contact, of the Energy & Fuels Branch (AFRL/RQTF), Turbine Engine Division, Aerospace Systems Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio. The research reported herein was performed by Southwest Research Institute, 6220 Culebra Road, San Antonio, TX and covers the period of 06 December 2011 – 22 July 2014. This effort was funded by the Air Force Research Laboratory.

1.0 Executive Summary

An Alcohol-to-Jet (ATJ) fuel produced by the GEVO Inc. was purchased by the USAF. GEVO ATJ and GEVO ATJ/JP-8 Fit-for-purpose (FFP) testing is reported in AFRL-RQ-WP-TM-2013-0010, Appendix E. Upon completion of the FFP testing, the USAF desired to further study the effect this fuel blend would have on ground vehicle engines and support equipment.

The overall aim of this program was to provide subject matter expertise and technical and engineering services to UTC/AFRL in support of the evaluation of this ATJ fuel. Tasks included diesel engine and pump testing and evaluation of Alcohol-to-Jet (ATJ) fuel blends. The planned evaluations of ATJ fuel blends were successfully accomplished. Based on the elastomer evaluations, the neat (100%) ATJ fuel is not recommended for use. Blends up to 50% volume do show acceptable elastomer compatibility.

A summary of each task is provided below.

2.0 Introduction

2.1 Task Order Reports

This final report contains a compilation of results for selected tasks under Contract Number FA-8650-08-D-2806 Task Order 0021 in partial fulfillment of UTC Subcontract Number 12-S590-0021-02-C1.

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3.0 Report Contents

The following tasks are documented in full standalone reports included as appendices below:

3.1 Evaluation of an ATJ/JP-8 Fuel Blend in the Ford 6.7L High Pressure Common Rail Diesel Engine

Commercial Off-The-Shelf (COTS) diesel engines are available to the U.S. Military that employ High Pressure Common Rail (HPCR) fuel injection systems. Overall performance and endurance of these HPCR systems has the potential to vary with use of military or alternative fuels due to critical chemical and physical property differences compared to standard diesel fuels. Of the critical property differences of military fuels, changes in fuel viscosity and lubricity are of particular interest. Many modern HPCR systems utilize fuel lubricated high pressure pumps, and can generate upwards of 2000-bar fuel rail pressures placing large demands on the fuel to adequately lubricate and protect internal components.

To understand critical fuel related impacts, performance and endurance testing was conducted using a fired engine equipped with a modern fuel lubricated HPCR fuel system using an ATJ/JP-8 blend at nominal fuel inlet temperatures (34°C, system temperature) treated with 14-ppm of a QPL-25017 additive. Testing was completed using a Ford 6.7L V8 turbocharged diesel engine. The engine used was tested in its "export" configuration, which does not utilize Exhaust Gas Recirculation (EGR) or exhaust after treatment systems. Testing was completed following a modified version of the U.S. Army 210-hr Tactical Wheeled Vehicle Cycle (TWVC).

At the completion of testing, the fuel injection pump and injectors were removed and disassembled for inspection and comparison. Component inspections for the ATJ/JP-8 test were compared to component conditions from previous work performed for the US Army and US Air Force. [1, 2, 3] Engine power curves and emissions were taken at the start and end of testing, and used to document any engine performance degradation incurred over the test duration.

The engine fueled with ATJ/JP-8 was successfully operated over the entire test duration without experiencing any unusual fuel related operational conditions or hardware failures. At the tested lubricity enhancing treat rate, the ATJ/JP-8 fuel provided adequate component protection and system performance. Post-test fuel injection system inspection found tested components to be in similar condition compared to all previously fuels tested. Results from testing support the durability of the fuel lubricated HPCR fuel system utilized on the Ford 6.7L with a military specified ATJ/JP-8.

3.2 JP-8 and ATJ/JP-8 Rotary Fuel Injection Pump Wear Testing

Endurance tests were performed using a motorized pump stand to define the effects of fuel and fuel additives on full-scale fuel injection system equipment durability. Two distinct tests were performed utilizing a 500-hour fuel injection pump operating procedure. The specific tests performed included:

1. MIL-DTL-83133H Grade JP-8 with a fuel inlet temperature of 77°C.
2. Blend of 50-percent JP-8 and 50-percent ATJ, the level of CI/LI additive to be specified by AFRL, with a fuel inlet temperature of 40°C.

The JP-8 chosen for the study represented fuel bought in the marketplace that included all the MIL-DTL-83133H additives. The concentration of the CI/LI additive used in the purchased fuel was very near the QPL-25017 approved minimum effective concentration. The early time failure of the fuel injection pumps at elevated temperature operation with the purchased JP-8 was unexpected. It was postulated the low aromatic levels of the purchased JP-8 altered the CI/LI additive effectiveness. A brief fractional factorial study of CI/LI effectiveness with fuel aromatic levels suggested the additives are more effective in higher aromatic fuels.

The 50/50 ATJ/JP-8 fuel blend permitted completion of the 500-hours in the rotary diesel fuel injection pump test, but the fuel injection pumps did not meet performance specifications at the end of testing.

The technical feasibility of using JP-8 at elevated temperatures and using ATJ fuel in rotary fuel injection equipment when blended with a CI/LI additive and petroleum based commercial aviation kerosene has been investigated:

1. At elevated fuel inlet temperatures the maximum effective concentration of a QPL-25017 CI/LI should be utilized in JP-8.
2. It is recommended that blends of ATJ and JP-8 fuels include the addition of the maximum effective concentration of CI/LI for use in diesel rotary fuel injection equipment.

3.3 Evaluation of the Effects of Cetane in the Ford 6.7L High Pressure Common Rail Diesel Engine and the GEP 6.5L Turbo Diesel Engine

A fuel’s cetane number is very important for the operation of modern diesel engines. The U.S. military currently uses petroleum-based jet fuels in diesel engine-powered ground vehicles and is studying the use of alternative jet fuels obtained from a variety of sources. Currently there is no cetane number specification for petroleum derived jet fuels as this property holds no significance for turbine engine operation. There does exist a minimum Derived Cetane Number of 40 for blended products, but it remains of interest to identify a window, or range, of cetane number which would be acceptable to ensure the reliable operation of diesel engine-powered military ground vehicles.

The TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute identified 3 candidate fuels with cetane numbers ranging from 30 to 51. The fuels selected were JP-8 and synthetic blends. The European Stationary Cycle 13 mode test, and a full load, 5 point power curve, were performed on a Ford 6.7L turbocharged V-8 diesel engine for each test fuel. Full engine instrumentation included in-cylinder pressure measurements. Engine operating parameters and exhaust gas emissions were recorded. For the Ford 6.7L engine with the range of fuels selected, there were not any observed major negative impacts on performance or emissions.

The two fuels with cetane numbers of 30 and 51 were also used for testing a GEP 6.5L turbocharged V-8 diesel engine operation in a cold box. This engine architecture is traditionally sensitive to cold start and was able to show large changes in operability between the two fuels. At a relatively warm 40°F, the low cetane fuel was unable to start in the engine without the aid of glow plugs. The low cetane fuel had two cylinders deactivate after ignition at only +20°F even with the glow plugs continuing to activate. At the -20°F condition, the low cetane fuel caused cylinders 4 and 6 to cease firing for 17 and 20 minutes respectively. The high cetane fuel did not experience any cylinders ceasing combustion after ignition until the temperature dropped to -20°F.

The results from this work should help the military integrate emerging and future fuels into the supply chain.

3.3.1 O-Ring Evaluation

The o-ring evaluation of a 50/50 blend of the GEVO ATJ fuel (CL14-5998) and a low aromatic JP-8, (CL13-5864, 11.3 % Aromatics) was conducted by SwRI. The tensile strength was relatively unaffected for all materials. For volume swell that there is some spread in the individual replicates, but the average for the fluorosilicone was nearly the same as a baseline JP-8. However, compared to the same JP-8, the nitrile and Viton o-rings were more severely impacted. The nitrile O-rings were reduced from ~10% to ~4% swell and the Viton o-rings increased from approximately -0.5% swell to ~3% swell.” Data is presented in Appendix D.

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4.0 References

[1] Brandt, Adam; Yost, Douglas, “Evaluation of Military Fuels using a Ford 6.7L Powerstroke Diesel Engine”, Interim Report TFLRF No. 415, August 2011, ADA560574.

[2] Brandt, A.C. and Yost, D.M., “Evaluation of 50/50 Hydroprocessed Renewable Jet Fuel & JP-8 in the Ford 6.7L High Pressure Common Rail Diesel Engine”, AFRL-RQ-WP-TR-2013-0007, December 2012, ADA583392.

[3] Yost, D.M., Brandt, A.C., Advanced Propulsion Fuels Research and Development Support to AFRL/RZPF Task Order 0011: Rapid Response Research and Development (R&D) for Propulsion Directorate, Final Report, Appendix D, “Evaluation of JP-8 at High Temperature in the Ford 6.7L High Pressure Common Rail Diesel Engine”, AFRL-RZ-WP-TM-2013-0010, December 2012.

Appendix A

Task 4 – Engine Tests

EVALUATION OF AN ATJ/JP-8 FUEL BLEND IN THE FORD 6.7L HIGH PRESSURE COMMON RAIL DIESEL ENGINE

Prepared by

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Prepared for

Universal Technology Corporation

July 2014

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List of Tables

Acronyms and Abbreviations

°	Degree
%	Percent
Al	Aluminum
ATJ	Alcohol to Jet
CN	Cetane Number
CO	Monoxide
COA	Certificate of Analysis
COTS	Commercial Off-The-Shelf
Cu	Copper
DFCM	Diesel Fuel Condition Module
EGR	Exhaust Gas Recirculation
EI	Emissions Index
Fe	Iron
FIP	Fuel Injection Pumps
HC	Hydrocarbon
H/C	Hydrogen/Carbon atom ratio
HEFA	Hydroprocessed Esters and Fatty Acids
HPCR	High Pressure Common Rail
HofC	Heat of Combustion
HRJ	Hydroprocessed Renewable Jet
IQT	Ignition Quality Test
NO$_X$	Carbon Dioxide, Oxygen, and Oxides of Nitrogen
PCM	Powertrain Control Module
PCV	Pressure Control Valve
Pb	lead
ppm	Parts per Million
SwRI	Southwest Research Institute
TAN	Total Acid Number
TBN	Total Base Number
TWVC	Tactical Wheeled Vehicle Cycle
VCV	Volume Control Valve

Executive Summary

Commercial Off-The-Shelf (COTS) diesel engines are available to the U.S. Military that employ High Pressure Common Rail (HPCR) fuel injection systems. Overall performance and endurance of these HPCR systems has the potential to vary with use of military or alternative fuels due to critical chemical and physical property differences compared to standard diesel fuels. Of the critical property differences of military fuels, changes in fuel viscosity and lubricity are of particular interest. Many modern HPCR systems utilize fuel lubricated high pressure pumps, and can generate upwards of 2000-bar fuel rail pressures placing large demands on the fuel to adequately lubricate and protect internal components.

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At the completion of testing, the fuel injection pump and injectors were removed and disassembled for inspection and comparison. Component inspections for the ATJ/JP-8 test were compared to component conditions from previous work performed for the US Army and US Air Force. [A-3, A-4, A-5] Engine power curves and emissions were taken at the start and end of testing, and used to document any engine performance degradation incurred over the test duration.

The engine fueled with ATJ/JP-8 was successfully operated over the entire test duration without experiencing any unusual fuel related operational conditions or hardware failures. At the tested lubricity enhancing treat rate, the ATJ/JP-8 fuel provided adequate component protection and system performance. Post-test fuel injection system inspection found tested components to be in similar condition compared to all previously fuels tested. Results from testing support the durability of the fuel lubricated HPCR fuel system utilized on the Ford 6.7L with a military specified ATJ/JP-8.

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A.1.0 INTRODUCTION

A large number of current Commercial Off-The-Shelf (COTS) diesel engines available to the U.S. Military employ High Pressure Common Rail (HPCR) fuel injection systems. Life cycle performance and endurance of these HPCR fuel systems have the potential to be impacted by critical chemical and physical property differences between military specification fuels and standard diesel fuels. Although these critical factors can include many different properties, primary concerns lie with the fuels lubricity and viscosity, as these can have major impacts on fuel system hardware durability. With the large in-flux of HPCR technology into the diesel engine market, questions have arisen on whether these modern HPCR systems can maintain adequate performance and durability using military fuels in extreme operating conditions.

A.1.1 Objective

The test objective was to determine the performance and endurance of a modern high pressure common rail diesel fuel injection system when operated on an Alcohol-to-Jet (ATJ)/JP8 fuel blend at ambient fuel inlet temperatures. This test was an additional test completed to complement previous testing under Project 08.16246, in which a high pressure common rail diesel fuel system was evaluated using a 50/50 blend of Hydroprocessed Renewable Jet (HR-J), JP-8, and high-temperature JP-8. Similar to previous evaluations, testing was completed following a modified version of the 210-hour Tactical Wheeled Vehicle Cycle engine endurance test cycle (CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test). [A-1] Evaluations of performance and durability included, but were not limited to, fuel system hardware interactions, engine performance changes, and engine out emissions evaluations. This work was completed in support of Project 08.17049, Advanced Propulsion Fuels Research and Development.

A.2.0 RESULTS AND DISCUSSIONS

A.2.1 Test Engine

Consistent with previous testing, the Ford 6.7L diesel engine was utilized as a representative engine equipped with a modern high pressure common rail fuel injection system. The Ford 6.7L engine is a V8, direct injected, turbo-charged, intercooled engine, which employs a fuel lubricated high pressure common rail injection pump and piezo-electric fuel injectors. The 6.7L engine used for testing was the same engine used during the 50/50 HR-J/JP-8 evaluation, and was produced by Ford as an "export" version intended for sale outside of U.S borders or to military forces. In the export configuration, the engine is not equipped with an engine exhaust aftertreatment system or exhaust gas recirculation (EGR) system. The 6.7L export version engine is rated at approximately 320hp (238kW) at 2800rpm, and produces approximately 700 lb-ft (950 N-m) of torque at 1800rpm when using diesel fuel. Figure A-1 below shows the 6.7L engine test installation. Since the test engine had been previously used under Project 16246, it was fitted with all new fuel system hardware to bring it to "as-new" condition prior to testing.

Figure A-1. Ford 6.7L Engine Test Stand Installation

A.2.2 Fuel System Description

The fuel injection system on the Ford 6.7L engine utilizes a fuel lubricated high pressure pump supplying two pressure controlled fuel rails and 8 piezo-electric actuated fuel injectors. The Fuel Injection Pump (FIP) is mounted at the front of the engine valley and gear driven at 1:1 engine speed. The FIP is a two cylinder design and utilizes a two lobe cam to provide four pulses per revolution. The FIP is timed to the crankshaft and camshaft orientation to optimize pressure pulses within the fuel system during operation. Fuel management is controlled by the Powertrain Control Module (PCM) through the use of a FIP mounted Volume Control Valve (VCV) and a fuel rail mounted Pressure Control Valve (PCV). The engine primarily operates in VCV mode, in which the VCV valve regulates the amount of fuel entering the high pressure portion of the FIP based on engine demands. The PCV allows the PCM to trim the fuel rail pressure as needed, to regulate total fuel rail pressure and adjust as engine demands change. This design is primarily utilized to increase the efficiency of the fuel injection system, as only the fuel required for operation is compressed by the pump and sent to the fuel rails. Figure A-2 below shows the Ford 6.7L fuel injection pump, fuel pressure rail, and fuel injector. The VCV is located atop the center of the FIP between the two high pressure cylinder head assemblies. The PCV valve is located at the left end of the high pressure fuel rail as seen below.

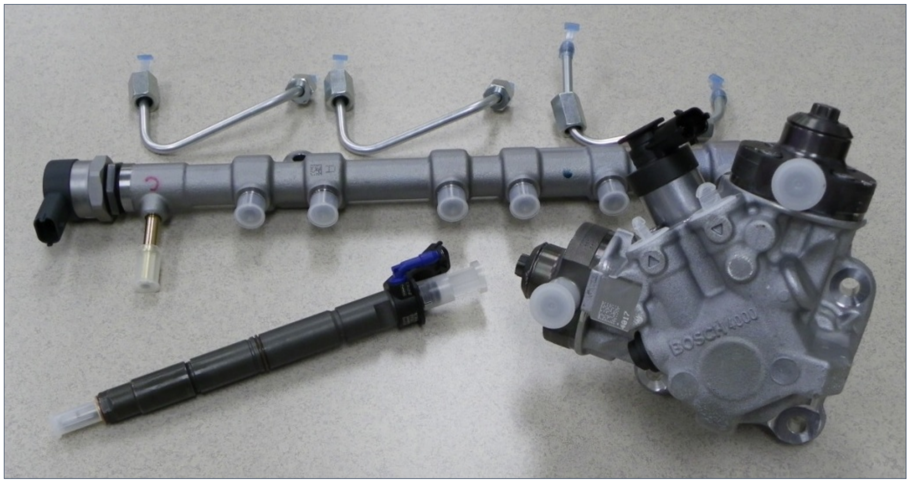


Figure A-2. For 6.7L Fuel Injection Pump, Rail, and Injector

The high pressure portion of the FIP consists of a high pressure plunger and barrel assembly that is actuated by roller follower assembly driven from the FIP camshaft. Regulated fuel from the VCV valve is drawn into the barrel assembly on the downward stroke, and then compressed and brought to the specified rail pressure upon plunger ascent. High pressure fuel exits the barrel assembly through a spring loaded check ball into high pressure fuel lines that supply the fuel rails. Figure A-3 below shows the orientation of high pressure pumping assembly. Critical wear points for these components can include: roller and shoe surface wear, scuffing on the follower and follower bore surfaces, plunger and barrel surface wear, and scuffing wear between high pressure plunger head and shoe assembly, as well as fuel check valve and seat wear.

Figure A-3. Camshaft Follower and High Pressure Plunger and Barrel Assembly

Figure A-4 below shows a parts break-out of the fuel injector. The fuel injector is a piezo-electric actuated unit that acts against one piston (upper) of a hydraulic coupler (Figure A-5) that is filled with fuel from the low pressure lift pump portion of the fuel system. The hydraulic coupler translates the small linear movement of the piezo-stack to a larger movement by the difference in piston diameters within the hydraulic coupler. The second piston (lower) of the hydraulic coupler acts against the injector control valve (Figure A-6), that regulates the pressure on the top of the injector needle controlling the needle lift. When the control valve is forced down, the high pressure fuel passage is blocked lowering the pressure acting on the top of the needle and allowing the high pressure fuel acting below to lift the needle and inject fuel into the combustion chamber. Figure A-5 and Figure A-6 show larger views of the hydraulic coupler and control valve assembly. Critical wear points for these components can include: control valve and seat wear, wear and scuffing on needle surface from guide, needle seat wear, and deposit formation on nozzle.

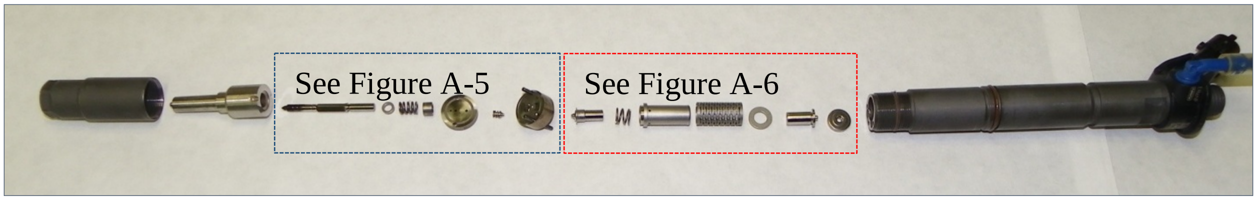


Figure A-4. Fuel Injector Component Break-Out

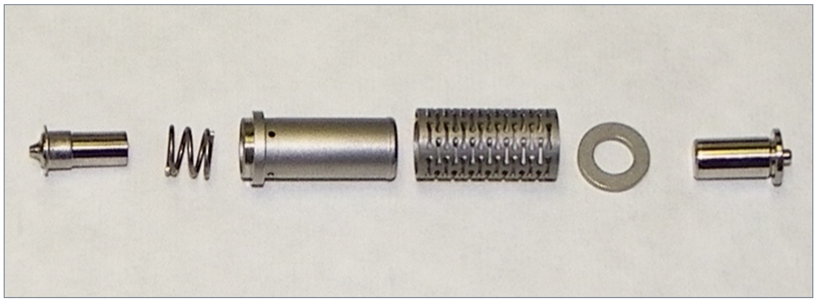


Figure A-5. Fuel Injector Hydraulic Coupler

Figure A-6. Fuel Injector Control Valve Assembly

A.2.3 Test Stand Configuration

The engine was mounted in a test stand specifically configured for Ford 6.7L engine testing. The following list outlines the general test stand set-up in regards to the engine installation, and ancillary equipment used during testing.

- The engine was fully instrumented to monitor various engine parameters, temperatures, and pressures throughout testing. A SwRI developed data acquisition and controls system (PRISM) was used to display and log real time engine data during testing.
- Engine speed was controlled by an absorption eddy current dynamometer. Engine load was controlled using a PRISM controller and actuator to manipulate the drive-by-wire throttle pedal attached to the engine's dynamometer harness.
- Coolant temperature (engine water jacket and secondary coolant loop) was controlled by PRISM using the building supplied process water and appropriately sized heat exchangers in place of the engines radiators.
- The engine was supplied with fuel by using a "day tank" at ambient temperature and pressure conditions. The day tank allows the engine to feed and return fuel as required during operation. Fuel in the day tank is kept at a constant level by a secondary fuel pump that replenishes the tank supply as necessary from bulk fuel storage. The make-up fuel flow rate into the day tank is the resulting fuel used by the engine, and is measured by a Micro Motion Coriolis flow meter and logged with PRISM as the engine fuel consumption rate.

- Fuel from the day tank was supplied to the engines diesel fuel condition module (DFCM) at ambient pressure and the specified fuel inlet temperature. The DFCM houses the primary fuel filter and low pressure lift pump for the engine. The DFCM also contains a temperature controlled recirculation device that re-routes engine return fuel to the engine supply until a desired fuel temperature is met.
- Inlet air was drawn in at ambient conditions from the test cell through a radiator core into the engine air box. The radiator core is supplied building process water to prevent extreme heat buildup in the test cell from elevating inlet air temperatures.
- Engine exhaust is drawn from the engine by the buildings exhaust handling system and discharged outside to the atmosphere. A butterfly valve was used to regulate engine exhaust backpressure to the Ford recommended 11psi specification.
- Emissions were directly sampled from an exhaust probe installed between the engine and exhaust system backpressure valve. Emissions were measured using a Horiba MEXA-1600D Motor Exhaust Gas Analyzer. Exhaust sample handling was carried out by the Horiba systems heated filter and line routed into the emission bench sample conditioning unit.
- Crankcase blow-by gasses were recirculated into the turbo compressor inlet via the factory blow-by control devices.
- The engine was lubricated with commercially available full synthetic CJ-4 SAE 5W-40 engine oil per Ford specifications for heavy duty applications.
- Used oil samples were collected from the engine daily to monitor engine and oil condition, and to determine oil change intervals needed during testing.

A.2.4 Engine Run-In

Prior to testing, the engine was run-in following the Ford specified engine run-in procedure. The run-in was performed with all new fuel injection system components. Although the engine build had been used in prior testing the run-in was performed to condition the new fuel injection system components. Table A-1 on the following page outlines the Ford recommended engine run-in procedure.

Table A-1. Ford Recommended Run-In Procedure

Step	Duration, minutes	Speed	Load	
		[rpm]	[lb-ft]	[N-m]
1	0:05	650	0	
2	0:30	1000	72	97
3	0:30	1200	103	140
4	0:30	1400	141	191
5	0:30	1500	162	219
6	0:30	1600	184	249
7	0:30	1700	208	282
8	0:30	1800	233	316
9	0:30	2000	287	390
10	0:30	2200	348	472
11	0:30	2400	414	561
12	0:30	2500	449	609
13	0:30	2600	486	659
14	0:30	2700	524	710
15	0:30	2800	563	764

A.2.5 Pre and Post Test Engine Performance Checks

Before and after testing, engine power curves were completed at varying speeds and loads to determine pre-test engine performance. Engine performance was documented at engine speeds of 1400, 1800, 2200, 2400, and 2800rpm, with load intervals of 25%, 50%, 75%, and 100% of full load. Power curves were completed at both ambient (95°F) and desert condition (120°F) inlet fuel temperatures. Exhaust gas emissions were sampled at each point on the curve to document engine out emissions. Power curve plots can be seen in the Engine Performance Curves section.

A.2.6 Test Cycle

The test cycle followed during fuel system evaluation was a modified version of the 210hr Tactical Wheeled Vehicle cycle as outlined in CRC Report No. 406, Development of Military Fuel/Lubricant/Engine Compatibility Test. Modifications were made to the outlined test cycle to accelerate the overall testing schedule, resulting in daily runtime of 21hrs (15hr at rated speed/load, 6hrs idle) followed by a 3hr engine off soak. The modified daily cycle was arranged in a manner to preserve the total number of rated and idle hours over the entire test duration consistent with the standard cycle. The modified daily cycle consisted of 6 repeating segments of 2hr 10min at rated speed/load followed by a 1hr idle step. At the completion of the 6 cycles, the engine completed a final 2hr rated step, and then entered the engine off soak period. Throughout testing engine coolant temperatures were maintained at Ford specifications to ensure engine integrity. Engine coolant utilized was a 50/50 blend of ethylene glycol antifreeze and deionized water. Engine operating parameters were controlled as specified in Table A-2 below. These operating parameters were based on Ford’s recommended specifications, except for the fuel inlet temperature which was maintained at a specified fuel inlet temperature of 35°C/95°F.

(Note – Engine idle speed was controlled by PCM at approximately 600 RPM (i.e. no throttle input). Temperature controllers remained at rated speed set points for idle conditions, but were allowed to reach their natural steady state value during idle testing steps. Engine oil cooler plumbing was integral to the engine water jacket, thus not directly controlled in either idle or rated steps. Oil temperatures were allowed to meet their own steady state temperature based on water jacket temperature and engine load/speed throughout testing.)

Table A-2. Test Cycle Operation Parameters

Parameter	Rated Speed	Idle
Engine Speed	2800RPM +/-25	NC
High Temp Coolant Loop	203°F +/- 3	NC
Low Temp Coolant Loop	100°F +/- 3	NC
Oil Sump Temperature	NC	NC
Fuel Inlet Temperature	95°F +/-3	95°F +/-3
*NC = not controlled		

A.2.7 Oil Sampling

Four ounces of engine oil was sampled every 21-hours (daily) for used oil analysis. Used oil analysis consisted of the following tests as seen in Table A-3 on the following page. Engine oil changes were to be performed on the engine based on used oil condition. In this case the lubricant did not require a change during the 210-hour cycle. Engine oil level was checked daily, and replenished as needed to restore oil level to full mark. This process occurred after the completion of the 3-hour soak prior to restarting testing the next day. Used oil analysis results can be seen in the engine oil analysis and engine oil analysis trends section of the report.

Table A-3. Used Oil Analysis Procedures

Daily Used Oil Analysis		
ASTM	**D4739**	Total Base Number
ASTM	**D664**	Total Acid Number
ASTM	**D445**	Kinematic Viscosity @ 100°C
ASTM	**D4052**	Density
ASTM	**TGA SOOT**	TGA Soot
ASTM	**E168**	Oxidation
ASTM	**E168**	Nitration
ASTM	**D5185**	Wear Metals by ICP

A.2.8 Test Fuel

An ATJ fuel was supplied as GFE by WPAFB for blending at a 50/50 ratio by volume with JP-8. A JP-8 fuel meeting MIL-DTL-83133H was purchased from a local supplier. Table A-4 summarizes the critical properties of the locally sourced JP-8.

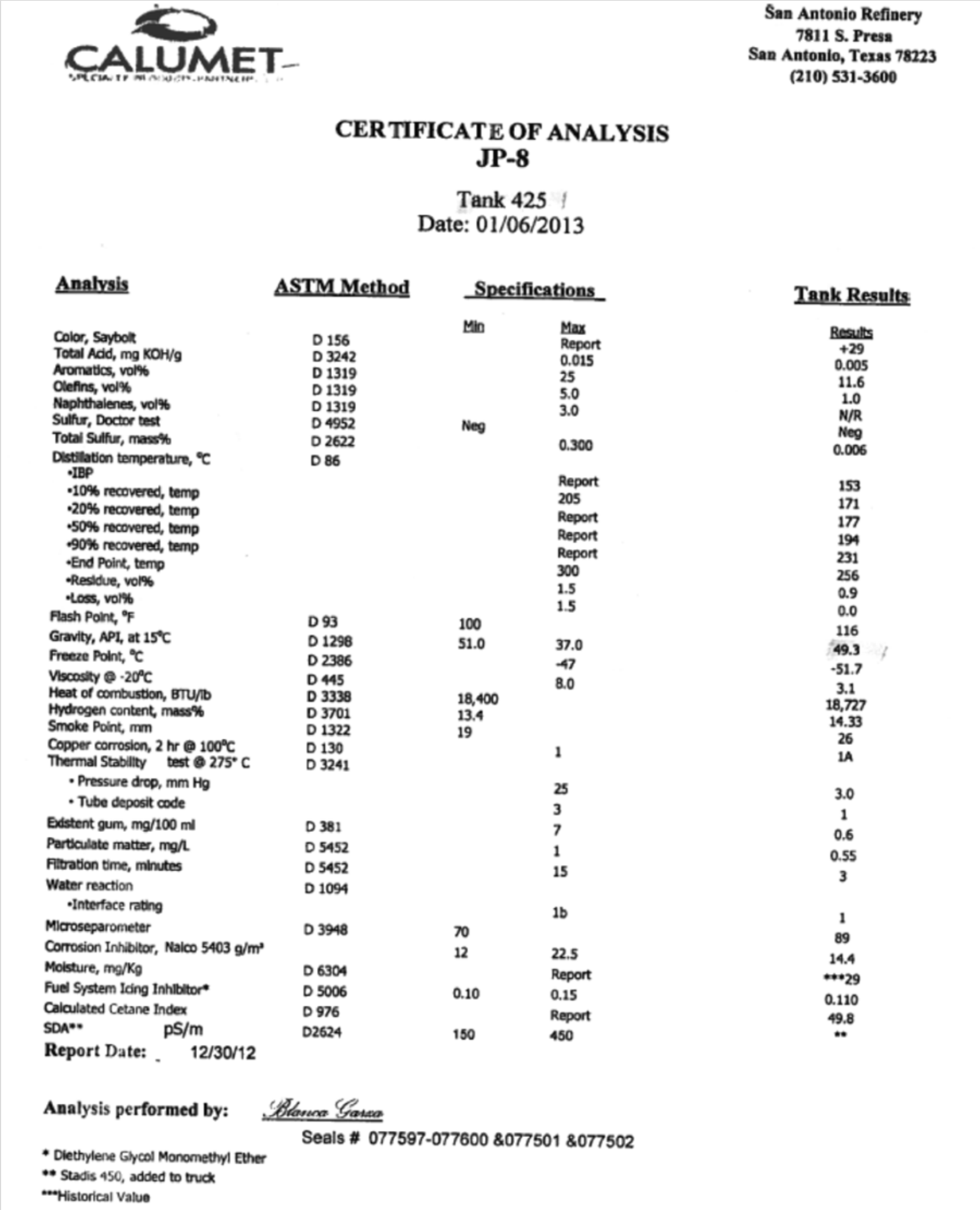
Concerns were raised as to whether the batch of JP-8 fuel was representative due to the poor pump durability performance at elevated temperature in another phase of the test program. The JP-8 as purchased has a low CI/LI treatment rate, but still meets the BOCLE requirement. The fuel does have low aromatic levels (11.6%), that when blended 50-percent with a “zero”-aromatic synthetic fuel would fall below the minimum recommended aromatic levels (8.0%). A question was raised as to whether the resulting low aromatic level of the fuel blend could affect

CI/LI additive effectiveness for diesel fuel injection pump protection. If the engine test was performed at low aromatics levels, it was felt an adverse engine durability result could possibly be misinterpreted.

A JP-8/ATJ blend that met the aromatics requirements, when aromatics are tested by ASTM D6379, was identified at WPAFB, and is shown in Table A-5. This fuel blend was used as the target for the durability test blend. Three drums of the fuel were sent to SwRI and used for rotary pump testing and FORD 6.7L engine combustion studies.

An additional Jet A/Jet A-1 blend with ATJ was identified that met the minimum aromatics content, and was available in sufficient quantity to run the engine test. The partial test fuel blend arrived at SwRI from WPAFB, and the analysis of the partial blend is included in Table A-6. SwRI blended in the remaining ATJ needed to obtain a 50/50 blend, along with adding sufficient INNOSPEC DCI-4A to achieve a 14.4-ppm treatment of the CI/LI additive. SwRI analyzed the durability test blend for the three bench lubricity tests, aromatics content by UV and GC, and the cetane number and derived cetane numbers. Table A-7 shows the SwRI analysis of the final durability test blend. Five gallons of the final blend was sent to AFRL at WPAFB, whose analysis is shown in Table A-8 for AFRL fuel POSF-10399.

Table A-4. Initial JP-8 Test Fuel Chemical and Physical Analysis



CALUMET

San Antonio Refinery
7811 S. Presa
San Antonio, Texas 78223
(210) 531-3600

CERTIFICATE OF ANALYSIS
JP-8

Tank 425
Date: 01/06/2013

Analysis	ASTM Method	Specifications Min	Specifications Max	Tank Results
Color, Saybolt	D 156		Report	+29
Total Acid, mg KOH/g	D 3242		0.015	0.005
Aromatics, vol%	D 1319		25	11.6
Olefins, vol%	D 1319		5.0	1.0
Naphthalenes, vol%	D 1319		3.0	N/R
Sulfur, Doctor test	D 4952	Neg		Neg
Total Sulfur, mass%	D 2622		0.300	0.006
Distillation temperature, °C	D 86			
•IBP			Report	153
•10% recovered, temp			205	171
•20% recovered, temp			Report	177
•50% recovered, temp			Report	194
•90% recovered, temp			Report	231
•End Point, temp			300	256
•Residue, vol%			1.5	0.9
•Loss, vol%			1.5	0.0
Flash Point, °F	D 93	100		116
Gravity, API, at 15°C	D 1298	51.0	37.0	49.3
Freeze Point, °C	D 2386		-47	-51.7
Viscosity @ -20°C	D 445		8.0	3.1
Heat of combustion, BTU/lb	D 3338	18,400		18,727
Hydrogen content, mass%	D 3701	13.4		14.33
Smoke Point, mm	D 1322	19		26
Copper corrosion, 2 hr @ 100°C	D 130		1	1A
Thermal Stability test @ 275° C	D 3241			
• Pressure drop, mm Hg			25	3.0
• Tube deposit code			3	1
Existent gum, mg/100 ml	D 381		7	0.6
Particulate matter, mg/L	D 5452		1	0.55
Filtration time, minutes	D 5452		15	3
Water reaction	D 1094			
•Interface rating			1b	1
Microseparometer	D 3948	70		89
Corrosion Inhibitor, Nalco 5403 g/m³		12	22.5	14.4
Moisture, mg/Kg	D 6304		Report	***29
Fuel System Icing Inhibitor*	D 5006	0.10	0.15	0.110
Calculated Cetane Index	D 976		Report	49.8
SDA** pS/m	D2624	150	450	**

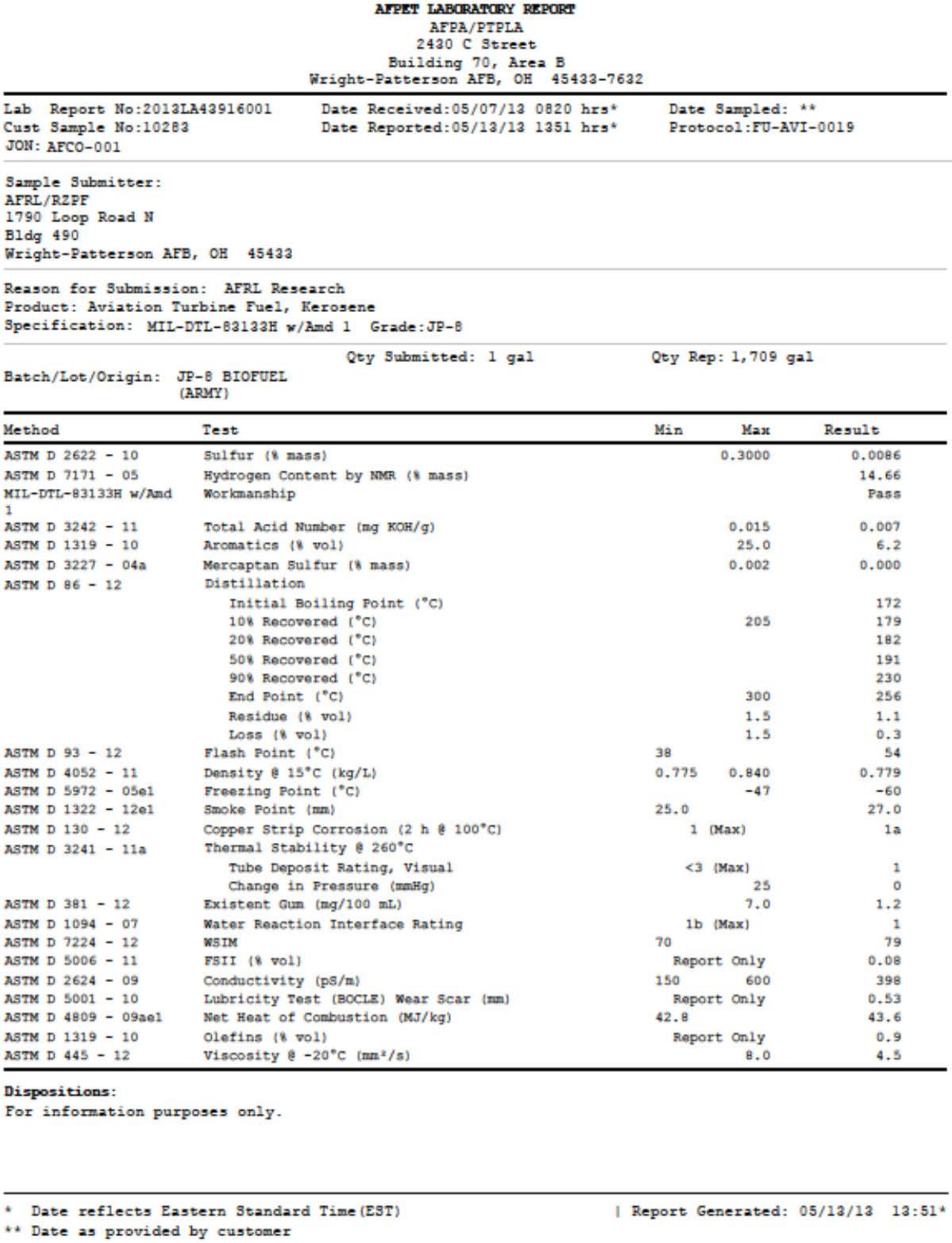
Report Date: 12/30/12

Analysis performed by: Blanca Garza

Seals # 077597-077600 &077501 &077502

* Diethylene Glycol Monomethyl Ether
** Stadis 450, added to truck
***Historical Value

Table A-5. Target Blend for Engine Testing



AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA43916001   Date Received:05/07/13 0820 hrs*   Date Sampled: **
Cust Sample No:10283   Date Reported:05/13/13 1351 hrs*   Protocol:FU-AVI-0019
JON: AFCO-001

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: MIL-DTL-83133H w/Amd 1   Grade:JP-8

Qty Submitted: 1 gal   Qty Rep: 1,709 gal
Batch/Lot/Origin: JP-8 BIOFUEL
(ARMY)

Method	Test	Min	Max	Result
ASTM D 2622 - 10	Sulfur (% mass)		0.3000	0.0086
ASTM D 7171 - 05	Hydrogen Content by NMR (% mass)			14.66
MIL-DTL-83133H w/Amd 1	Workmanship			Pass
ASTM D 3242 - 11	Total Acid Number (mg KOH/g)		0.015	0.007
ASTM D 1319 - 10	Aromatics (% vol)		25.0	6.2
ASTM D 3227 - 04a	Mercaptan Sulfur (% mass)		0.002	0.000
ASTM D 86 - 12	Distillation			
	Initial Boiling Point (°C)			172
	10% Recovered (°C)		205	179
	20% Recovered (°C)			182
	50% Recovered (°C)			191
	90% Recovered (°C)			230
	End Point (°C)		300	256
	Residue (% vol)		1.5	1.1
	Loss (% vol)		1.5	0.3
ASTM D 93 - 12	Flash Point (°C)	38		54
ASTM D 4052 - 11	Density @ 15°C (kg/L)	0.775	0.840	0.779
ASTM D 5972 - 05e1	Freezing Point (°C)		-47	-60
ASTM D 1322 - 12e1	Smoke Point (mm)	25.0		27.0
ASTM D 130 - 12	Copper Strip Corrosion (2 h @ 100°C)		1 (Max)	1a
ASTM D 3241 - 11a	Thermal Stability @ 260°C			
	Tube Deposit Rating, Visual		<3 (Max)	1
	Change in Pressure (mmHg)		25	0
ASTM D 381 - 12	Existent Gum (mg/100 mL)		7.0	1.2
ASTM D 1094 - 07	Water Reaction Interface Rating		1b (Max)	1
ASTM D 7224 - 12	WSIM	70		79
ASTM D 5006 - 11	FSII (% vol)		Report Only	0.08
ASTM D 2624 - 09	Conductivity (pS/m)	150	600	398
ASTM D 5001 - 10	Lubricity Test (BOCLE) Wear Scar (mm)		Report Only	0.53
ASTM D 4809 - 09ae1	Net Heat of Combustion (MJ/kg)	42.8		43.6
ASTM D 1319 - 10	Olefins (% vol)		Report Only	0.9
ASTM D 445 - 12	Viscosity @ -20°C (mm^2/s)		8.0	4.5

Dispositions:
For information purposes only.

* Date reflects Eastern Standard Time(EST)   \| Report Generated: 05/13/13 13:51*
** Date as provided by customer

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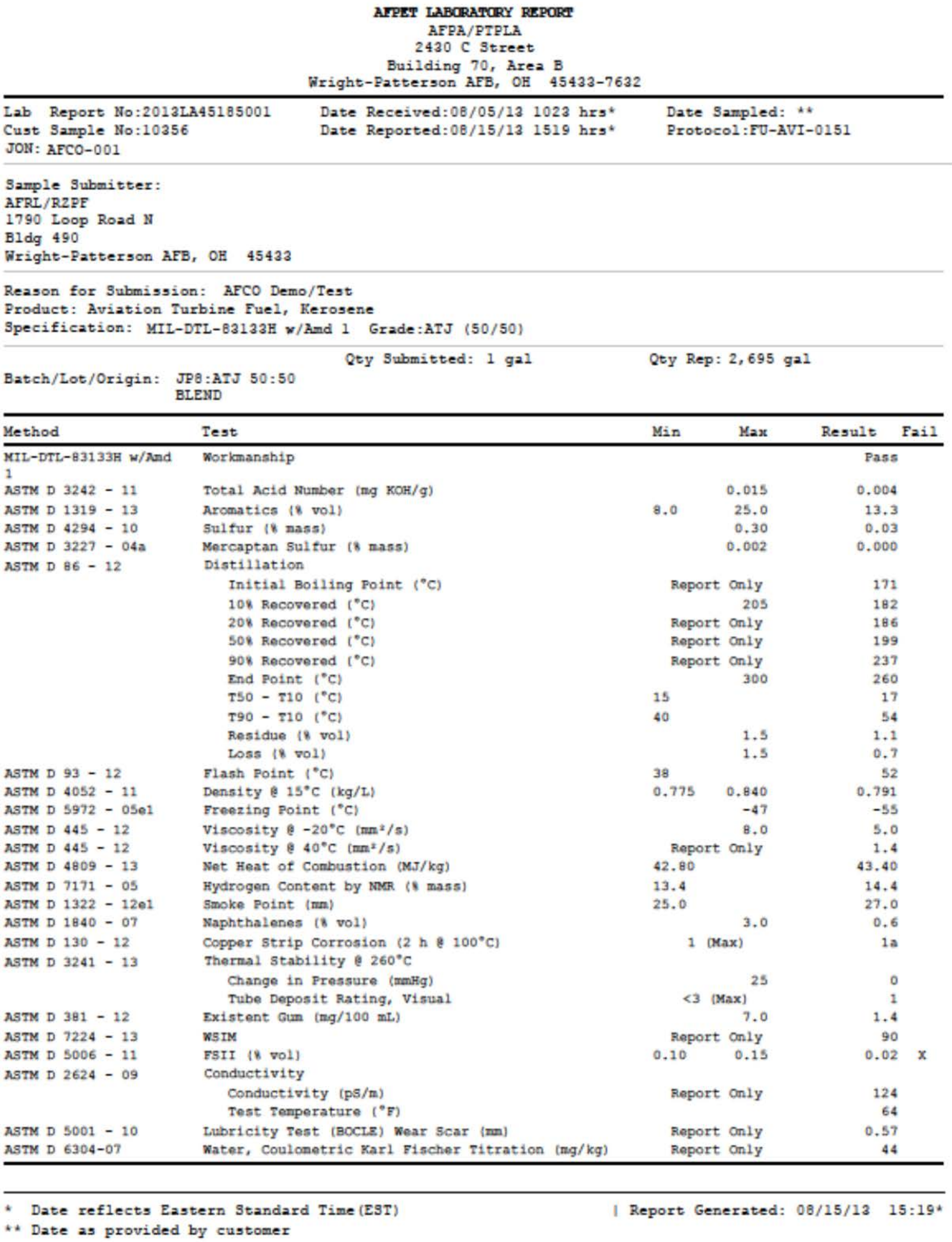
Table A-6. Blend Stock Provided by AFRL with Sufficient Fuel Aromatics Content



AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA45185001   Date Received:08/05/13 1023 hrs*   Date Sampled: **
Cust Sample No:10356   Date Reported:08/15/13 1519 hrs*   Protocol:FU-AVI-0151
JON: AFCO-001

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFCO Demo/Test
Product: Aviation Turbine Fuel, Kerosene
Specification: MIL-DTL-83133H w/Amd 1 Grade:ATJ (50/50)

Qty Submitted: 1 gal   Qty Rep: 2,695 gal
Batch/Lot/Origin: JP8:ATJ 50:50
BLEND

Method	Test	Min	Max	Result	Fail
MIL-DTL-83133H w/Amd 1	Workmanship			Pass	
ASTM D 3242 - 11	Total Acid Number (mg KOH/g)		0.015	0.004	
ASTM D 1319 - 13	Aromatics (% vol)	8.0	25.0	13.3	
ASTM D 4294 - 10	Sulfur (% mass)		0.30	0.03	
ASTM D 3227 - 04a	Mercaptan Sulfur (% mass)		0.002	0.000	
ASTM D 86 - 12	Distillation				
	Initial Boiling Point (°C)		Report Only	171	
	10% Recovered (°C)		205	182	
	20% Recovered (°C)		Report Only	186	
	50% Recovered (°C)		Report Only	199	
	90% Recovered (°C)		Report Only	237	
	End Point (°C)		300	260	
	T50 - T10 (°C)	15		17	
	T90 - T10 (°C)	40		54	
	Residue (% vol)		1.5	1.1	
	Loss (% vol)		1.5	0.7	
ASTM D 93 - 12	Flash Point (°C)	38		52	
ASTM D 4052 - 11	Density @ 15°C (kg/L)	0.775	0.840	0.791	
ASTM D 5972 - 05e1	Freezing Point (°C)		-47	-55	
ASTM D 445 - 12	Viscosity @ -20°C (mm^2/s)		8.0	5.0	
ASTM D 445 - 12	Viscosity @ 40°C (mm^2/s)		Report Only	1.4	
ASTM D 4809 - 13	Net Heat of Combustion (MJ/kg)	42.80		43.40	
ASTM D 7171 - 05	Hydrogen Content by NMR (% mass)	13.4		14.4	
ASTM D 1322 - 12e1	Smoke Point (mm)	25.0		27.0	
ASTM D 1840 - 07	Naphthalenes (% vol)		3.0	0.6	
ASTM D 130 - 12	Copper Strip Corrosion (2 h @ 100°C)		1 (Max)	1a	
ASTM D 3241 - 13	Thermal Stability @ 260°C				
	Change in Pressure (mmHg)		25	0	
	Tube Deposit Rating, Visual		<3 (Max)	1	
ASTM D 381 - 12	Existent Gum (mg/100 mL)		7.0	1.4	
ASTM D 7224 - 13	WSIM		Report Only	90	
ASTM D 5006 - 11	FSII (% vol)	0.10	0.15	0.02	X
ASTM D 2624 - 09	Conductivity				
	Conductivity (pS/m)		Report Only	124	
	Test Temperature (°F)			64	
ASTM D 5001 - 10	Lubricity Test (BOCLE) Wear Scar (mm)		Report Only	0.57	
ASTM D 6304-07	Water, Coulometric Karl Fischer Titration (mg/kg)		Report Only	44	

* Date reflects Eastern Standard Time(EST) | Report Generated: 08/15/13 15:19*
** Date as provided by customer

Table A-7. Analysis of Final RFLRF Blend for Engine Testing

Property	Method	Units	Result
Aromatics	D1319	Wt.%	7.0
Aromatics	D6379	Wt/%	8.38
Cetane Number	D613	CN	34.1
Derived Cetane Number	D6890	DCN	39.42
Lubricity, BOCLE	D5001	mm	0.630
Lubricity, HFRR, 60°C	D6079	mm	0.761
Lubricity, SLBOCLE	D6078	grams	2250
Carbon	D5219	Wt.%	85.35
Hydrogen	D5291	Wt.%	14.76

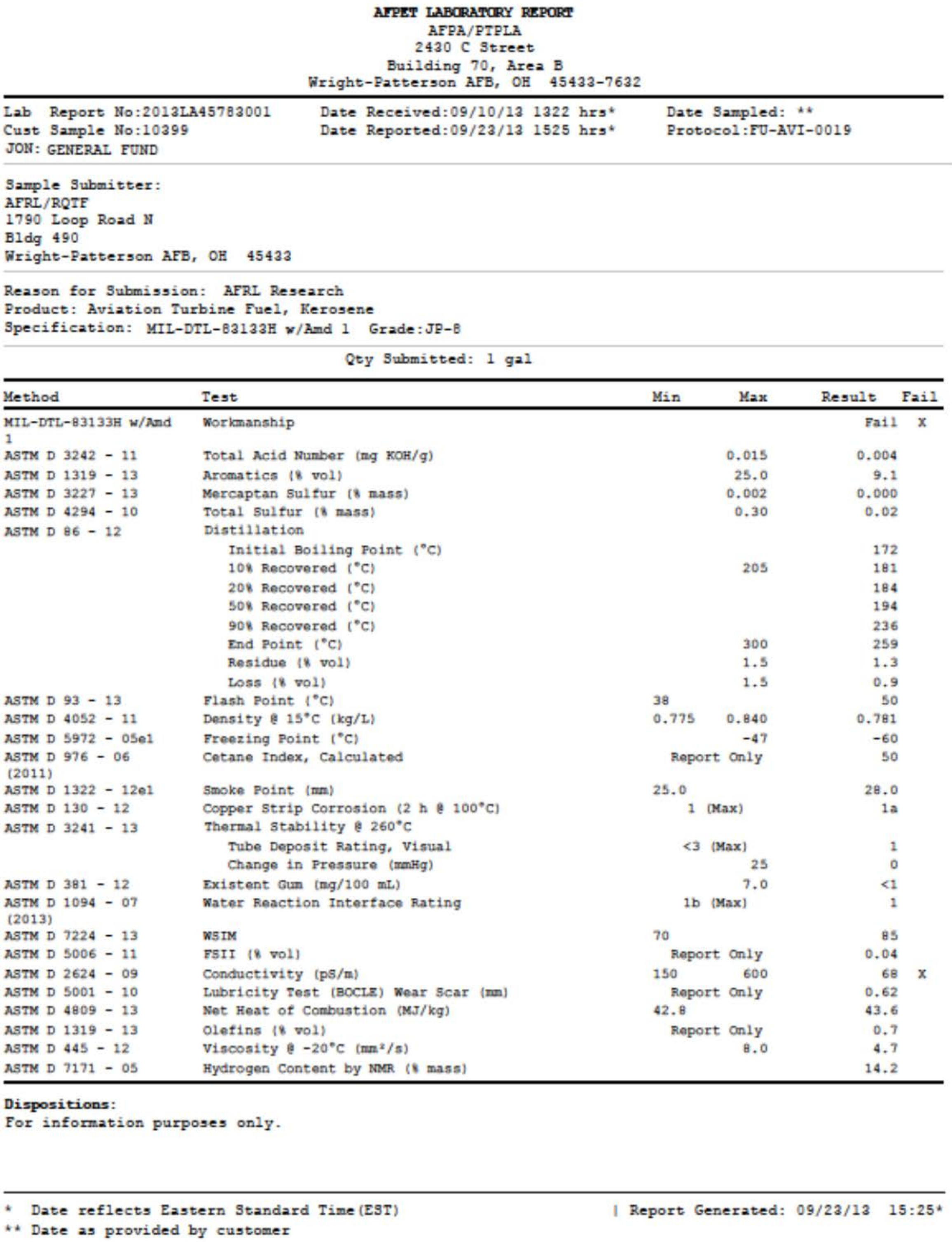
A.3.0 ENDURANCE TEST CYCLE RESULTS

The following information summarizes the results of the engine fuel system endurance tests. Data includes: engine operating summary, power curve analysis, engine out emissions, used oil analysis, post test component inspection, post test component photos, and listing of any problem areas or anomalies experienced during testing.

A.3.1 Engine Operating Conditions Summary

Table A-9 is a summary of the engine operating conditions averaged over the test duration, for both the idle mode and the rated condition mode.

Table A-8. AFRL Analysis of POSF-10399 Engine ATJ/JP-8 Test Fuel Blend



AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA45783001
Cust Sample No:10399
JON: GENERAL FUND

Date Received:09/10/13 1322 hrs*
Date Reported:09/23/13 1525 hrs*

Date Sampled: **
Protocol:FU-AVI-0019

Sample Submitter:
AFRL/RQTF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: MIL-DTL-83133H w/Amd 1 Grade:JP-8

Qty Submitted: 1 gal

Method	Test	Min	Max	Result	Fail
MIL-DTL-83133H w/Amd 1	Workmanship			Fail	X
ASTM D 3242 - 11	Total Acid Number (mg KOH/g)		0.015	0.004	
ASTM D 1319 - 13	Aromatics (% vol)		25.0	9.1	
ASTM D 3227 - 13	Mercaptan Sulfur (% mass)		0.002	0.000	
ASTM D 4294 - 10	Total Sulfur (% mass)		0.30	0.02	
ASTM D 86 - 12	Distillation				
	Initial Boiling Point (°C)			172	
	10% Recovered (°C)		205	181	
	20% Recovered (°C)			184	
	50% Recovered (°C)			194	
	90% Recovered (°C)			236	
	End Point (°C)		300	259	
	Residue (% vol)		1.5	1.3	
	Loss (% vol)		1.5	0.9	
ASTM D 93 - 13	Flash Point (°C)	38		50	
ASTM D 4052 - 11	Density @ 15°C (kg/L)	0.775	0.840	0.781	
ASTM D 5972 - 05e1	Freezing Point (°C)		-47	-60	
ASTM D 976 - 06 (2011)	Cetane Index, Calculated	Report Only		50	
ASTM D 1322 - 12e1	Smoke Point (mm)	25.0		28.0	
ASTM D 130 - 12	Copper Strip Corrosion (2 h @ 100°C)	1 (Max)		1a	
ASTM D 3241 - 13	Thermal Stability @ 260°C				
	Tube Deposit Rating, Visual	<3 (Max)		1	
	Change in Pressure (mmHg)		25	0	
ASTM D 381 - 12	Existent Gum (mg/100 mL)		7.0	<1	
ASTM D 1094 - 07 (2013)	Water Reaction Interface Rating	1b (Max)		1	
ASTM D 7224 - 13	WSIM	70		85	
ASTM D 5006 - 11	FSII (% vol)	Report Only		0.04	
ASTM D 2624 - 09	Conductivity (pS/m)	150	600	68	X
ASTM D 5001 - 10	Lubricity Test (BOCLE) Wear Scar (mm)	Report Only		0.62	
ASTM D 4809 - 13	Net Heat of Combustion (MJ/kg)	42.8		43.6	
ASTM D 1319 - 13	Olefins (% vol)	Report Only		0.7	
ASTM D 445 - 12	Viscosity @ -20°C (mm²/s)		8.0	4.7	
ASTM D 7171 - 05	Hydrogen Content by NMR (% mass)			14.2	

Dispositions:
For information purposes only.

* Date reflects Eastern Standard Time(EST) | Report Generated: 09/23/13 15:25*
** Date as provided by customer

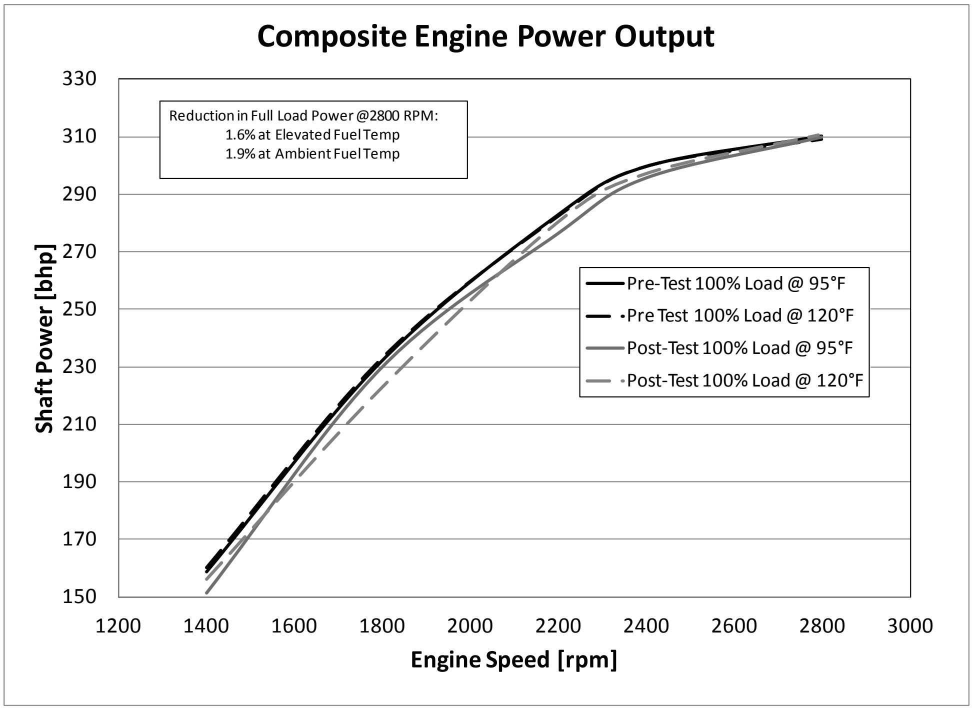
Table A-9. Engine Operating Condition Summary

		Rated Conditions (2800 RPM)		Idle Conditions (600 RPM)	
Parameter:	**Units**	**Average**	**Std. Dev.**	**Average**	**Std. Dev.**
Engine Speed	RPM	2800	2	598	3
Torque*	ft*lb	584	5.9	28	2.1
Fuel Flow	lb/hr	127.2	1.2	1.4	0.4
Power*	bhp	312	3.1	3	0.2
BSFC*	lb/bhp*hr	0.408	0.006	0.453	0.171
Temperatures:					
High Temperature Loop Coolant In	°F	185.4	0.5	178.3	9.2
High Temperature Loop Coolant Out	°F	203.0	0.4	180.4	9.4
Low Temperature Loop Coolant In	°F	102.4	13.4	96.6	14.0
Low Temperature Loop Coolant Out	°F	136.6	2.4	95.6	4.4
Oil Sump	°F	235.5	0.6	184.3	9.9
Fuel In	°F	95.3	1.3	94.8	0.7
Fuel Pump Drain	°F	99.0	10.5	90.7	6.3
Fuel Return	°F	110.7	1.7	97.2	1.0
Intake Air Before Compressor	°F	85.4	1.4	85.1	1.5
Intake Air After Compressor	°F	353.8	4.0	99.8	2.6
Intake Air After Charge Cooler	°F	108.1	2.3	94.9	4.5
Cylinder 1 Exhaust	°F	1398	13	256	14
Cylinder 2 Exhaust	°F	1376	20	254	12
Cylinder 3 Exhaust	°F	1417	18	256	10
Cylinder 4 Exhaust	°F	1447	18	254	10
Cylinder 5 Exhaust	°F	1391	11	260	11
Cylinder 6 Exhaust	°F	1427	12	272	10
Cylinder 7 Exhaust	°F	1430	15	263	9
Cylinder 8 Exhaust	°F	1412	17	251	9
Exhaust After Turbo	°F	1167	18	222	14
Pressures:					
Oil Gallery	psi	56.2	0.2	27.5	1.9
Ambient Pressure	psiA	14.28	0.03	14.28	0.03
Intake Restriction	psi	0.51	0.01	-0.01	0.00
Exhaust Restriction	psi	10.91	0.41	-0.05	0.05
Boost Pressure	psi	19.52	0.53	0.40	0.02
Fuel Rail Pressure	psi	19429	28	3951	25

*Non-corrected Values

A.3.2 Engine Performance Curves

The plots below show the pre and post test engine power curves. Figure A-7reveals the pre, and post test composite full load power curve for both fuel inlet temperatures of 95°F and 120°F. After 210-hours of operation using ATJ JP-8, the engine max power had decreased by 1.9% at ambient fuel temperature and 1.6% at the elevated 120°F fuel temperature.



Reduction in Full Load Power @2800 RPM:
1.6% at Elevated Fuel Temp
1.9% at Ambient Fuel Temp

Figure A-7. Composite Engine Power Output

Figure A-8 and Figure A-9, shows the pre, and post test engine power output performance maps generated with JP-8 fuel at the 95°F, and 120°F fuel inlet temperatures respectively, for the 25%, 50%, 75%, and 100% pedal positions. Slight power deviations are seen at the lower engine speeds, more pronounced at the 120°F fuel inlet condition, after 210-hours of operation with the ATJ/JP-8 blend. Exhaust emission data was taken at each one of the speed/load points on the maps. Figure A-10 and Figure A-11, shows the pre, and post test engine torque output performance maps generated with JP-8 fuel at the 95°F, and 120°F fuel inlet temperatures respectively, for the 25%, 50%, 75%, and 100% pedal positions. The torque variations reflect the power deviations noted after engine operation on the ATJ/JP-8 blend.

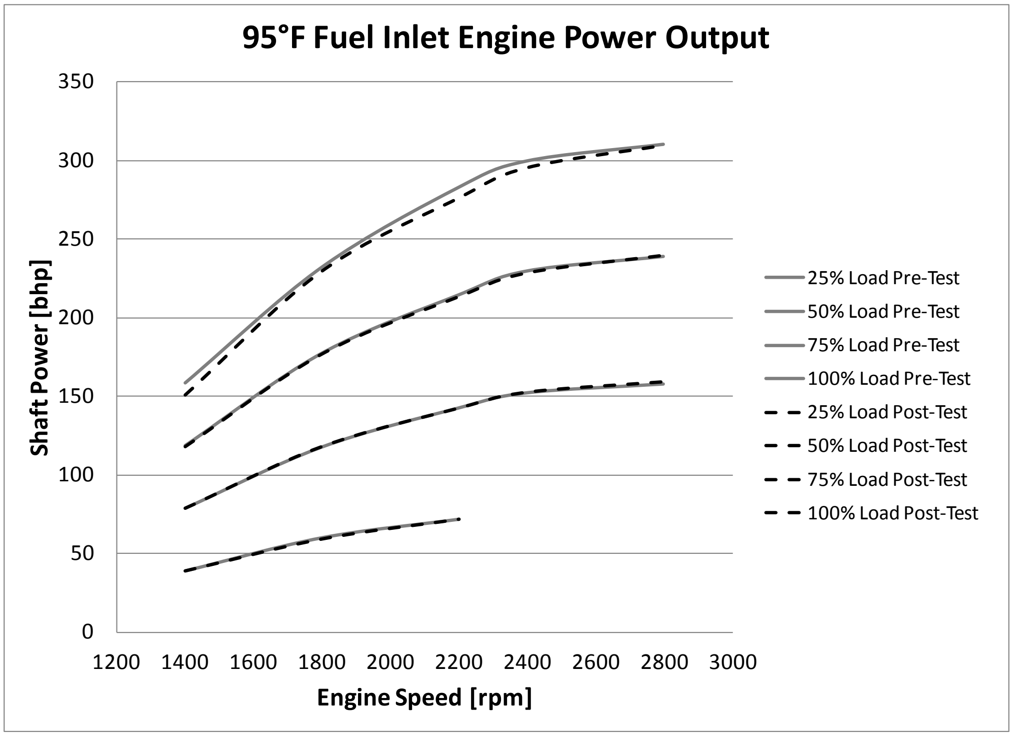


Figure A-8. Pre & Post Test Engine Power Output as 95 °F Fuel Inlet Temperature

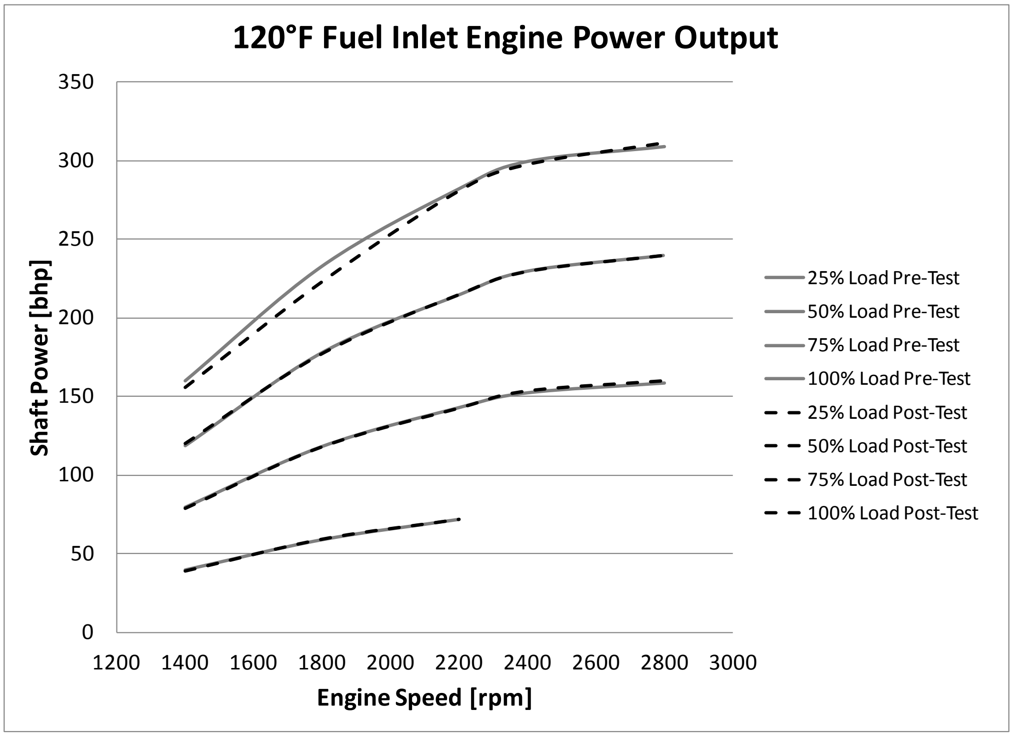


Figure A-9. Pre and Post Test Engine Power Output as 120 °F Fuel Inlet Temperature

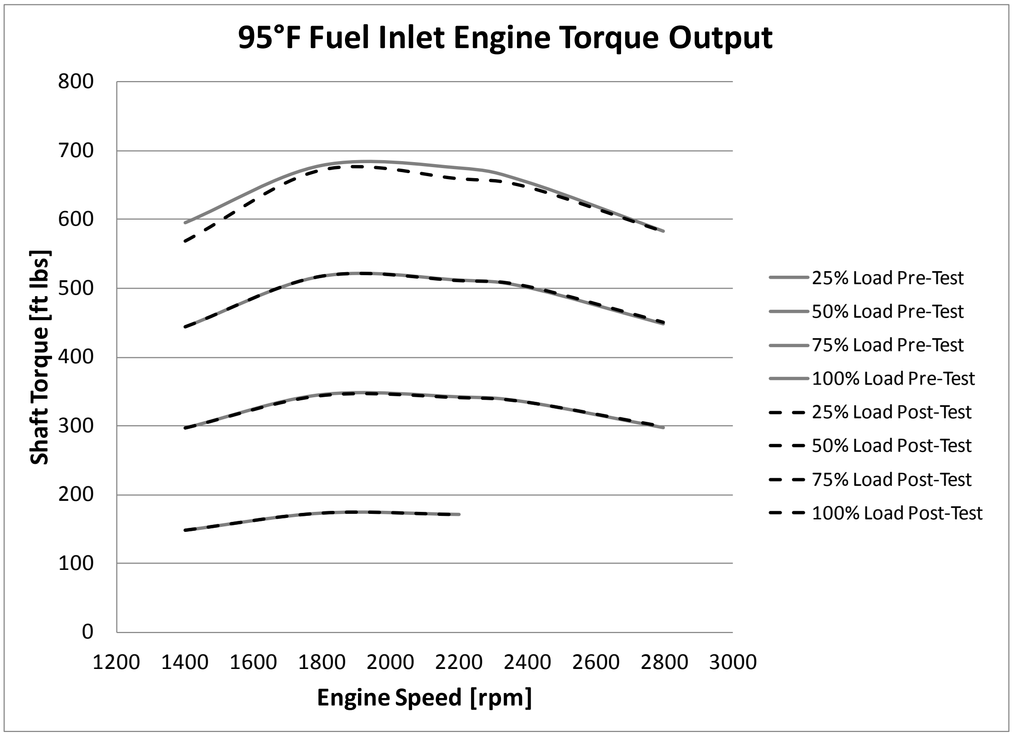


Figure A-10. Pre and Post Test Engine Torque Output as 95 °F Fuel Inlet Temperature

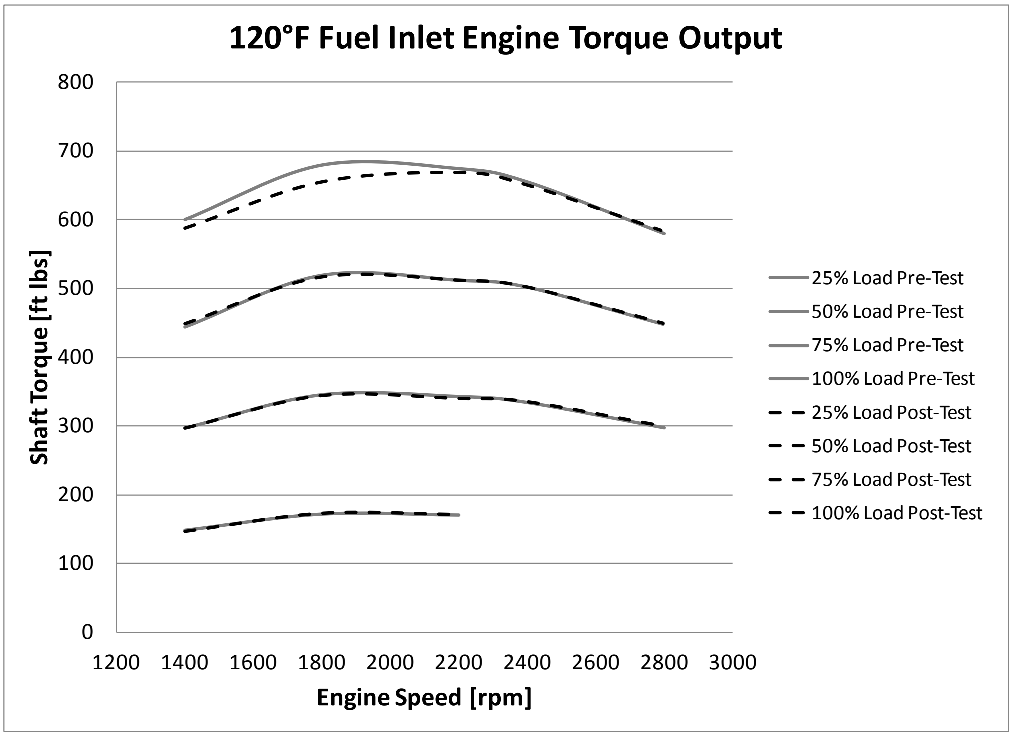


Figure A-11. Pre and Post Test Engine Torque Output as 120 °F Fuel Inlet Temperature

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A.3.3 Engine Out Emissions

As in previous testing, the engine out exhaust emissions for the Ford 6.7L Power Stroke diesel engine was measured as raw emissions downstream of the turbocharger outlet. The emissions instrumentation was a Horiba MEXA-1600D Motor Exhaust Gas Analyzer measurement system calibrated for detecting unburned hydrocarbon (HC), carbon monoxide (CO), carbon dioxide, oxygen, and oxides of nitrogen (NO_X) species in the exhaust. Direct engine out exhaust emission measurements were taken during the pre, and post test power curve testing segments to document the engine's overall condition, as tailpipe emission changes over the test duration could help identify fuel system degradation and engine performance changes. Mass based calculations were determined following methodology outlined in the Code of Federal Regulations, Title 40, Part 86, and Subpart D. [A-2] Final mass based emissions values were then correlated to engine fuel consumption rates to provide direct comparison of mass emission produced per unit mass of fuel. These values are denoted as the Emissions Index (EI).

Data shown with from the JP-8 evaluation is the emission measurements made prior-to, and after the 210-hour durability test. As there was little deviation between pre-test and post-test emission measurements, it is implicit that both the engine and fuel system integrity did not vary significantly due to the durability cycle with the ATJ/JP-8 fuel. Figure A-12 and Figure A-13 show the HC Emissions Index (HCEI), grams HC/lb fuel, for JP-8 over the performance matrices performed at the two fuel temperatures. As seen previously with other fuels [A-3], the 25% load points on the JP-8 show slightly higher HC, at the lean Air/Fuel Ratio (AFR) due to lower in-cylinder temperatures. The HCEI at 50% load was slightly elevated over the higher loads but less than the 25% load points. The 75% and 100% load points show similar HCEI response at all engine speeds. Generally at all engine loads the HCEI shows a trend of decreasing emissions after 210-hours operation, indicating possible further run-in conditioning of the fuel injection system components.

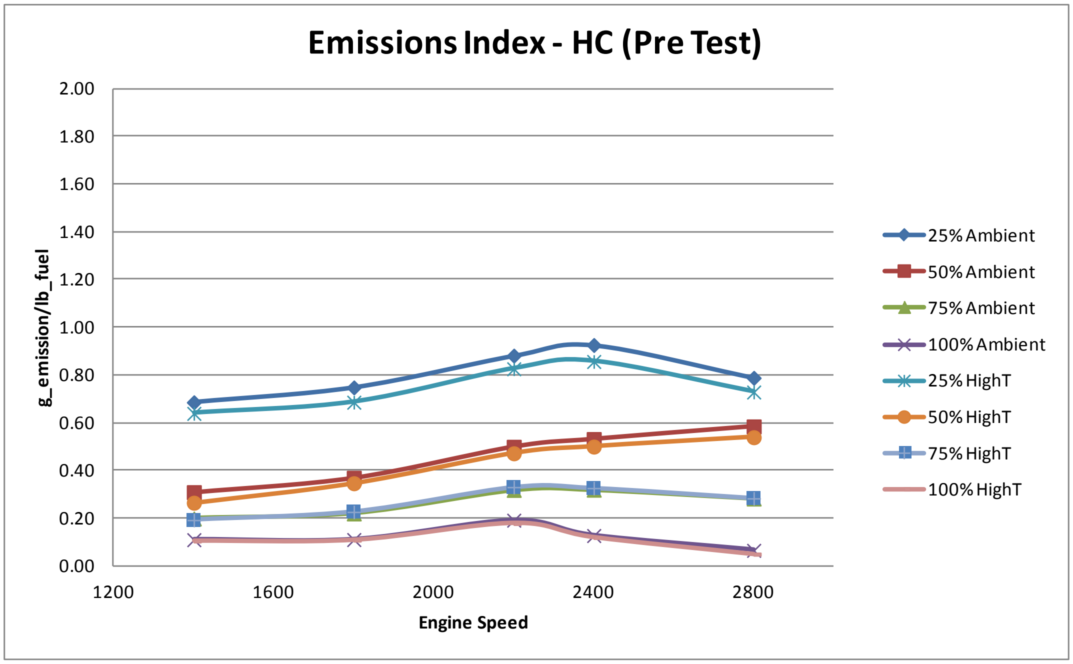


Figure A-12. AF8646 ATJ/JP-8 Blend, Pre Test HC Emission

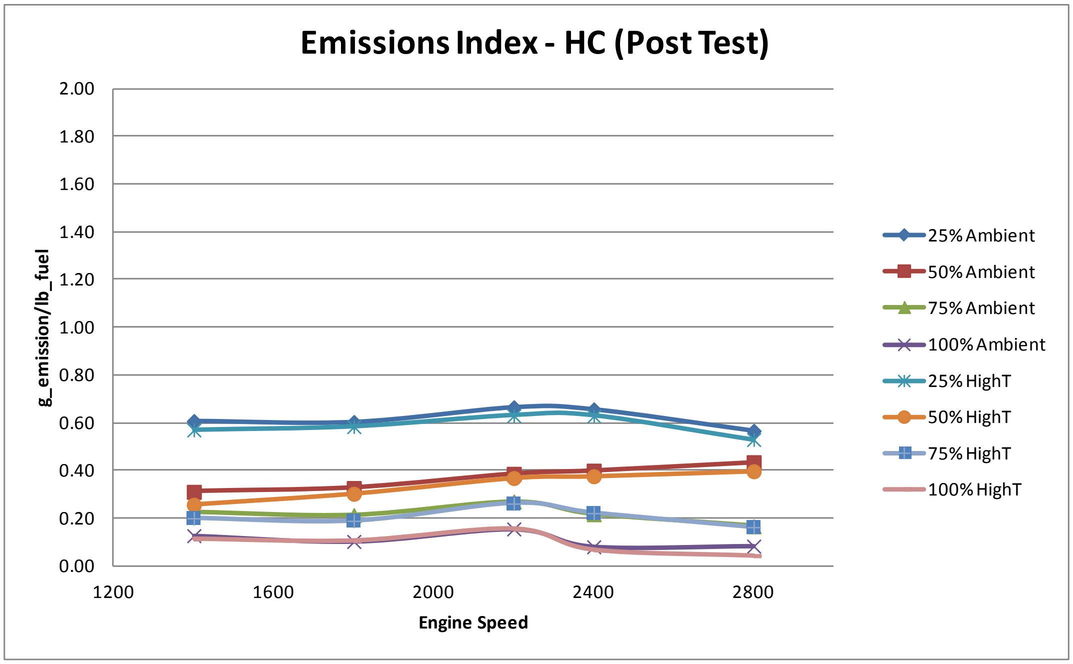


Figure A-13. AF8646 ATJ/JP-8 Blend, Post Test HC Emissions

Figure A-14 and Figure A-15 show the CO Emissions Index (COEI), grams CO/lb fuel, for the ATJ/JP-8 blend over the performance matrices performed at two fuel temperatures, at each testing interval. The 25% load points reveal significantly higher CO due to lower in-cylinder temperatures, and incomplete combustion at lean Air/Fuel Ratios. The 50%, 75%, and 100% load points show similar COEI results at the two lowest engine speeds, but at higher engine speeds the 50% load points exhibit more incomplete combustion. The 75% and 100% load points have very similar COEI response with the ATJ/JP-8 blend. Except for the 25% load points, the COEI increases with increasing engine speed, due to shorter time available for combustion completion. The post-test COEI results indicate an emissions improvement over the test duration.

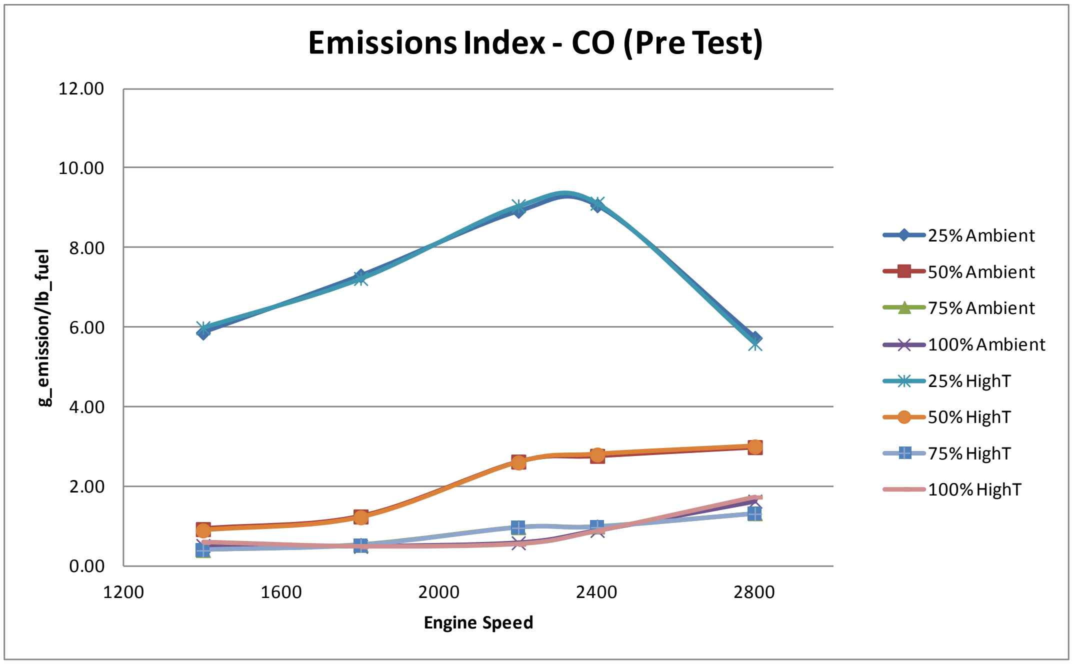


Figure A-14. AF8646 ATJ/JP-8 Blend, Pre Test CO Emissions

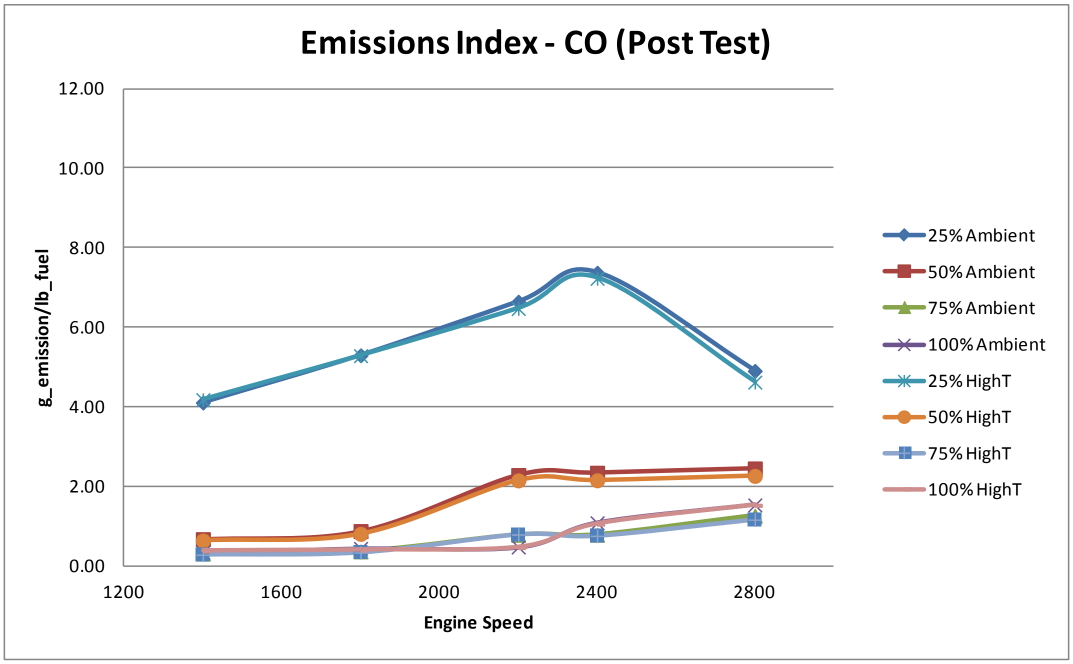


Figure A-15. AF8646 ATJ/JP-8 Blend, Post Test CO Emissions

Figure A-16 and Figure A-17 shows the NO_X Emissions Index (NO_XEI), grams NO_X/lb fuel, for the ATJ/JP-8 fuel over the performance matrices performed at two fuel temperatures, at each testing interval. The 25% and 50% load points show the highest NO_XEI, suggesting a greater portion of premixed burning during the heat release event. As the engine load increases the pilot fuel injection parameters are relatively more effective in rate-shaping the combustion event and the relative amount of NO_X formed decreases. The decrease of NO_XEI with increasing engine speed may be attributed to less premixed fuel from less physical time available for evaporation and mixing during the ignition delay period. The ATJ/JP-8 NO_XEI responses were very consistent throughout the testing. Slight increases in NO_XEI after the durability testing are anticipated due to the prior noted decreases of the HCEI and COEI emissions.

A comparison of the overall averaged criteria pollutant emission indices for the various aviation turbine fuels evaluated in the FORD 6.7L engine to date are shown in Figure A-18. [A-3, A-4, A-5] The results in Figure A-18 are normalized to the emission index values measured with DF-2 fuel. Except for the HCEI of the SPK fuel, the result which was compromised by a leaking turbocharger seal, all alternative source aviation turbine fuels result in lower diesel engine criteria pollutant emission indices.

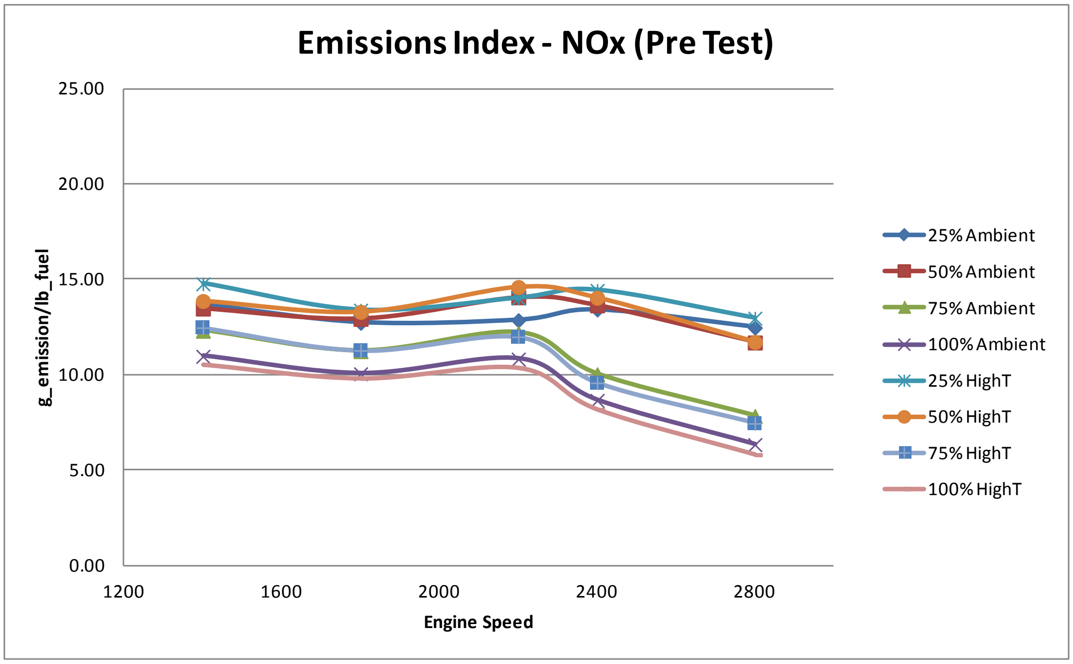


Figure A-16. AF8646 ATJ/JP-8 Blend, Pre Test NOx Emissions

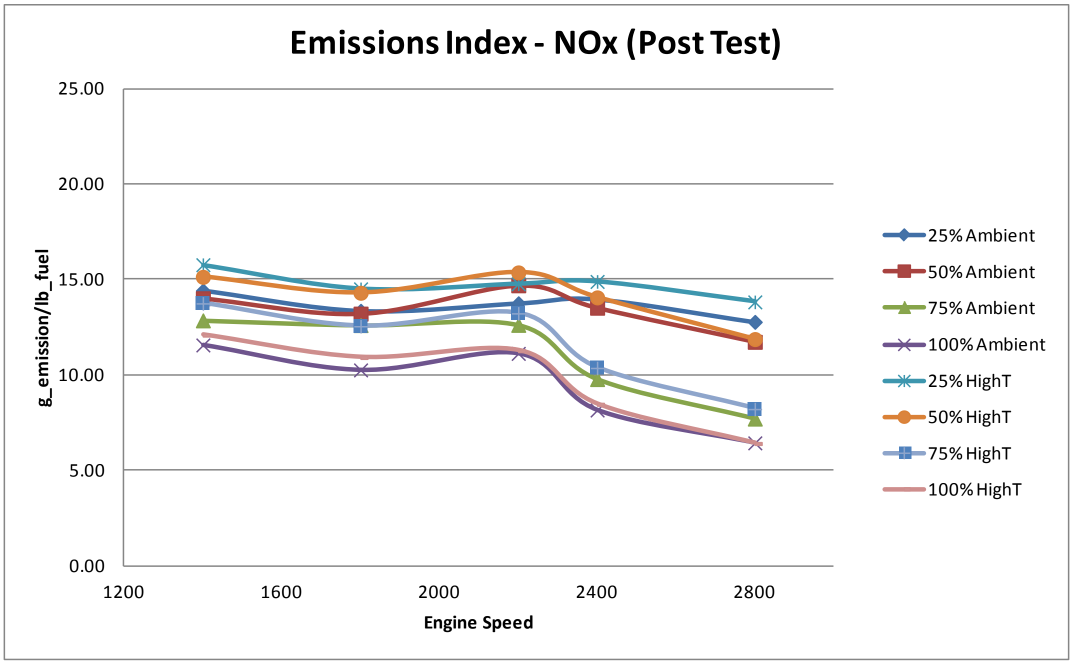
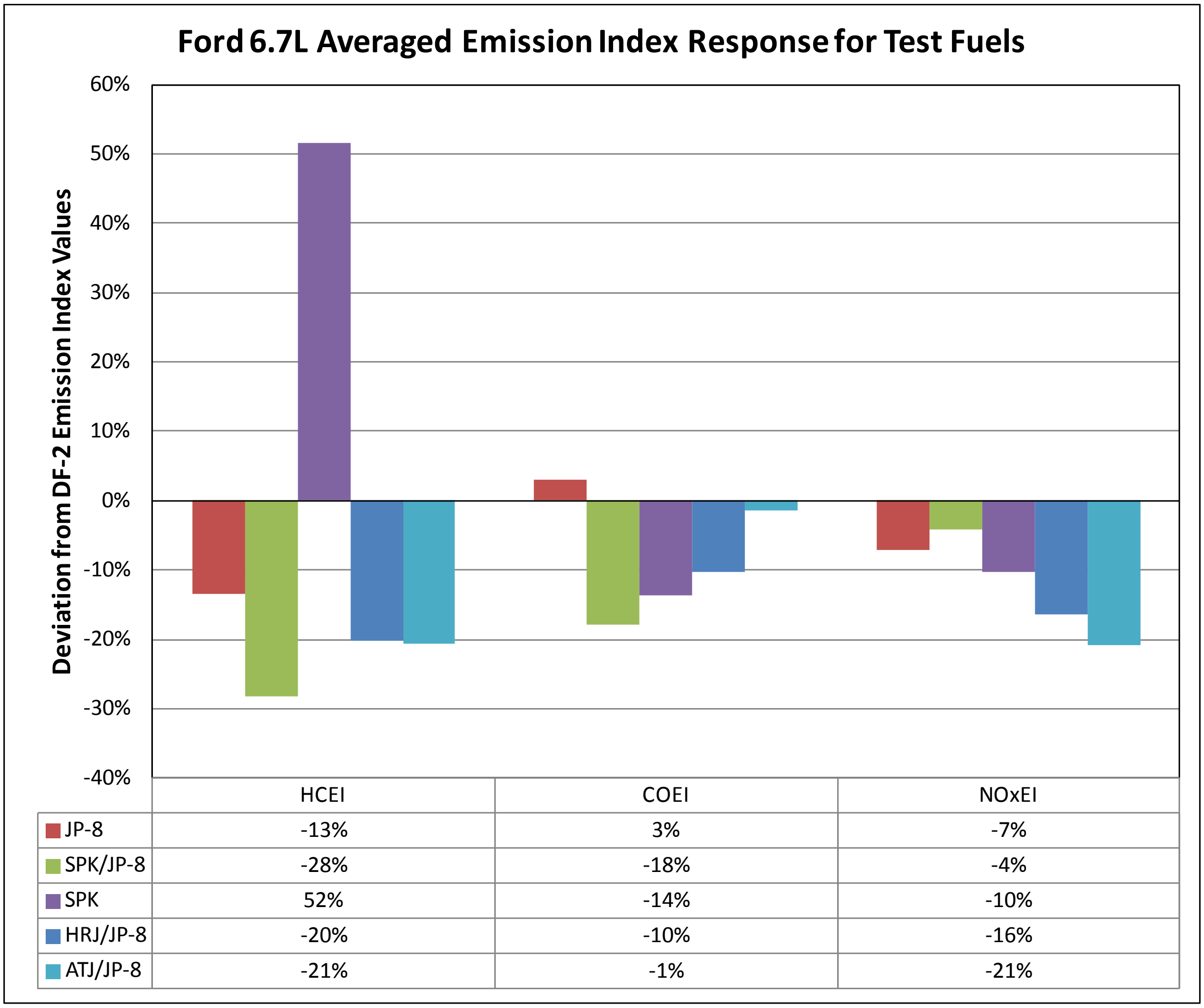


Figure A-17. AF8646 ATJ/JP-8 Blend, Post Test NOx Emissions



	HCEI	COEI	NOxEI
🟥 JP-8	-13%	3%	-7%
🟩 SPK/JP-8	-28%	-18%	-4%
🟪 SPK	52%	-14%	-10%
🟦 HRJ/JP-8	-20%	-10%	-16%
■ ATJ/JP-8	-21%	-1%	-21%

Figure A-18. Emission Response of Various Alternative Source Fuels in FORD 6.7L Engine

A.3.4 Engine Oil Analysis

Table A-10 below shows the engine used oil analysis performed over the test duration. No oil changes were required during the 210-hour test segment. Plots of various pertinent used oil property trends are shown subsequently.

Table A-10. Engine Oil Analysis for 210-hour ATJ/JP-8 Blend Diesel Engine Test

Property (units)	Test Method	Test Hours										
		0	**21**	**42**	**63**	**84**	**105**	**126**	**147**	**168**	**189**	**210**
Density @ 15°C (kg/L)	**D4052**	0.8542	0.8596	0.8601	0.8632	0.8987	0.8702	0.8736	0.8764	0.8808	0.8842	0.8887
Viscosty @ 100°C (cSt)	**D445**	13.9	14.851	14.823	15.087	15.389	15.804	16.209	16.629	17.392	18.107	18.862
Total Acid Number (mg KOH/g)	**D664**	1.87	2	2.04	2.11	2.23	2.47	2.54	2.61	2.8	2.99	3.02
Total Base Number (mg KOH/g)	**D4739**	8.7	7.24	6.79	6.56	6.25	5.92	5.44	5.28	4.8	4.69	4.67
Oxidation (Abs./cm)	**E168 FTIR**	0	32.81	47.6	75.32	92.98	118.85	134.01	145.47	169.22	187.43	342.42
Nitration (Abs./cm)	**E168 FTIR**	0	6.67	10.91	16.54	19.04	25.79	35.12	24.03	23.75	52.31	93.9
Soot (%)	**Soot TGA**	0.314	1.191	1.279	1.79	2.264	3.079	3.773	4.095	4.842	5.477	6.505
Elemental Analysis (ppm)	**D5185**	**Test Hours**										
		0	**21**	**42**	**63**	**84**	**105**	**126**	**147**	**168**	**189**	**210**
Al		1	2	2	2	2	2	3	4	4	5	5
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		71	44	35	30	28	22	20	20	20	18	18
Ca		839	882	874	890	898	925	928	969	988	996	1004
Cr		<1	<1	<1	2	2	2	3	3	4	4	5
Cu		<1	2	<1	1	1	2	2	3	3	3	4
Fe		<1	26	17	32	47	71	95	119	153	178	214
Pb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Mg		1194	1215	1230	1265	1270	1306	1322	1355	1378	1392	1403
Mn		<1	<1	<1	<1	<1	<1	<1	1	1	1	2
Mo		66	69	68	71	71	72	73	75	77	76	78
Ni		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	1
P		1148	1098	1064	1056	1037	1039	1043	1065	1078	1084	1078
Si		5	6	6	6	7	7	7	7	8	8	9
Ag		<1	<1	<1	<1	<1	<1	2	2	3	3	3
Na		7	9	8	8	8	10	9	12	12	12	12
Sn		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Zn		1284	1252	1198	1185	1181	1198	1200	1259	1276	1288	1301
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

A.3.5 Engine Oil Analysis Trends

Figure A-19 shows the lubricant kinematic viscosity change throughout testing with the 5W-40 grade lubricant. The lubricant did thicken, increase out of grade (>16.3 cSt @ 100°C) prior to the 210-hour change, but as shown in Figure A-20 retained reserve alkalinity, or Total Base Number (TBN). Generally in engine testing, the TBN should be kept greater than 4.0, or the TBN should be greater than the Total Acid Number (TAN), to ensure the lubricant provides adequate engine protection. Since the lubricant retained its alkalinity during testing, no lubricant change was required.

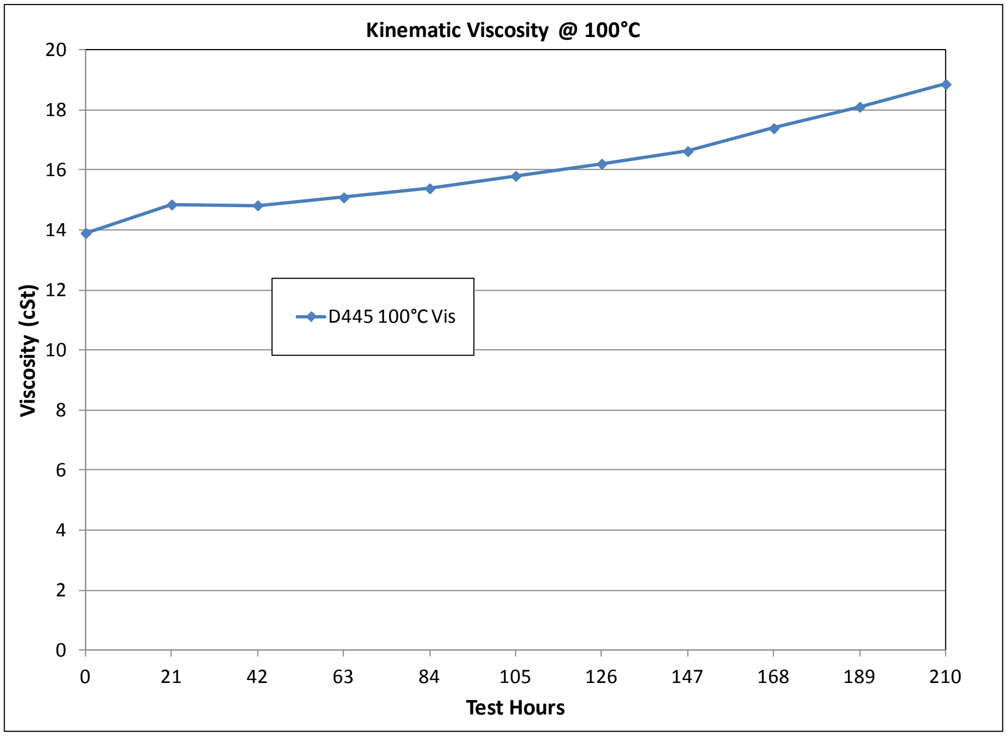


Figure A-19. Lubricant Kinematic Viscosity Change

The soot accumulation in the lubricant is shown in Figure A-21. A comparison of the soot accumulation and the viscosity change suggest soot accumulation in the lubricant was at least partially responsible, along with lubricant oxidation, for the viscosity increases that are shown in Figure A-19.

Elemental analysis of the lubricant for typical wear metals is shown in Figure A-22. The only element with any accumulation is iron (Fe), but the levels are typical for 210-hours operation in the FORD 6.7L engine. Additive elements are shown in Figure A-23, with the major additive elements of Ca, P, Mg, and Zn revealing concentration with test duration.

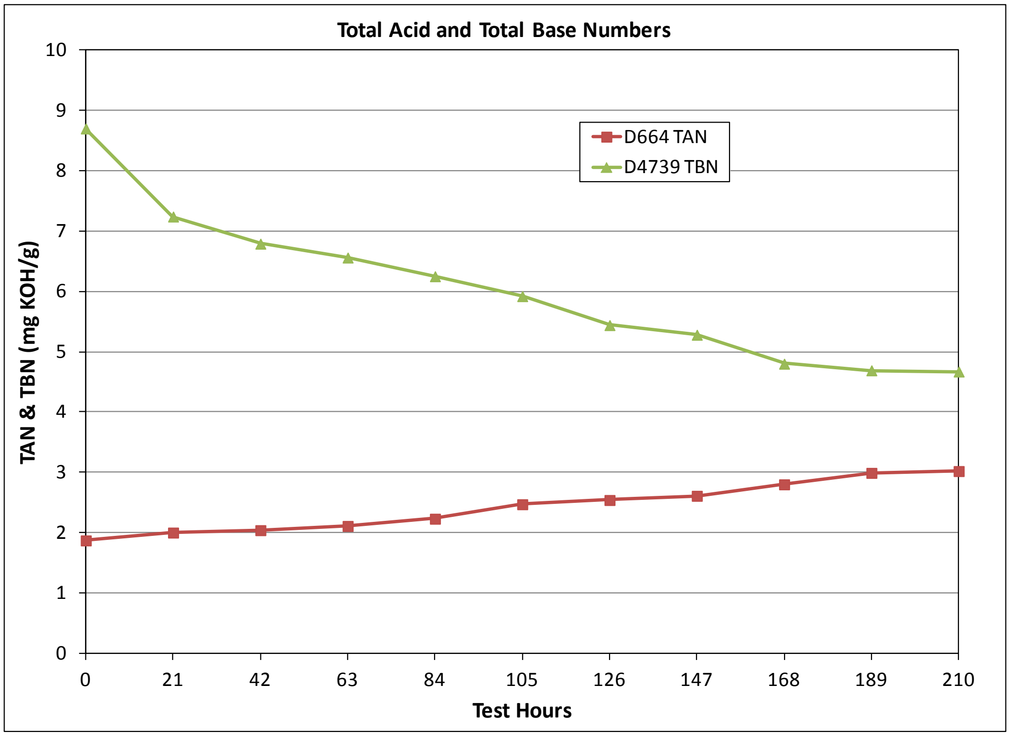


Figure A-20. Lubricant Acid and Base Number Change

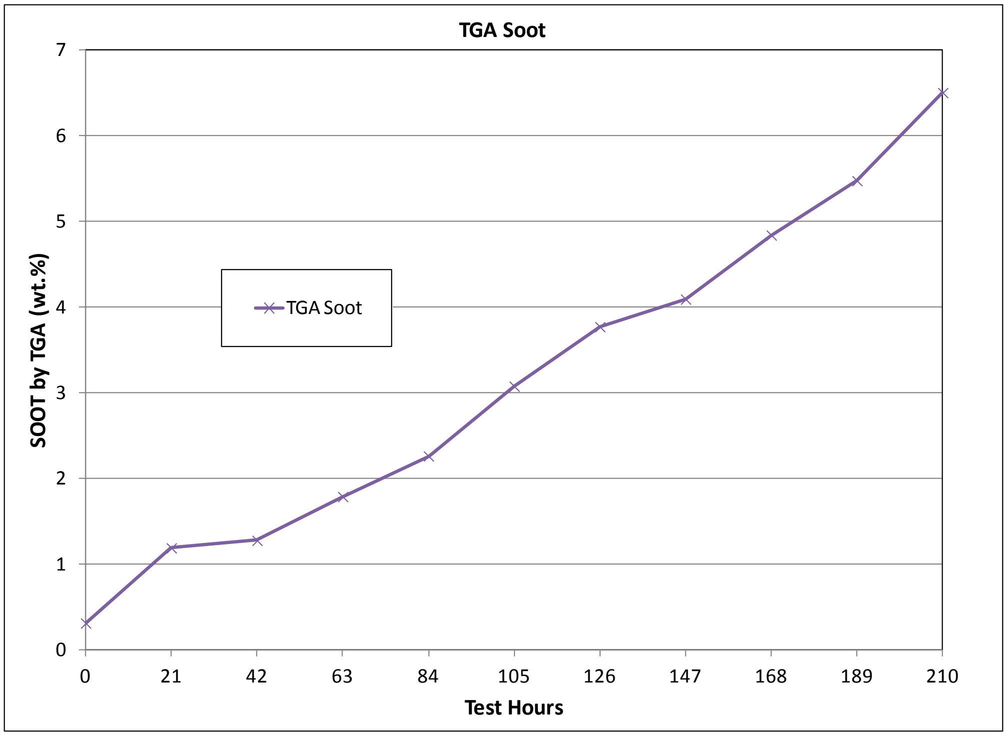


Figure A-21. Lubricant Soot Accumulation

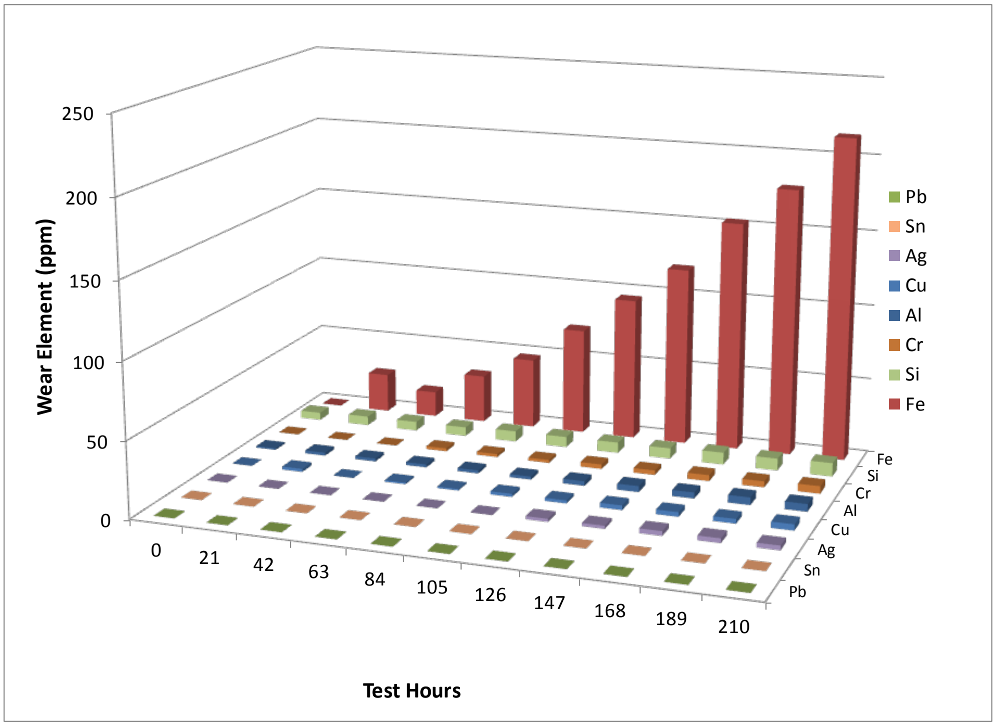


Figure A-22. Wear Metals from Used Lubricant Elemental Analysis

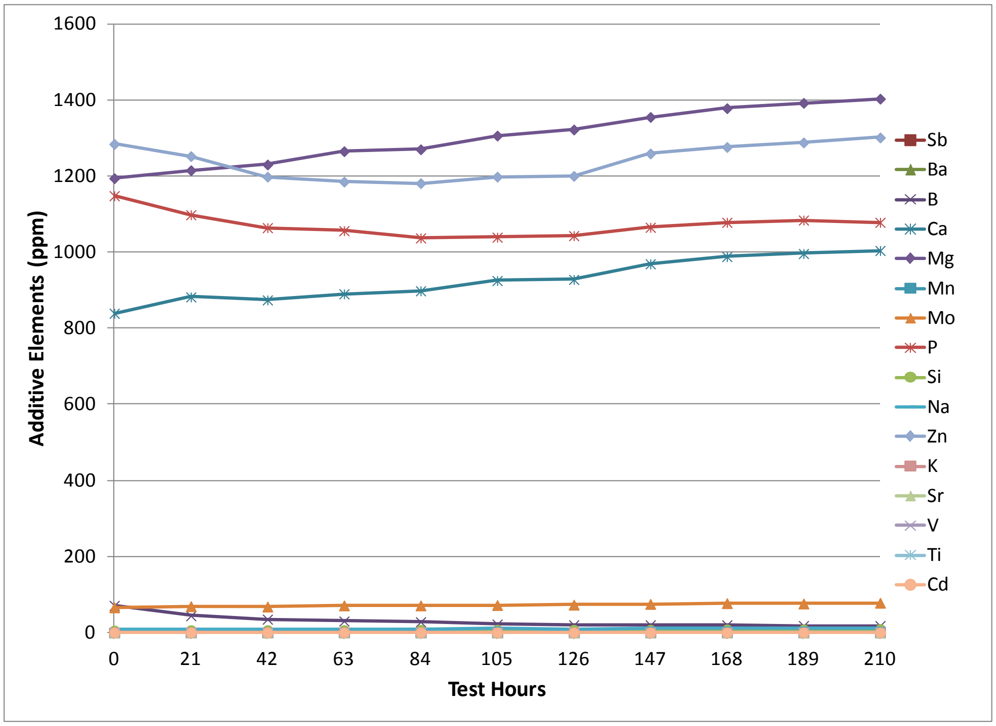


Figure A-23. Additive Metals from Used Lubricant Elemental Analysis

A.3.6 Oil Consumption Data

A tally sheet was kept of lubricant addition and samples from the 6.7L engine during testing. The tally sheet is shown as Table A-11. The average oil consumption per test hour during the ATJ/JP-8 fuel blend testing was 0.026 lbs/hour.

Table A-11. Lubricant Additions Over Test Duration

OIL SAMPLE LOG

Test Time	Date	Sample + Container Weight, lbs		Container Weight, lbs		Sample Weight, lbs	
21	9/12/2013	0.26	-	0.05	=	0.21	
42	9/13/2013	0.30	-	0.05	=	0.25	
63	9/14/2013	0.30	-	0.06	=	0.24	
84	9/15/2013	0.30	-	0.05	=	0.25	
105	9/16/2013	0.30	-	0.06	=	0.24	
126	9/17/2013	0.31	-	0.06	=	0.25	
147	9/18/2013	0.30	-	0.06	=	0.24	
168	9/19/2013	0.30	-	0.06	=	0.24	
189	9/20/2013	0.30	-	0.06	=	0.24	
210	9/21/2013	0.30	-	0.06	=	0.24	
				Total Samples	=	2.40	lbs

OIL ADDITION LOG

Test Time	Date	Sample + Container Weight, lbs		Container Weight, lbs		Sample Weight, lbs	
21	9/12/2013	1.08	-	0.22	=	0.86	
42	9/13/2013	0.70	-	0.22	=	0.48	
63	9/14/2013	1.14	-	0.22	=	0.92	
84	9/15/2013	0.83	-	0.22	=	0.61	
105	9/16/2013	1.20	-	0.22	=	0.98	
126	9/17/2013	1.94	-	0.22	=	1.72	
147	9/18/2013	0.00	-	0.00	=	0.00	
168	9/19/2013	1.38	-	0.22	=	1.16	
189	9/20/2013	0.00	-	0.00	=	0.00	
210	9/21/2013	1.42	-	0.22	=	1.20	
				Total Additions	=	7.93	lbs
				Total Oil Used	=	5.53	lbs
				Oil Consumption Rate	=	0.026	lbs/hr

A.3.7 Post Test Fuel Injection Hardware Inspection

The fuel injection pump can be broken down into four critical areas for evaluation: the interface of the fuel pump body bore and cam follower, cam and roller interface, cam and bushing (bearing) interface, and high pressure plunger and barrel. A visual inspection and description of each of these components can be seen below in Table A-12, followed by a discussion of wear present and representative pictures. Overall inspections indicate the wear seen after 210-hours operation with the ATJ/JP-8 fuel blend was found to be similar to the wear results seen in all earlier Army/Air Force tests with the 6.7L engine with alternative sourced aviation turbine fuels. [A-3, A-4, A-5]

Table A-12. Fuel Injection System Component Inspections for Various Test Fuels

Hours	0	210	210	210	210	420	210	210
Part\Fuel	**New**	**DF-2**	**JP-8**	**SPK/JP-8**	**SPK**	**HRJ/JP-8**	**JP-8-70°C FIT**	**ATJ/JP-8**
Volume Control Valve	New	As new	As new	As new	As new	As new	As new	As new
Pump Body	Very light polish of bores	Very light polish of bores, top & bottom	Very light polish of bores, top & bottom	Light polish & light scuff of bores, top & bottom	Light polish & very light scuff of bores, top & bottom	Light polish & very light scuff of bores, top & bottom	Light polish & very light scuff of Left & Right bores, top & bottom; Right bore mild scuff at bottom	Light polish & very light scuff of Left & Right bores, top & bottom
Pump Bushings	Both new	Both as new	Both as new	Both as new	Both as new	Discoloration at zones corresponding to load direction, otherwise as new	Discoloration at zones corresponding to load direction, otherwise as new	Discoloration at zones corresponding to load direction, otherwise as new
Cam	Visible light grinding marks	Light polish, not measureable, seal contact wear	Light polish & very light burnish, not measureable, seal contact wear	Polish & light burnish, not measureable, seal contact wear, journals V.L. burnish	Light polish & very light burnish, not measureable, seal contact wear	Light polish & very light burnish, not measureable, seal contact wear	Light polish & very light burnish, not measureable, seal contact wear	Light polish & very light burnish, not measureable, seal contact wear

Table A-12. Fuel Injection System Component Inspections for Various Test Fuels *(Cont'd)*

Hours	**0**	**210**	**210**	**210**	**210**	**420**	**210**	**210**
Part\Fuel	**New**	**DF-2**	**JP-8**	**SPK/JP-8**	**SPK**	**HRJ/JP-8**	**JP-8-70°C FIT**	**ATJ/JP-8**
Roller - L	New, bright & shiny	Light polish	Very light burnish & polish	Light burnish & polish, Heavy roller end wear against follower	Very light burnish & polish	Very light burnish & polish	Very light burnish & polish	Very light polish
Roller - R	New, bright & shiny	Light polish	Very light burnish & polish	Light burnish & polish	Very light burnish & polish	Very light burnish & polish	Very light burnish & polish	Very light polish
Roller Shoe - L	New	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button
Roller Shoe - R	New	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button	New, polish from plunger button

Table A-12. Fuel Injection System Component Inspections for Various Test Fuels *(Cont'd)*

Hours	0	210	210	210	210	420	210	210
Part\Fuel	**New**	**DF-2**	**JP-8**	**SPK/JP-8**	**SPK**	**HRJ/JP-8**	**JP-8-70°C FIT**	**ATJ/JP-8**
Follower - L	New	Very light polish	Polish, very light scuff, top & bottom	Polish, light scuff, top & bottom	Polish, very light scuff, top & bottom	Polish, light scuff, top & bottom	Polish, light scuff, top & bottom	Light polish, very light scuff, top & bottom
Follower - R	New	Very light polish	Polish, very light scuff, top & bottom	Polish, light scuff, top & bottom	Polish, very light scuff, top & bottom	Polish, light scuff, top & bottom	Polish, light scuff, top & bottom, mild scuff side corresponding to pump bore mild scuff	Light polish, very light scuff, top & bottom
Plunger - L	New	Very light polish on plunger button, more than right	Light polish on plunger button, more than right	Light polish on plunger button, more than right, more polish than JP-8	Light polish on plunger button, more than right	One very light circumferential scratch, light polish on plunger button, more than right	Light polish on plunger button	Light polish on plunger button
Plunger - R	New	Very light polish on plunger button	Light polish on plunger button	Light polish on plunger button	Light polish on plunger button	Light polish on plunger button	Light polish on plunger button	Light polish on plunger button
Barrel – L	New	As new	As new	As new	As new	As new	As new	As new
Barrel – R	New	As new	As new	As new	As new	As new	As new	As new
Inlet Check – L	New	As new	As new	As new	As new	As new	As new	As new
Inlet Check – R	New	As new	As new	As new	As new	As new	As new	As new

A.3.8 Post Test Fuel Injection Hardware Photos (No Magnification)

The following photos document the post test fuel injection hardware condition. Figure A-24 and Figure A-25 below show a representative photo of the HPCR pump body. Frame of reference for left and right notations are taken from Figure A-25 as the pump is installed in the engine.

Figure A-24. HPCR Pump Body, Front (Representative Photo)

Figure A-25. HPCR Pump Body, Rear (Representative Photo)

Figure A-26 shows the left hand pump body bore. Figure A-27 shows a close up picture of the light polish and very light scuffing found on the bore surface from interaction with the cam follower assembly. The wear present on the pump body bore and cam follower surfaces were found to be similar to previous fuels testing. The bores in each of the pumps showed some polishing on their surface from interactions with the cam follower. Markings tended to be present primarily at the top and bottom of the travel area of the follower, which is consistent with areas of largest side loading present on the follower from the forces applied by the pumps camshaft and plunger return spring. A new unused pump also shows similar but smaller markings likely produced at end of line testing during manufacturing.

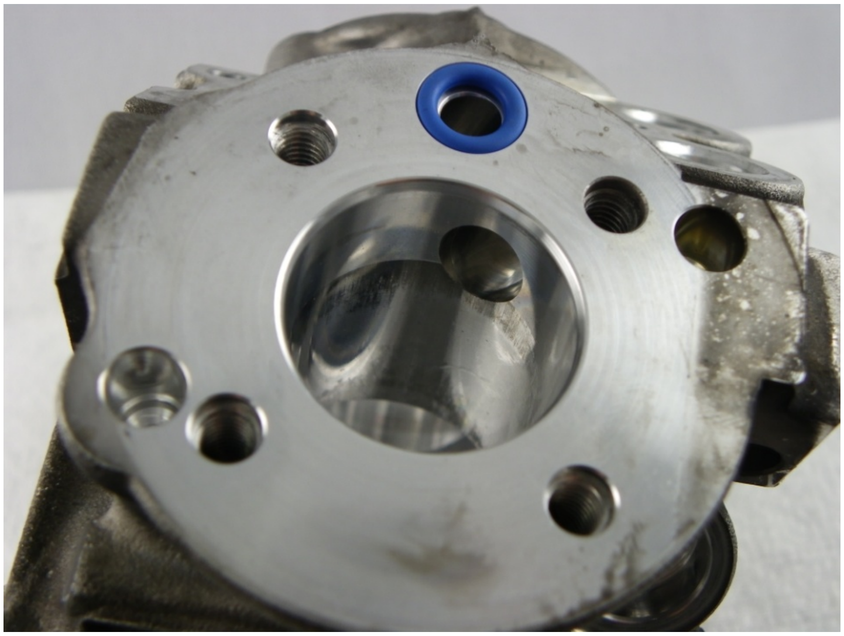


Figure A-26. AF8646 ATJ/JP-8 Blend, Post Test, Left Pump Bore

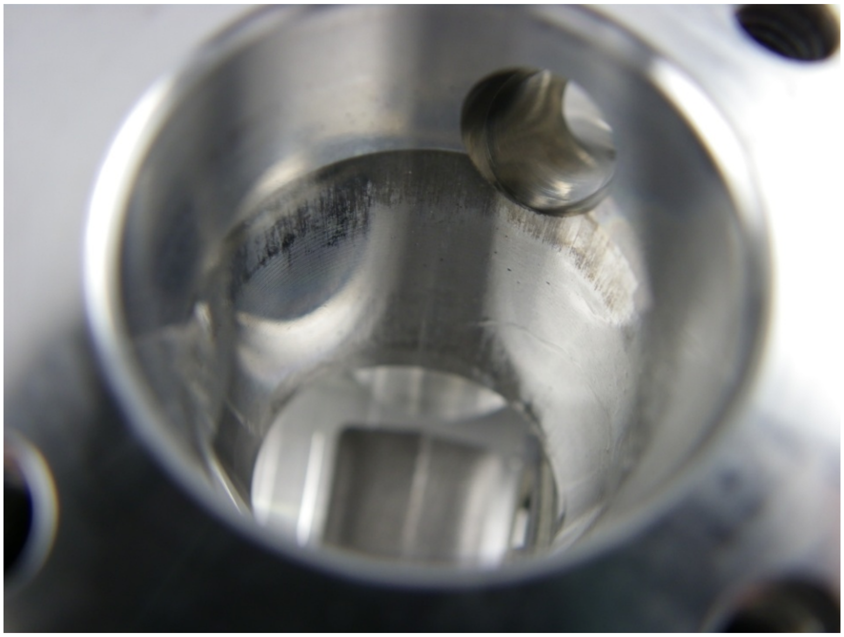


Figure A-27. AF8646 ATJ/JP-8 Blend Post Test, Left Pump Bore Close

Figure A-28 shows the right hand pump body bore. Figure A-29 below shows a close up picture of the light polish found on the bore surface, similar to the left hand bore. The follower bore wear for the left and right sides of the pump were very similar.

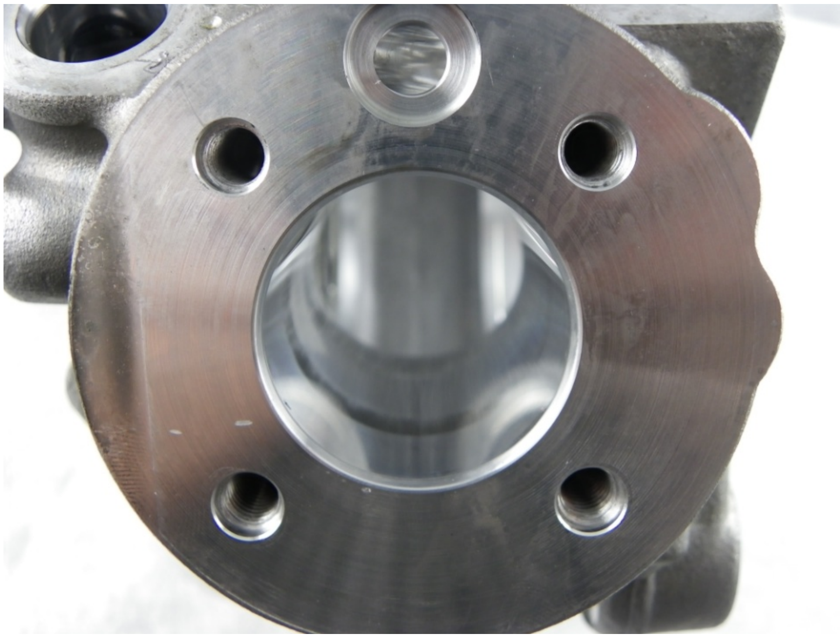


Figure A-28. AF8646 ATJ/JP-8 Blend, Post Test, Right Pump Bore

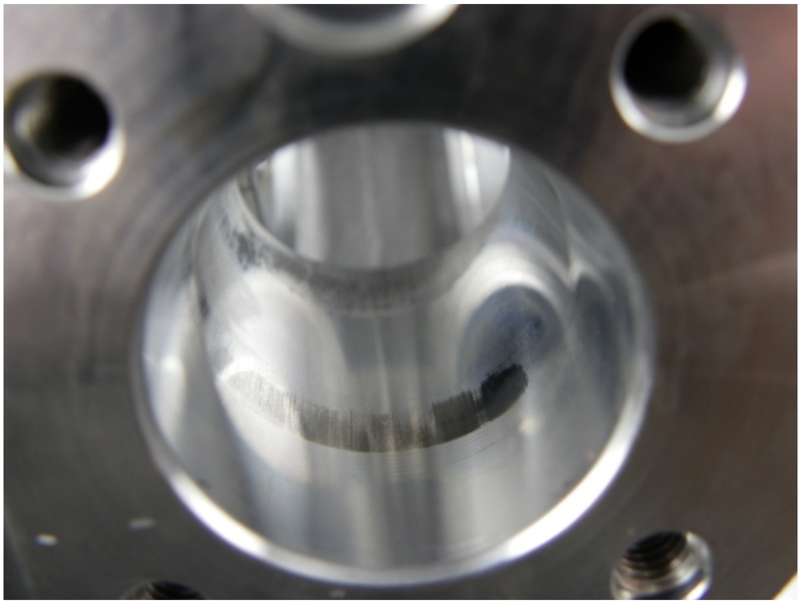


Figure A-29. AF8646 ATJ/JP-8 Blend, Post Test, Right Pump Bore Close

Figure A-30 shows the left bore cam follower and roller assembly. The follower was oriented to show the most severe areas of wear present on the follower surface. All follower surfaces showed only minor polishing and very light scuffing on their surfaces consistent with the polishing found on the pump bore surface. This again corresponded with areas that typically experience the greatest side load forces. Figure A-31 below shows the left hand roller surface, with very light polishing evident.

Figure A-30. AF8646 ATJ/JP-8 Blend, Left Cam Follower

Figure A-31. AF8646 ATJ/JP-8 Blend, Left Cam Follower Roller

Figure A-32 shows the left cam follower under crown and the contact area with the high pressure plunger head. Figure A-33 shows the left hand high pressure plunger. Note the similar contact markings where it contacts the follower under crown. Polishing at this interface was visible, but no physical wear was tactilely distinguishable.

Figure A-32. AF8646 ATJ/JP-8 Blend, Left Cam Follower Under Crown

The barrel and plunger assemblies for the test did not show any wear distinguishing themselves from the new unused components. All surfaces treating to the high pressure plunger was intact and showed no variation. The inside diameter of the barrel surfaces also appeared to be smooth and unworn.

Figure A-33. AF8646 ATJ/JP-8 Blend, Left High Pressure Plunger

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Figure A-34 shows the right bore cam follower and roller assembly. The follower was oriented to show the most severe areas of wear present on the follower surface. All follower surfaces showed only minor polishing and very light scuffing on their surfaces consistent with the polishing found on the pump bore surface. Figure A-35 below shows the right hand roller surface. The follower and roller wear for the left and right sides of the pump were very similar overall to wear seen in previous testing.

Figure A-34. AF8646 ATJ/JP-8 Blend, Right Cam Follower

Figure A-35. AF8646 ATJ/JP-8 Blend, Right Cam Follower Roller

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Figure A-36 shows the right cam follower under crown and the contact area with the high pressure plunger head. Figure A-37 shows the right hand high pressure plunger. Similar to the left hand assembly, polishing at this interface was visible, but no physical wear was tactilely distinguishable. The right barrel and plunger assembly wear was similar to that seen on the left, and similar to all previously run test fuels.

Figure A-36. AF8646 ATJ/JP-8 Blend, Right Cam Follower Under Crown

Figure A-37. AF8646 ATJ/JP-8 Blend, Right High Pressure Plunger

Figure A-38 and Figure A-39 below show the pump body rear and front camshaft bushings respectively. The bushings showed no signs of wear with the ATJ/JP-8 fuel blend. This was consistent with all of the other fuels tested in the 6.7L engine using the wheeled vehicle cycle.

Figure A-38. AF8646 ATJ/JP-8 Blend, Rear Pump Body Camshaft Bushing

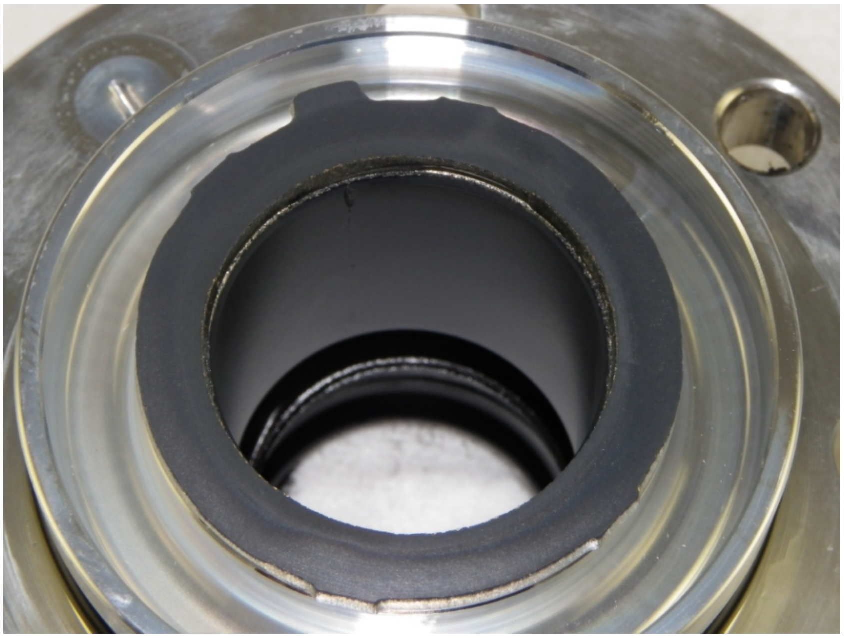

Figure A-39. AF8646 ATJ/JP-8 Blend, Front Pump Body Camshaft Bushing

Figure A-40 shows the HPCR fuel injection pump camshaft for the ATJ/JP-8 test. As was seen with the other tests, only light burnishing is present at the cam lobe/roller follower contact, and slight wear is seen at the contact location of the shaft seal.

Figure A-40. AF8646 ATJ/JP-8 Blend, HPCR Pump Camshaft

Figure A-41 shows a close-up of one of the cam lobe peaks, which is in very good condition with only light polish and light burnishing for the fuel lubricated, heavily loaded contact.

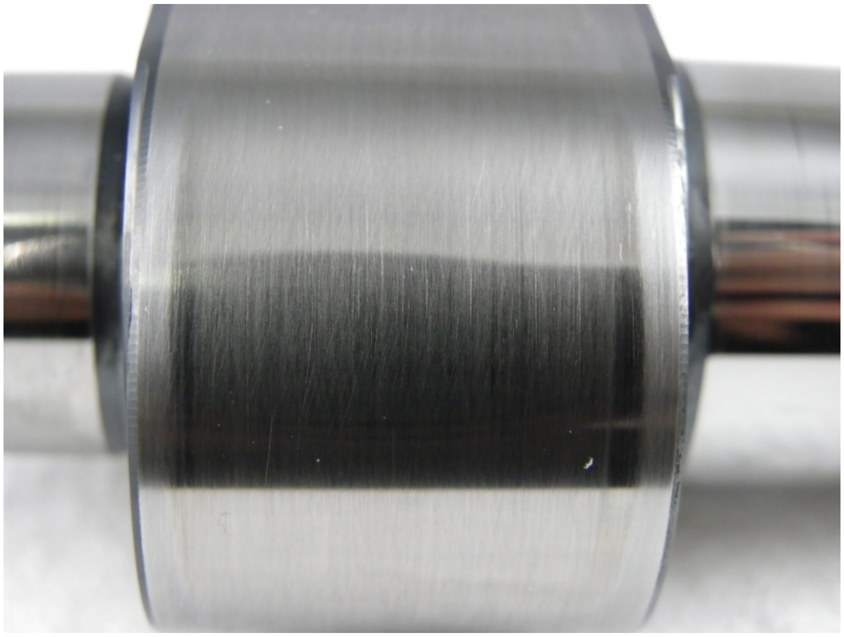

Figure A-41. AF8646 ATJ/JP-8 Blend, HPCR Pump Camshaft, Lobe Surface Close-Up

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A.3.9 Post Test Fuel Injection High Magnification Photos

Consistent with the high pressure fuel pump inspection, fuel injectors from the test were removed and disassembled for inspection and photographs. Due to the size of the fuel injectors internal components, many photos were taken under magnification to better determine any wear patterns present. Inspections were made to the hydraulic coupler pistons, control valve, control plates, injector needle, and nozzle.

Figure A-42 shows the injector nozzle tip. No substantial deposit formations were seen under low magnification. Figure A-43 below shows the injector needle tip. No abnormal wear, deposits, or markings were found on the tapered tip.

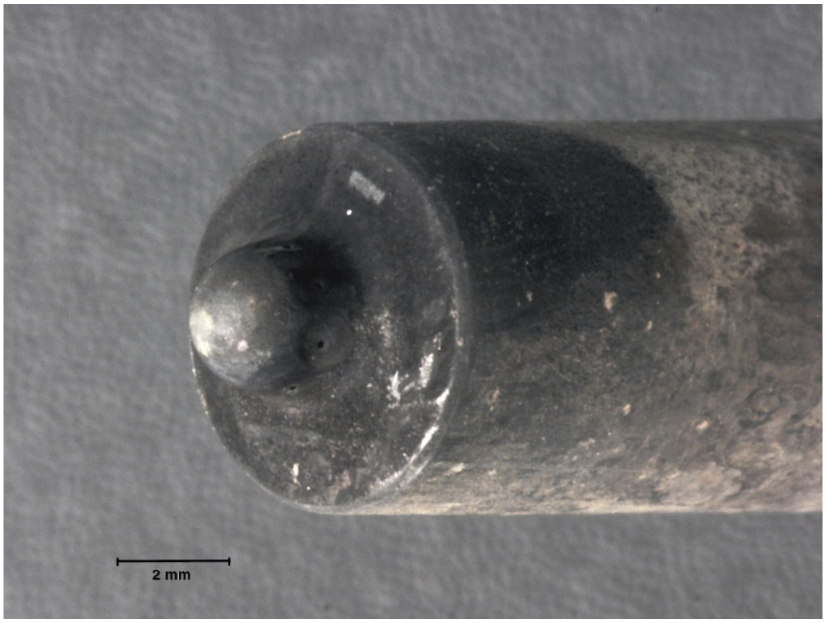

Figure A-42. AF8646 ATJ/JP-8 Blend, Injector Nozzle

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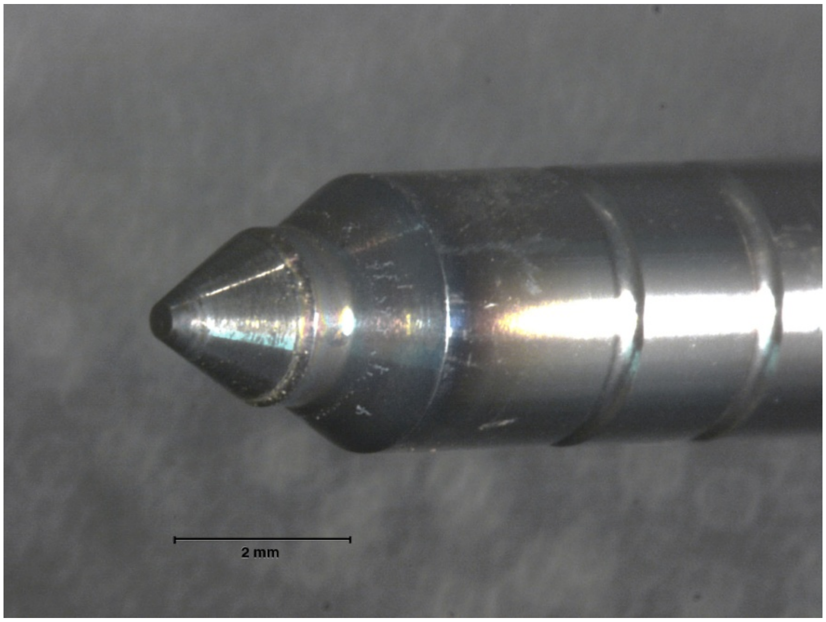

Figure A-43. AF8646 ATJ/JP-8 Blend, Injector Needle

Consistent with what was seen in previous testing, the only internal injector components showing any appreciable wear patterns were the upper pistons of the hydraulic coupling. As previously explained in the fuel system description section, the hydraulic coupler is used to translate the small linear movement of the piezoelectric-stack to a larger linear movement to operate the injector control valve and regulate needle lift. From the inspection, it appeared that the piezoelectric-stack imparts a slight side load on the upper piston causing a reacting wear scar to be formed on the outer piston surface. This wear scar was seen in each of the test fuels in previous testing, and was found to be slightly more severe in size and condition for the ATJ/JP-8 evaluation, but did not impact engine operation or emissions. Figure A-44 and Figure A-45 show the side profile of the upper hydraulic coupler piston. Although this wear did not impact the testing at hand, this type of wear is typical of wear that can be detrimental to fuel injector function if continued. Binding or sticking of the hydraulic coupler has the potential to impair the action of the control valve which can potentially result in no fuel being injected into the engine, or a constant flow of injected fuel. Either of these occurring during engine operation would require immediate fuel injector replacement to ensure proper engine operation.

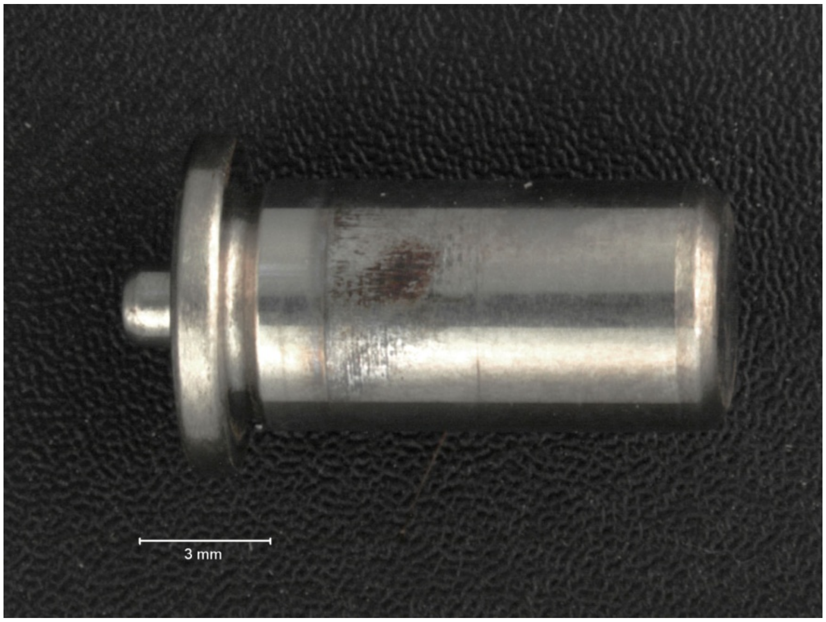

Figure A-44. AF8646 ATJ/JP-8 Blend, Upper Hydraulic Coupler Piston, Profile

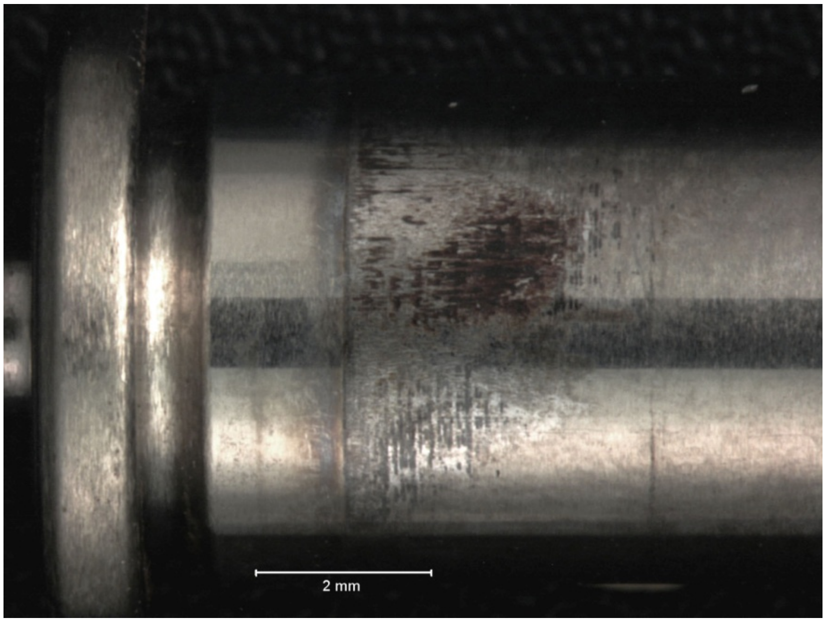

Figure A-45. AF8646 ATJ/JP-8 Blend, Lower Hydraulic Coupler Piston, Wear Scar Close Up

Figure A-46 and Figure A-47 show the upper and lower hydraulic coupler pistons contact surfaces respectively. No noticeable wear was seen on the piston surface interface, or at the heads of the piston at the piezoelectric stack and control valve interface.

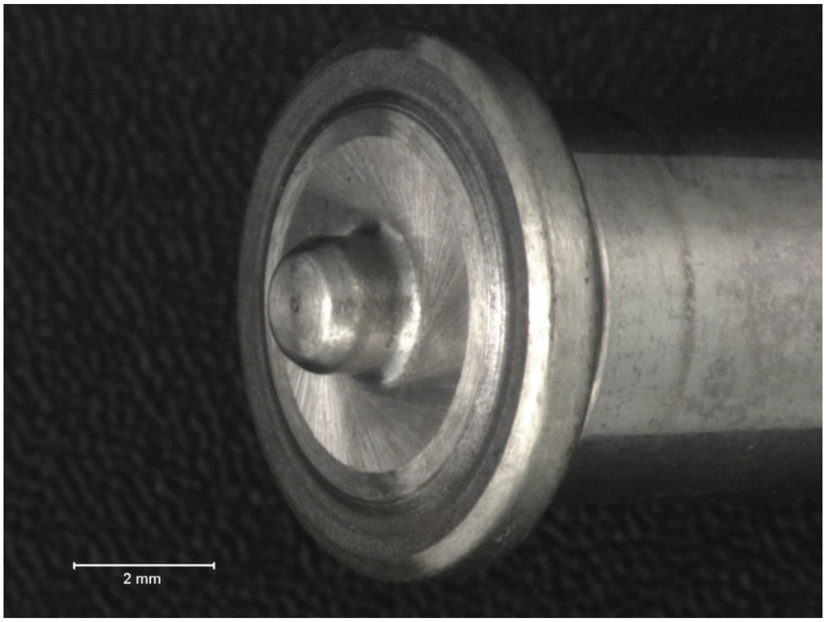

Figure A-46. AF8646 ATJ/JP-8 Blend, Upper Hydraulic Coupler Piston

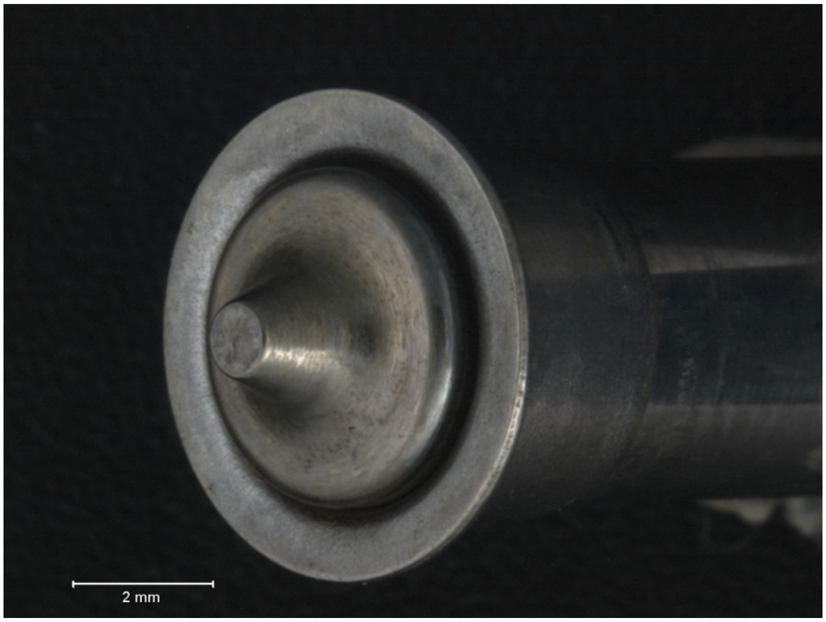

Figure A-47. AF8646 ATJ/JP-8 Blend, Lower Hydraulic Coupler Piston

Figure A-48 and Figure A-49 show the top and bottom surfaces of the intermediate plate. This plate contains the fuel control passages used to manipulate the needle position. Some fuel deposition is seen in Figure A-48 that did not interfere with injector, or engine function.

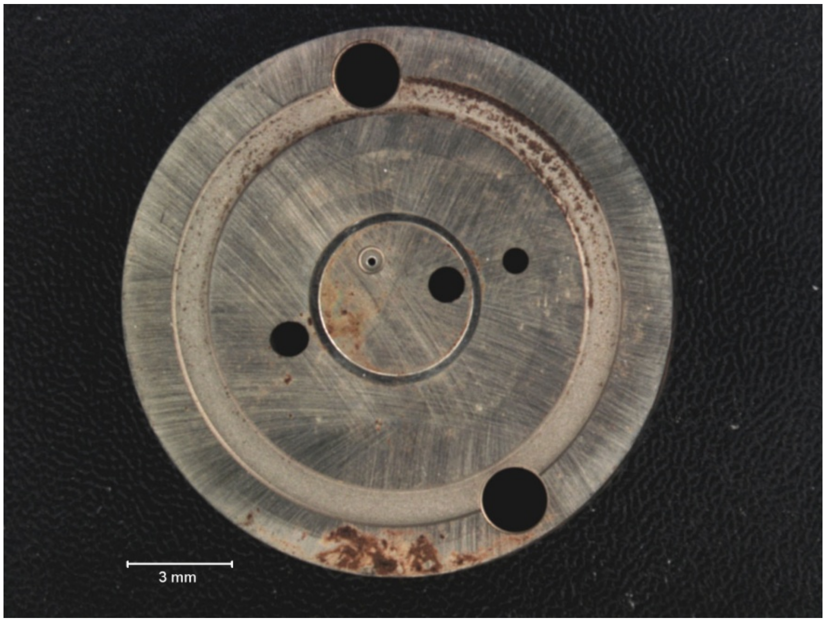

Figure A-48. AF8646 ATJ/JP-8 Blend, Intermediate Plate (Top)

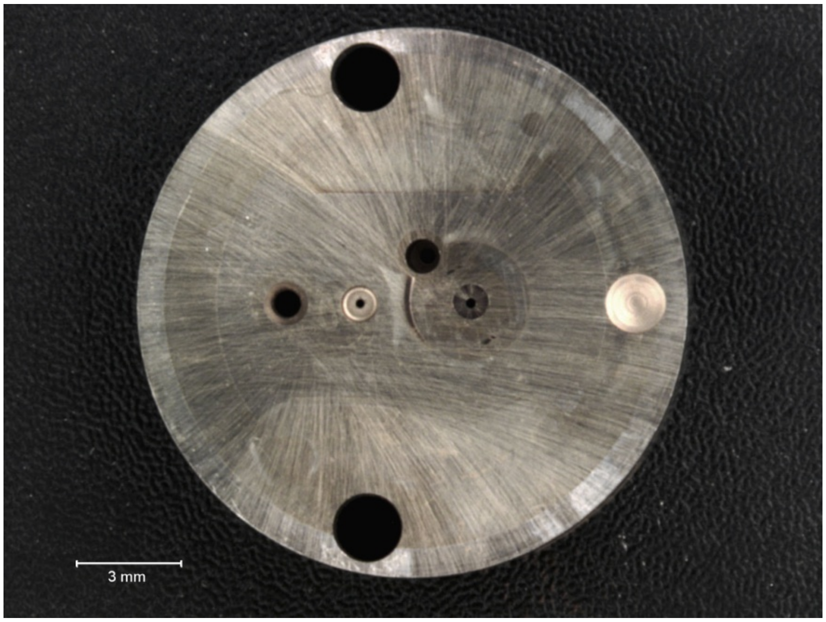

Figure A-49. AF8646 ATJ/JP-8 Blend, Intermediate Plate (Bottom)

Figure A-50 and Figure A-51 show the top and bottom of the control valve plate. Similar to previous testing, light fuel deposition was evident on the surfaces. The control valve sits in the bore shown in Figure A-51. The lower piston of the hydraulic coupler operates in the bore shown in Figure A-50.

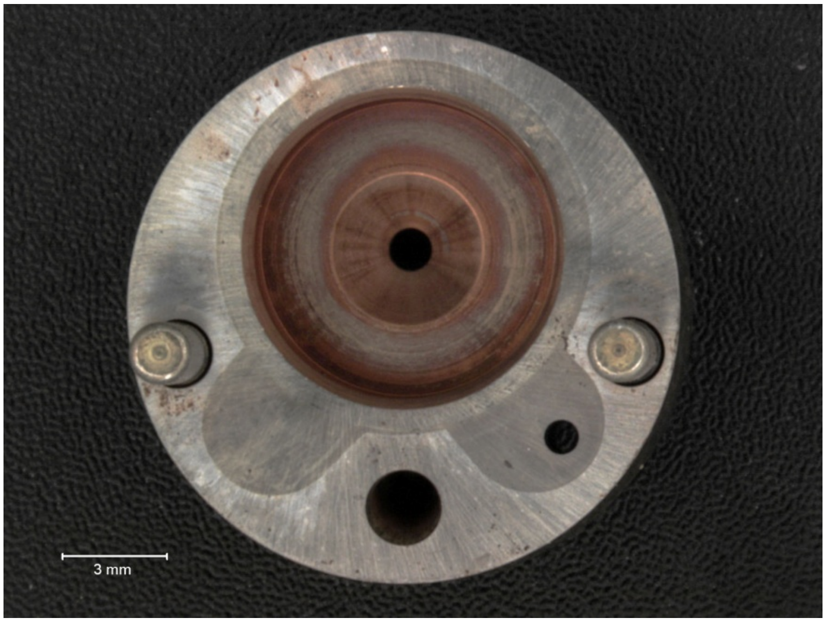

Figure A-50. AF8646 ATJ/JP-8 Blend, Control Valve Plate (Top)

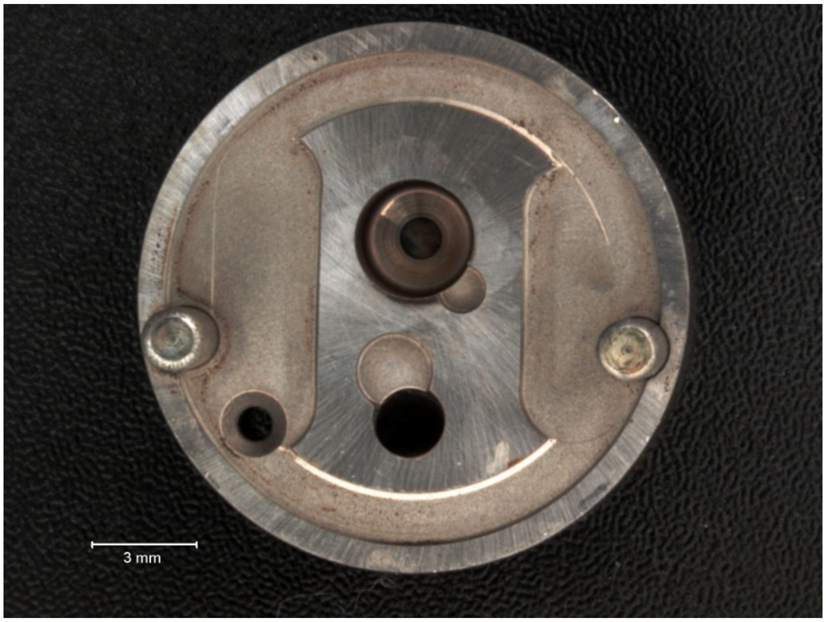

Figure A-51. AF8646 ATJ/JP-8 Blend, Control Valve Plate (Bottom)

Figure A-52 shows the control valve which regulates the pressure on top of the injector needle, thus controlling needle lift and injection timing. No unusual wear was found on the control valve.

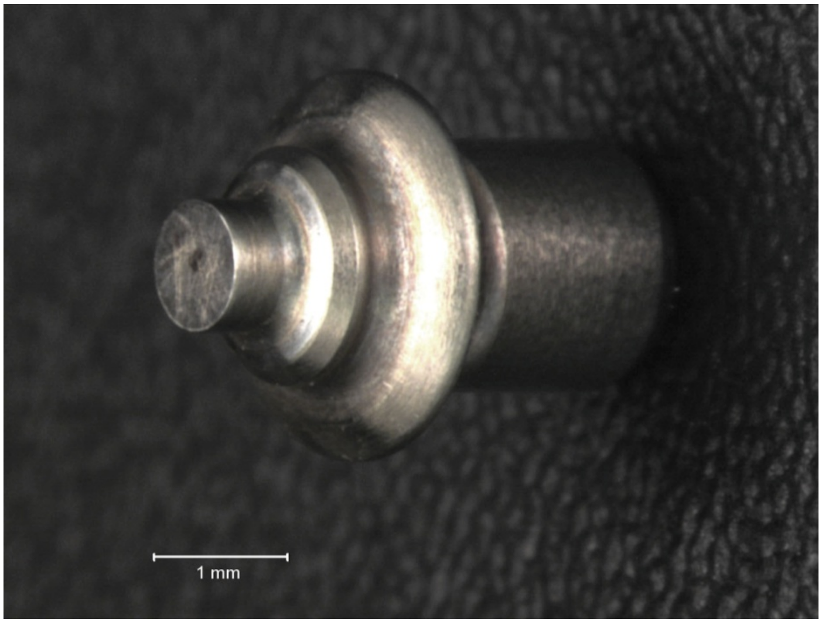

Figure A-52. AF8646 ATJ/JP-8 Blend, Fuel Injector Control Valve

A.4.0 CONCLUSIONS

Testing conducted supports that the Ford 6.7L fuel lubricated high pressure common rail fuel injection system can be successfully operated using an ATJ/JP-8 fuel blend at nominal ambient fuel inlet temperatures. Even at the close to minimum lubricity enhancing treat rates, the tested ATJ/JP-8 fuel provided adequate component protection and system performance when compared to previous fuels testing. No unusual fuel related operating conditions were experienced throughout testing, and engine performance remained consistent and satisfactory throughout. Post test fuel injection system inspections found used components to be in similar condition throughout all tests operated to date for U.S. Army and U.S. Air Force test fuel programs performed by SwRI in the Ford 6.7L engine. [A-3, A-4, A-5]

A.5.0 RECOMMENDATIONS

Ford 6.7L fuel injection system robustness has been observed utilizing a wide range of petroleum and synthetic test fuels at nominal fuel inlet temperatures, and with a petroleum JP-8 fuel at high fuel inlet temperatures. It is recommended high fuel inlet temperatures testing with synthetic kerosene fuels, that also may exhibit low density and low viscosity, be evaluated in the Ford 6.7L engine.

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A.6.0 REFERENCES

[A-1] Development of Military Fuel/Lubricant/Engine Compatibility Test, CRC Report 406, January 1967.

[A-2] Electronic Code of Federal Regulations, Title 40, Part 86, Subpart D, March 15, 2011.

[A-3] Brandt, Adam; Yost, Douglas, "Evaluation of Military Fuels using a Ford 6.7L Powerstroke Diesel Engine", Interim Report TFLRF No. 415, August 2011, ADA560574.

[A-4] Brandt, A.C. and Yost, D.M., "Evaluation of 50/50 Hydroprocessed Renewable Jet Fuel & JP-8 in the Ford 6.7L High Pressure Common Rail Diesel Engine", AFRL-RQ-WP-TR-2013-0007, December 2012, ADA583392.

[A-5] Yost, D.M., Brandt, A.C., Advanced Propulsion Fuels Research and Development Support to AFRL/RZPF Task Order 0011: Rapid Response Research and Development (R&D) for Propulsion Directorate, Final Report, Appendix D, "Evaluation of JP-8 at High Temperature in the Ford 6.7L High Pressure Common Rail Diesel Engine", AFRL-RZ-WP-TM-2013-0010, December 2012.

Appendix B

Task 5 – Pump Tests

JP-8 AND ATJ/JP-8 ROTARY FUEL INJECTION PUMP WEAR TESTING

Prepared by

Douglas M. Yost, Principal Engineer

Southwest Research Institute® (SwRI®)
San Antonio, TX

Prepared for

Universal Technology Corporation

July 2014

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Acronyms and Abbreviations

AFRL	Air Force Research Laboratory
ATJ	Alcohol to Jet Fuel
BOCLE	Ball On Cylinder Lubricity Evaluator
CARB	California Air Resources Board
cc	Cubic Centimeter, volume measure
CI/LI	Corrosion Inhibitor/Lubricity Improver
FT	Fischer-Tropsch
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
HFRR	High Frequency Reciprocating Rig
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
kW	Kilowatt
mg/L	milligrams per Liter concentration
MI	Michigan
MIL-DTL-25017	Military Performance Specification number 25017
QPL	Qualified Products List
RDECOM	Research, Development, and Engineering Command
rpm	Revolutions Per Minute
SLBOCLE	Scuffing Load Ball On Cylinder Lubricity Evaluator
SLWT	Scuffing Load Wear Test (SLBOCLE)
SPK	Synthetic Paraffinic Kerosene
SwRI	Southwest Research Institute
TARDEC	Tank-Automotive Research, Development, and Engineering Center
TFLRF	TARDEC Fuels and Lubricants Research Facility
U.S.	United States
ULSD	Ultra Low Sulfur Diesel fuel
WOT	Wide Open Throttle
WPAFB	Wright-Patterson Air Force Base
WSD	Wear Scar Diameter

Executive Summary

Endurance tests were performed using a motorized pump stand to define the effects of fuel and fuel additives on full-scale fuel injection system equipment durability. Two distinct tests were performed utilizing a 500-hour fuel injection pump operating procedure. The specific tests performed included:

1. MIL-DTL-83133H Grade JP-8 with a fuel inlet temperature of 77°C.
2. Blend of 50-percent JP-8 and 50-percent ATJ, the level of CI/LI additive to be specified by AFRL, with a fuel inlet temperature of 40°C.

The JP-8 chosen for the study represented fuel bought in the marketplace that included all the MIL-DTL-83133H additives. The concentration of the CI/LI additive used in the purchased fuel was very near the QPL-25017 approved minimum effective concentration. The early time failure of the fuel injection pumps at elevated temperature operation with the purchased JP-8 was unexpected. It was postulated the low aromatic levels of the purchased JP-8 altered the CI/LI additive effectiveness. A brief fractional factorial study of CI/LI effectiveness with fuel aromatic levels suggested the additives are more effective in higher aromatic fuels.

The 50/50 ATJ/JP-8 fuel blend permitted completion of the 500-hours in the rotary diesel fuel injection pump test, but the fuel injection pumps did not meet performance specifications at the end of testing.

The technical feasibility of using JP-8 at elevated temperatures and using ATJ fuel in rotary fuel injection equipment when blended with a CI/LI additive and petroleum based commercial aviation kerosene has been investigated:

1. At elevated fuel inlet temperatures the maximum effective concentration of a QPL-25017 CI/LI should be utilized in JP-8.
2. It is recommended that blends of ATJ and JP-8 fuels include the addition of the maximum effective concentration of CI/LI for use in diesel rotary fuel injection equipment.

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B.1.0 BACKGROUND AND OBJECTIVE

Initial tests with synthetic aviation kerosene fuels revealed severe wear and extreme life reduction of rotary fuel injection pumps for diesel engines. The untreated fuels caused performance degrading wear on rotary fuel injection pumps within 25-hours of operation on the untreated fuel. However, prior work with synthetic fuels have shown those fuels responded well to the addition of a Corrosion Inhibitor/Lubricity Improver (CI/LI) additive to extend the life of the rotary fuel injection equipment. In addition it is likely that most synthetic fuel will be used as a blending component with petroleum JP-8 fuel at a maximum 50-percent in order to maintain fuel density above the JP-8 specification minimum.

In conducting previous additive treated synthetic fuel pump stand tests, it was found that the tests could be operated to conclusion at 500-hours if the maximum concentration of CI/LI additive is utilized. Prior testing also indicated a synthetic fuel is that blended 50-percent with JP-8, and treated with an approved CI/LI additive, will also provide adequate diesel fuel injection pump wear protection.

A study was performed to look at the effectiveness of a CI/LI additive at minimal treat rates, targeting ASTM D5001 Ball-On-Cylinder-Lubricity-Evaluator (BOCLE) Wear Scar Diameter (WSD) values, in extending rotary fuel injection equipment durability while operating on synthetic fuel. The targeted WSD values for rotary pump testing with CI/LI additive treated R8 fuels testing were 0.85-mm and 0.75-mm.

SwRI® will conduct endurance tests using a motorized pump stand to define the effects of fuel and fuel additives, and fuel temperature on fuel injection equipment durability.

B.2.0 APPROACH

Endurance tests were performed using a motorized pump stand to define the effects of fuel and fuel additives on full-scale fuel injection equipment durability. The test series attempted to determine the level of fuel injection system degradation due to wear and failure of the boundary film using the HMMWV engine opposed-piston, rotary distributor, fuel injection pumps with an Alcohol-to-Jet (ATJ) synthetic fuel with minimum specification level CI/LI additive treatments. Two distinct tests were performed utilizing a 500-hour fuel injection pump operating procedure. The specific tests performed included:

1. MIL-DTL-83133H Grade JP-8 with a fuel inlet temperature of 77°C.
2. Blend of 50-percent JP-8 and 50-percent ATJ, the level of CI/LI additive to be specified by AFRL, with a fuel inlet temperature of 40°C.

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B.3.0 SCOPE OF WORK

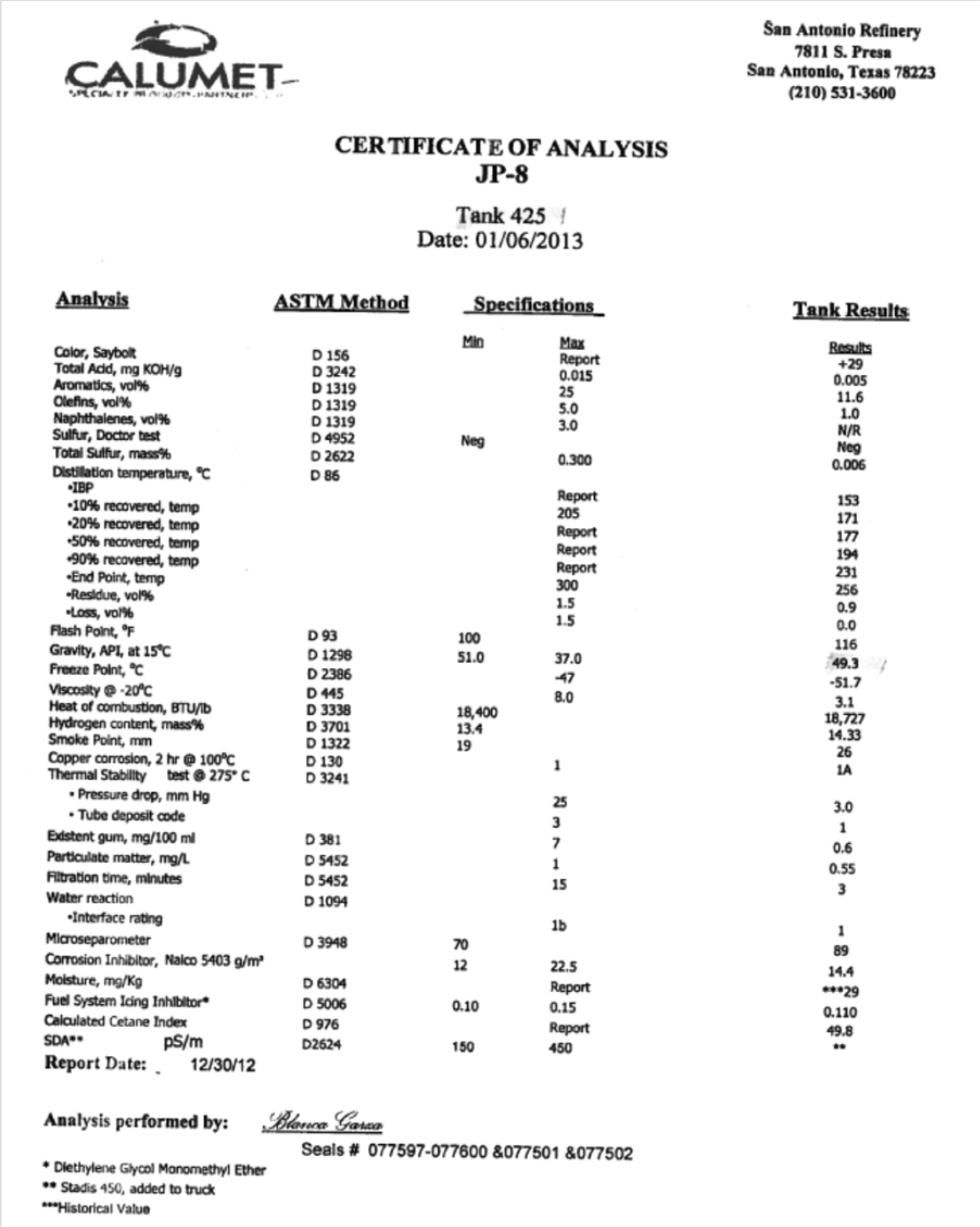
B.3.1 Fuels

An ATJ fuel was supplied as GFE by WPAFB for blending at a 50/50 ratio by volume with JP-8. A JP-8 fuel meeting MIL-DTL-83133H was purchased from a local supplier. Table B-1 summarizes the critical properties of the locally sourced JP-8.

The JP-8 fuel purchased for testing had nearly the minimum effective concentration of Nalco 5403 CI/LI additive, 14.2-g/m^3 from the certificate of analysis provided, versus 12-g/m^3 from the QPL-25017 listing. The ASTM D5001 BOCLE result was 0.55 mm, and the ASTM D6079 HFRR result was 823 microns for the JP-8 fuel. A rerun of the ASTM D5001 BOCLE test revealed a wear scar of 0.57 mm, the results for the JP-8 fuel appear consistent. The ASTM D6078 Scuffing Load BOCLE was 2100-grams for the first run and 1950-grams for the second evaluation, within repeatability of the method. A short time failure with the JP-8 fuel was not anticipated; however TFLRF testing at 77°C has primarily been done with Innospec DCI-4A CI/LI at the maximum effective concentration. Recent Army testing [B-1] has indicated the DCI-4A additive to offer more effective rotary fuel injection pump protection.

A conference call was convened to discuss the elevated temperature JP-8 results in the pump stand. Concerns were raised as to whether the batch of JP-8 fuel is representative due to the poor pump durability performance at elevated temperature. The JP-8 as purchased has a low CI/LI treatment rate, but meets the BOCLE requirement. The fuel does have low aromatic levels (11.6%), that when blended 50-percent with a “zero”-aromatic synthetic fuel would fall below the anticipated minimum ATJ-blend aromatic requirement (similar to FT and HEFA blends). A question was raised as to whether the aromatic level of the fuel could be affecting CI/LI additive effectiveness for diesel fuel injection pump protection. A fractional factorial matrix has been designed to look at two aromatic levels of JP-8, two CI/LI additives, and two additive concentrations on the combined effect on the HFRR wear scar value. The HFRR study was performed before any rotary pump testing with the ATJ/JP-8 fuel blend was initiated.

Table B-1. Initial JP-8 Test Fuel Chemical and Physical Analysis



CALUMET

San Antonio Refinery
7811 S. Presa
San Antonio, Texas 78223
(210) 531-3600

CERTIFICATE OF ANALYSIS
JP-8

Tank 425
Date: 01/06/2013

Analysis	ASTM Method	Specifications Min	Specifications Max	Tank Results
Color, Saybolt	D 156		Report	+29
Total Acid, mg KOH/g	D 3242		0.015	0.005
Aromatics, vol%	D 1319		25	11.6
Olefins, vol%	D 1319		5.0	1.0
Naphthalenes, vol%	D 1319		3.0	N/R
Sulfur, Doctor test	D 4952	Neg		Neg
Total Sulfur, mass%	D 2622		0.300	0.006
Distillation temperature, °C	D 86			
•IBP			Report	153
•10% recovered, temp			205	171
•20% recovered, temp			Report	177
•50% recovered, temp			Report	194
•90% recovered, temp			Report	231
•End Point, temp			300	256
•Residue, vol%			1.5	0.9
•Loss, vol%			1.5	0.0
Flash Point, °F	D 93	100		116
Gravity, API, at 15°C	D 1298	51.0	37.0	49.3
Freeze Point, °C	D 2386		-47	-51.7
Viscosity @ -20°C	D 445		8.0	3.1
Heat of combustion, BTU/lb	D 3338	18,400		18,727
Hydrogen content, mass%	D 3701	13.4		14.33
Smoke Point, mm	D 1322	19		26
Copper corrosion, 2 hr @ 100°C	D 130		1	1A
Thermal Stability test @ 275° C	D 3241			
• Pressure drop, mm Hg			25	3.0
• Tube deposit code			3	1
Existent gum, mg/100 ml	D 381		7	0.6
Particulate matter, mg/L	D 5452		1	0.55
Filtration time, minutes	D 5452		15	3
Water reaction	D 1094			
•Interface rating			1b	1
Microseparometer	D 3948	70		89
Corrosion Inhibitor, Nalco 5403 g/m³		12	22.5	14.4
Moisture, mg/Kg	D 6304		Report	***29
Fuel System Icing Inhibitor*	D 5006	0.10	0.15	0.110
Calculated Cetane Index	D 976		Report	49.8
SDA** pS/m	D2624	150	450	**

Report Date: 12/30/12

Analysis performed by: Blanca Garza

Seals # 077597-077600 &077501 &077502

* Diethylene Glycol Monomethyl Ether
** Stadis 450, added to truck
***Historical Value

The fractional factorial matrix for the HFRR additive/fuel aromatics effectiveness is shown as Table B-2 below. The JP-8 purchased for the study at SwRI is the low aromatic fuel, and the high aromatic fuel was supplied by AFRL. The high aromatic JP-8 supplied by AFRL was coded POSF-4751 and is included as Table B-3. Both fuels were clay filtered to remove all additives, and then all the MIL additives were blended into the fuels, with the CI/LI levels as noted.

Table B-2. JP-8 CI/LI Additive Matrix

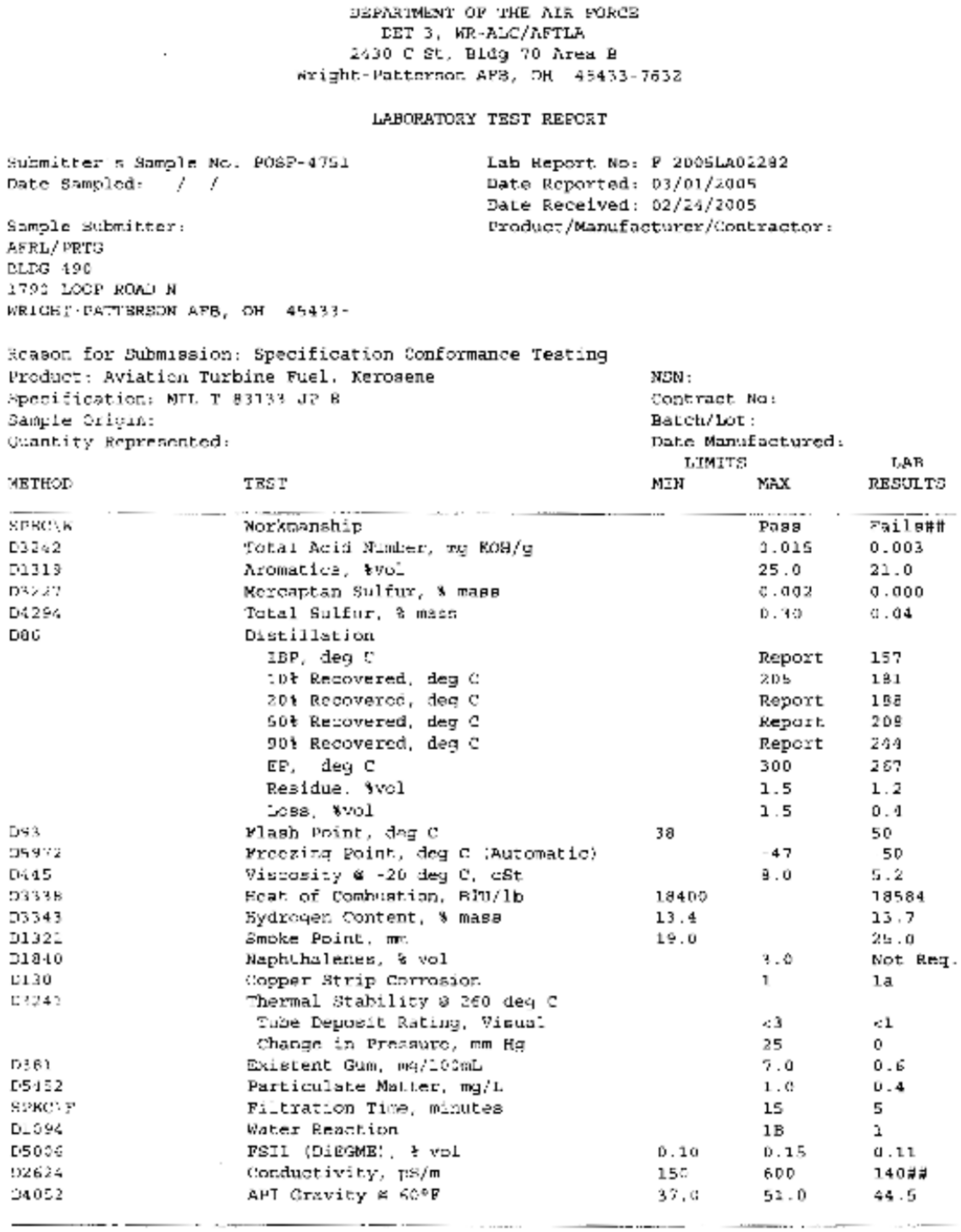
Sample	JP-8 Aromatics	CI/LI Additive Concentration (ppm)	Additive
CL13-4822 A	low	14.4	NALCO
CL13-4822 B	low	22.4	NALCO
CL13-4822 C	low	14.4	DCI
CL13-4822 D	low	22.4	DCI
CL13-5075 E	high	14.4	NALCO
CL13-5075 F	high	22.4	NALCO
CL13-5075 G	high	14.4	DCI
CL13-5075 H	high	22.4	DCI

The ASTM D6079 HFRR test matrix was performed in the order provided by the factorial experimental design. The run order and HFRR results are shown in Table B-4. Also included in Table B-4 are the ASTM D5001 BOCLE results for the same test fuel blends.

An analysis of the factorial experiment data suggested that fuel aromatic level was the only significant variable affecting HFRR lubricity values. The higher aromatic fuel trended to have lower HFRR lubricity wear scar results. Lubricity improver type or lubricity improver concentration did not have a significant effect.

A recommendation was made to perform the rotary pump testing at 40°C fuel inlet temperature, the fuel temperature used with prior testing, and to use a JP-8 fuel that would result in the minimum 8% aromatics of the 50/50 ATJ/JP-8 blend. Three drums of a ATJ/JP-8 blend were provided by AFRL, two for pump testing and one for engine cold start testing.

Table B-3. High Aromatic JP-8, POSF-4751, Provided by AFRL



DEPARTMENT OF THE AIR FORCE
DET 3, WR-ALC/AFTLA
2430 C St, Bldg 70 Area B
Wright-Patterson AFB, OH 45433-7632

LABORATORY TEST REPORT

Submitter's Sample No. POSF-4751
Date Sampled: / /

Lab Report No: F 2005LA02282
Date Reported: 03/01/2005
Date Received: 02/24/2005
Product/Manufacturer/Contractor:

Sample Submitter:
AFRL/PRTG
BLDG 490
1790 LOOP ROAD N
WRIGHT-PATTERSON AFB, OH 45433-

Reason for Submission: Specification Conformance Testing
Product: Aviation Turbine Fuel, Kerosene
Specification: MIL T 83133 JP 8
Sample Origin:
Quantity Represented:

NSN:
Contract No:
Batch/Lot:
Date Manufactured:

METHOD	TEST	LIMITS MIN	LIMITS MAX	LAB RESULTS
SPEC\K	Workmanship		Pass	Fail##
D3242	Total Acid Number, mg KOH/g		0.015	0.003
D1319	Aromatics, %vol		25.0	21.0
D3227	Mercaptan Sulfur, % mass		0.002	0.000
D4294	Total Sulfur, % mass		0.30	0.04
D86	Distillation			
	IBP, deg C		Report	157
	10% Recovered, deg C		205	181
	20% Recovered, deg C		Report	188
	50% Recovered, deg C		Report	209
	90% Recovered, deg C		Report	244
	EP, deg C		300	267
	Residue, %vol		1.5	1.2
	Loss, %vol		1.5	0.4
D93	Flash Point, deg C	38		50
D5972	Freezing Point, deg C (Automatic)		-47	-50
D445	Viscosity @ -20 deg C, cSt		8.0	5.2
D3338	Heat of Combustion, BTU/lb	18400		18584
D3343	Hydrogen Content, % mass	13.4		13.7
D1322	Smoke Point, mm	19.0		25.0
D1840	Naphthalenes, % vol		3.0	Not Req.
D130	Copper Strip Corrosion		1	1a
D3241	Thermal Stability @ 260 deg C			
	Tube Deposit Rating, Visual		<3	<1
	Change in Pressure, mm Hg		25	0
D381	Existent Gum, mg/100mL		7.0	0.6
D5452	Particulate Matter, mg/L		1.0	0.4
SPEC\F	Filtration Time, minutes		15	5
D1094	Water Reaction		1B	1
D5006	FSII (DiEGME), % vol	0.10	0.15	0.11
D2624	Conductivity, pS/m	150	600	140##
D4052	API Gravity @ 60°F	37.0	51.0	44.5

Table B-4. Factorial Matrix Lubricity Results

Run Order	Sample	ASTM D6079 HFRR Result (μm)	ASTM D5001 BOCLE Result (mm)
1	CL13-4822 B	753	0.51
2	CL13-5075 E	704	0.59
3	CL13-4822 D	782	0.54
4	CL13-5075 F	728	0.52
5	CL13-4822 C	764	0.59
6	CL13-5075 H	716	0.52
7	CL13-5075 G	713	0.62
8	CL13-4822 C	768	0.59
9	CL13-4822 D	800	0.54
10	CL13-5075 E	708	0.60
11	CL13-5075 G	706	0.61
12	CL13-4822 B	764	0.53
13	CL13-5075 H	741	0.60
14	CL13-5075 F	707	0.54
15	CL13-4822 A	788	0.60
16	CL13-4822 A	763	0.61

SwRI tested a sample from one of the drums of fuel received from AFRL. Tests performed were the ASTM D5001 BOCLE, D6079 HFRR, D613 Cetane Number, and D6890 Derived Cetane Number (DCN). Table B-5 shows the test results. The BOCLE test was repeated because the SwRI result differed from the AFRL analysis for the fuel. The AFRL result for BOCLE was 0.53-mm, outside the reproducibility of the ASTM method. The two SwRI results fall within the repeatability of the test method.

Table B-5. AFRL ATJ/JP-8 Test Fuel Results

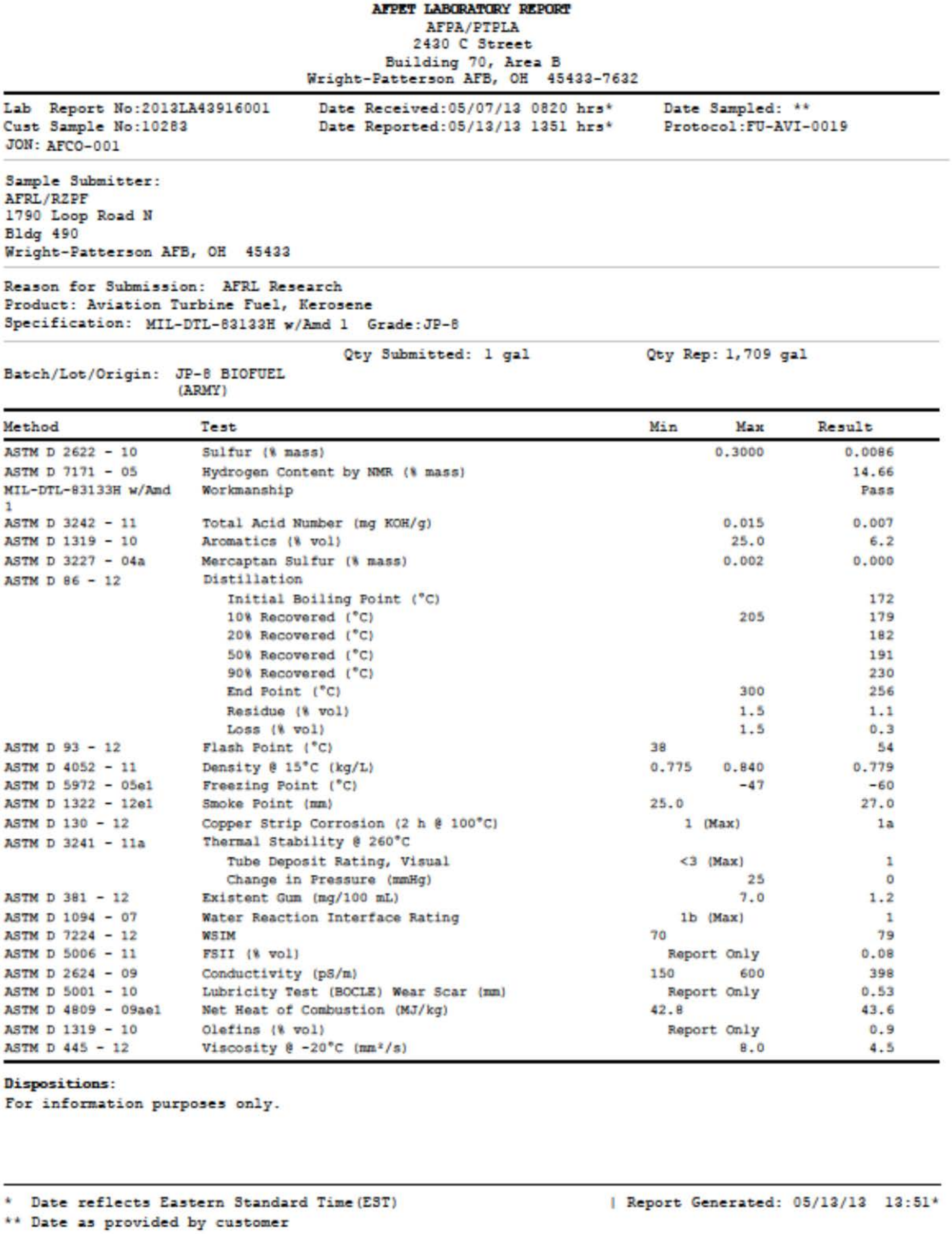
ASTM Method	Result	Units
D5001 BOCLE	0.61/0.59	mm
D6079 HFRR	799	microns
D613 Cetane Number	30.8	CN
D6890 DCN	37.02/36.97	DCN

For the test fuel received from AFRL, the ASTM D613 cetane number results look reasonable, considering the low CN value for the ATJ blend component. However the ASTM D6890 DCN results appear high. Usually the CN and DCN results are closer than 7 numbers. A repeat DCN determination result repeated well with the earlier result, and was also high at 36.97.

Prior testing with synthetic fuels have indicated adequate rotary fuel injection pump durability with fuels having BOCLE values of 0.67-mm, thus a decision was made to initiate the rotary pump tests with the fuel as received from AFRL. An ATJ/JP-8 blend that met the aromatics requirements, when aromatics are tested by ASTM D6379, was identified at WPAFB, and is shown in Table B-5. This fuel blend was used as the target for an engine durability test blend. Two drums of fuel POSF-10283 received from AFRL were used for the rotary fuel injection pump testing.

An additional Jet A/Jet A-1 blend with ATJ was identified that met the minimum aromatics content, and was available in sufficient quantity to run the engine test. The partial test fuel blend arrived at SwRI from WPAFB, and the analysis of the partial blend is included in Table B-6. This blend (POSF 10356) was 28.6 vol% ATJ. SwRI blended in the remaining ATJ needed to obtain a 50/50 blend, along with adding sufficient INNOSPEC DCI-4A to achieve a 14.4-ppm treatment of the CI/LI additive. SwRI analyzed the durability test blend for the three bench lubricity tests, aromatics content by UV and GC, and the cetane number and derived cetane numbers. Table B-7 shows the SwRI analysis of the final durability test blend. Five gallons of the final blend was sent to AFRL at WPAFB for analysis, with the results included in Table B-9 for fuel POSF-10399.

Table B-6. Target Blend for Engine Testing



AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA43916001 Date Received:05/07/13 0820 hrs* Date Sampled: **
Cust Sample No:10283 Date Reported:05/13/13 1351 hrs* Protocol:FU-AVI-0019
JON: AFCO-001

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: MIL-DTL-83133H w/Amd 1 Grade:JP-8

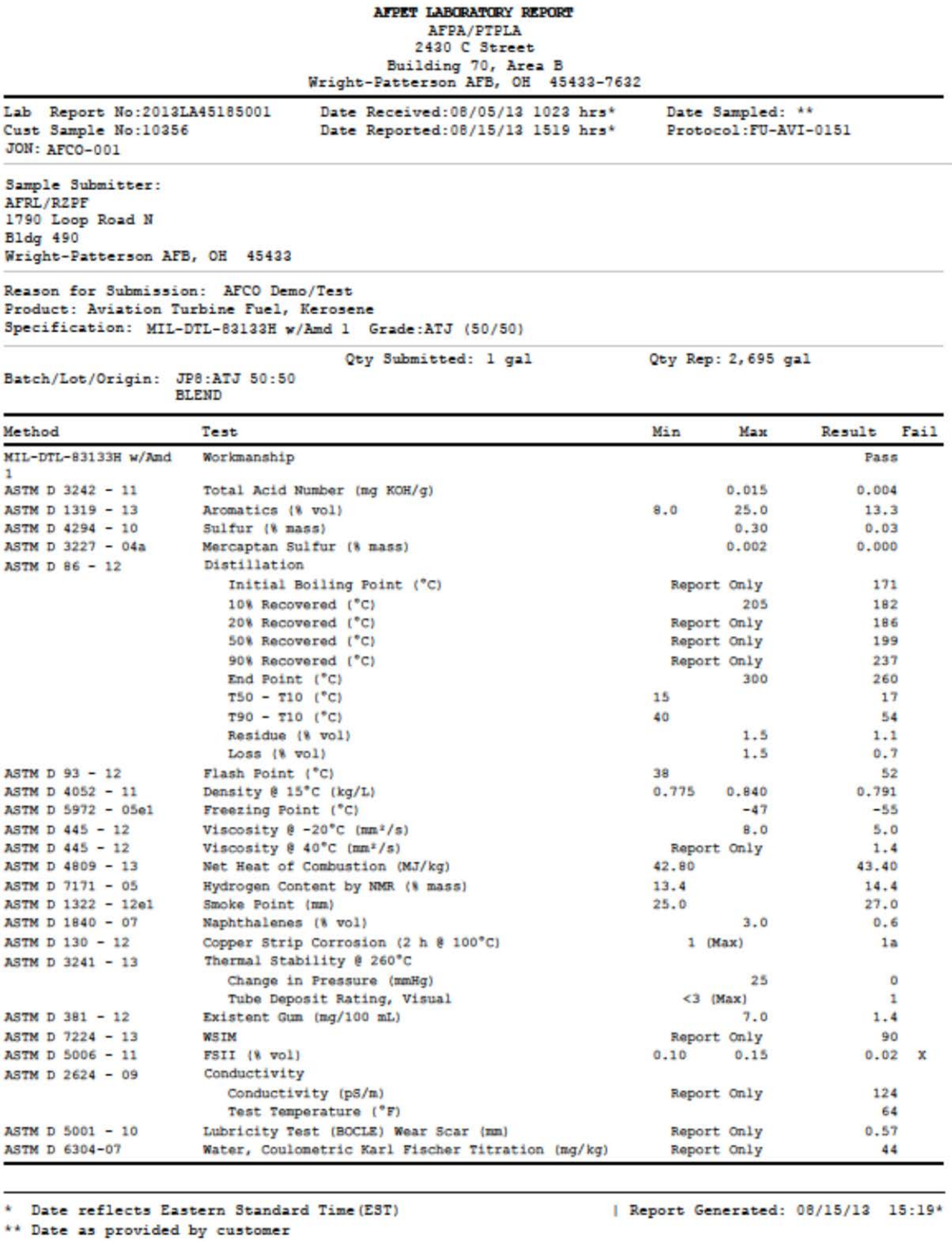
Qty Submitted: 1 gal Qty Rep: 1,709 gal
Batch/Lot/Origin: JP-8 BIOFUEL (ARMY)

Method	Test	Min	Max	Result
ASTM D 2622 - 10	Sulfur (% mass)		0.3000	0.0086
ASTM D 7171 - 05	Hydrogen Content by NMR (% mass)			14.66
MIL-DTL-83133H w/Amd 1	Workmanship			Pass
ASTM D 3242 - 11	Total Acid Number (mg KOH/g)		0.015	0.007
ASTM D 1319 - 10	Aromatics (% vol)		25.0	6.2
ASTM D 3227 - 04a	Mercaptan Sulfur (% mass)		0.002	0.000
ASTM D 86 - 12	Distillation			
	Initial Boiling Point (°C)			172
	10% Recovered (°C)		205	179
	20% Recovered (°C)			182
	50% Recovered (°C)			191
	90% Recovered (°C)			230
	End Point (°C)		300	256
	Residue (% vol)		1.5	1.1
	Loss (% vol)		1.5	0.3
ASTM D 93 - 12	Flash Point (°C)	38		54
ASTM D 4052 - 11	Density @ 15°C (kg/L)	0.775	0.840	0.779
ASTM D 5972 - 05e1	Freezing Point (°C)		-47	-60
ASTM D 1322 - 12e1	Smoke Point (mm)	25.0		27.0
ASTM D 130 - 12	Copper Strip Corrosion (2 h @ 100°C)		1 (Max)	1a
ASTM D 3241 - 11a	Thermal Stability @ 260°C			
	Tube Deposit Rating, Visual		<3 (Max)	1
	Change in Pressure (mmHg)		25	0
ASTM D 381 - 12	Existent Gum (mg/100 mL)		7.0	1.2
ASTM D 1094 - 07	Water Reaction Interface Rating		1b (Max)	1
ASTM D 7224 - 12	WSIM	70		79
ASTM D 5006 - 11	FSII (% vol)		Report Only	0.08
ASTM D 2624 - 09	Conductivity (pS/m)	150	600	398
ASTM D 5001 - 10	Lubricity Test (BOCLE) Wear Scar (mm)		Report Only	0.53
ASTM D 4809 - 09ae1	Net Heat of Combustion (MJ/kg)	42.8		43.6
ASTM D 1319 - 10	Olefins (% vol)		Report Only	0.9
ASTM D 445 - 12	Viscosity @ -20°C (mm^2/s)		8.0	4.5

Dispositions:
For information purposes only.

* Date reflects Eastern Standard Time(EST) | Report Generated: 05/13/13 13:51*
** Date as provided by customer

Table B-7. Blend Stock Provided by AFRL with Sufficient Fuel Aromatics Content



AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA45185001	Date Received:08/05/13 1023 hrs*	Date Sampled: **
Cust Sample No:10356	Date Reported:08/15/13 1519 hrs*	Protocol:FU-AVI-0151
JON: AFCO-001		

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFCO Demo/Test
Product: Aviation Turbine Fuel, Kerosene
Specification: MIL-DTL-83133H w/Amd 1 Grade:ATJ (50/50)

Qty Submitted: 1 gal Qty Rep: 2,695 gal

Batch/Lot/Origin: JP8:ATJ 50:50
BLEND

Method	Test	Min	Max	Result	Fail
MIL-DTL-83133H w/Amd 1	Workmanship			Pass	
ASTM D 3242 - 11	Total Acid Number (mg KOH/g)		0.015	0.004	
ASTM D 1319 - 13	Aromatics (% vol)	8.0	25.0	13.3	
ASTM D 4294 - 10	Sulfur (% mass)		0.30	0.03	
ASTM D 3227 - 04a	Mercaptan Sulfur (% mass)		0.002	0.000	
ASTM D 86 - 12	Distillation				
	Initial Boiling Point (°C)	Report Only		171	
	10% Recovered (°C)		205	182	
	20% Recovered (°C)	Report Only		186	
	50% Recovered (°C)	Report Only		199	
	90% Recovered (°C)	Report Only		237	
	End Point (°C)		300	260	
	T50 - T10 (°C)	15		17	
	T90 - T10 (°C)	40		54	
	Residue (% vol)		1.5	1.1	
	Loss (% vol)		1.5	0.7	
ASTM D 93 - 12	Flash Point (°C)	38		52	
ASTM D 4052 - 11	Density @ 15°C (kg/L)	0.775	0.840	0.791	
ASTM D 5972 - 05e1	Freezing Point (°C)		-47	-55	
ASTM D 445 - 12	Viscosity @ -20°C (mm^2/s)		8.0	5.0	
ASTM D 445 - 12	Viscosity @ 40°C (mm^2/s)	Report Only		1.4	
ASTM D 4809 - 13	Net Heat of Combustion (MJ/kg)	42.80		43.40	
ASTM D 7171 - 05	Hydrogen Content by NMR (% mass)	13.4		14.4	
ASTM D 1322 - 12e1	Smoke Point (mm)	25.0		27.0	
ASTM D 1840 - 07	Naphthalenes (% vol)		3.0	0.6	
ASTM D 130 - 12	Copper Strip Corrosion (2 h @ 100°C)	1 (Max)		1a	
ASTM D 3241 - 13	Thermal Stability @ 260°C				
	Change in Pressure (mmHg)		25	0	
	Tube Deposit Rating, Visual	<3 (Max)		1	
ASTM D 381 - 12	Existent Gum (mg/100 mL)		7.0	1.4	
ASTM D 7224 - 13	WSIM	Report Only		90	
ASTM D 5006 - 11	FSII (% vol)	0.10	0.15	0.02	X
ASTM D 2624 - 09	Conductivity				
	Conductivity (pS/m)	Report Only		124	
	Test Temperature (°F)			64	
ASTM D 5001 - 10	Lubricity Test (BOCLE) Wear Scar (mm)	Report Only		0.57	
ASTM D 6304-07	Water, Coulometric Karl Fischer Titration (mg/kg)	Report Only		44	

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** Date as provided by customer

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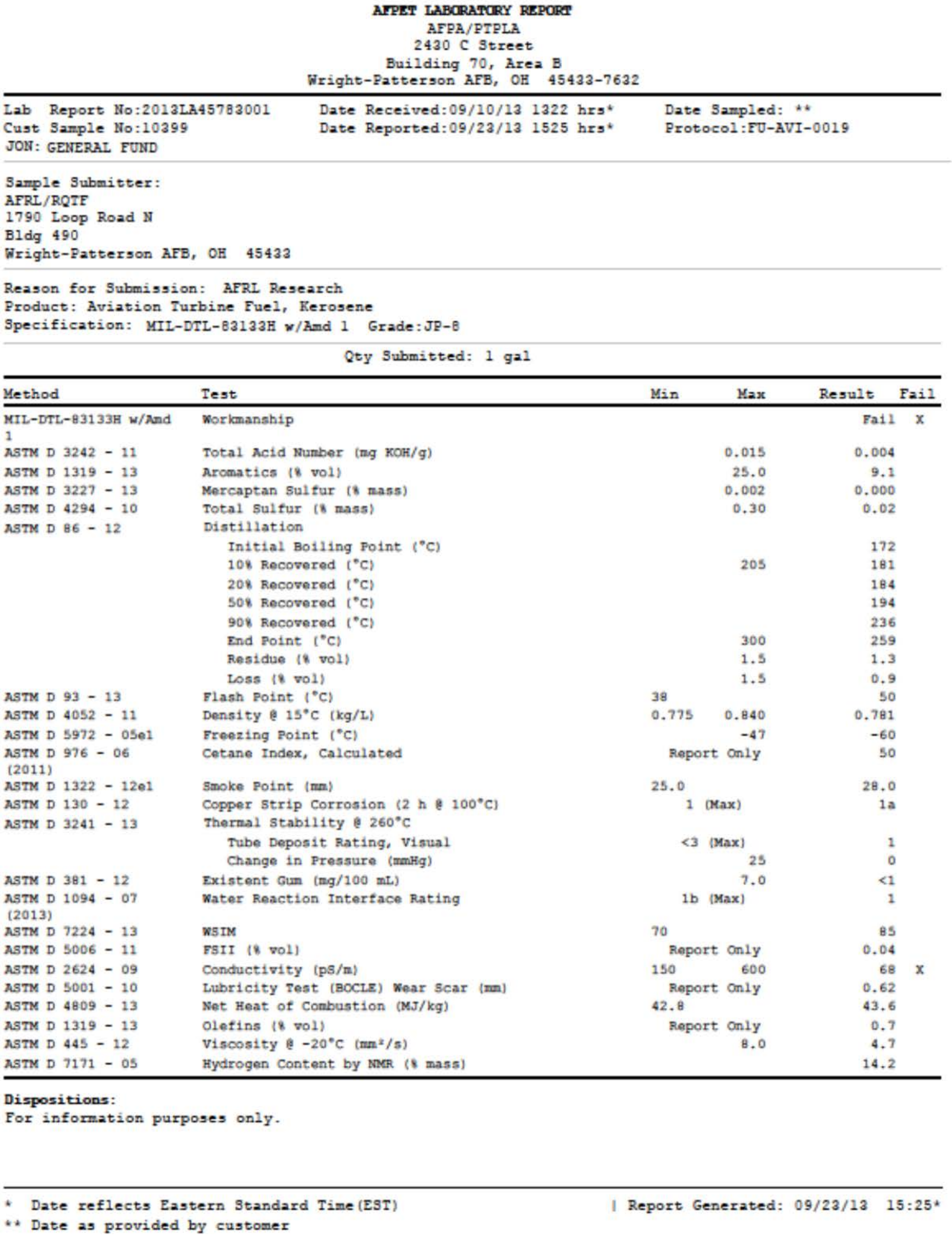
Table B-8. Analysis of Final TFLRF Blend for Engine Testing

Property	Method	Units	Result
Aromatics	D1319	Wt.%	7.0
Aromatics	D6379	Wt/%	8.38
Cetane Number	D613	CN	34.1
Derived Cetane Number	D6890	DCN	39.42
Lubricity, BOCLE	D5001	mm	0.630
Lubricity, HFRR, 60°C	D6079	mm	0.761
Lubricity, SLBOCLE	D6078	grams	2250
Carbon	D5219	Wt.%	85.35
Hydrogen	D5291	Wt.%	14.76

Table B-9. Fuel Analysis for POSF-10399 performed at AFRL



AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA45783001
Cust Sample No:10399
JON: GENERAL FUND

Date Received:09/10/13 1322 hrs*
Date Reported:09/23/13 1525 hrs*

Date Sampled: **
Protocol:FU-AVI-0019

Sample Submitter:
AFRL/RQTF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: MIL-DTL-83133H w/Amd 1 Grade:JP-8

Qty Submitted: 1 gal

Method	Test	Min	Max	Result	Fail
MIL-DTL-83133H w/Amd 1	Workmanship			Fail	X
ASTM D 3242 - 11	Total Acid Number (mg KOH/g)		0.015	0.004	
ASTM D 1319 - 13	Aromatics (% vol)		25.0	9.1	
ASTM D 3227 - 13	Mercaptan Sulfur (% mass)		0.002	0.000	
ASTM D 4294 - 10	Total Sulfur (% mass)		0.30	0.02	
ASTM D 86 - 12	Distillation				
	Initial Boiling Point (°C)			172	
	10% Recovered (°C)		205	181	
	20% Recovered (°C)			184	
	50% Recovered (°C)			194	
	90% Recovered (°C)			236	
	End Point (°C)		300	259	
	Residue (% vol)		1.5	1.3	
	Loss (% vol)		1.5	0.9	
ASTM D 93 - 13	Flash Point (°C)	38		50	
ASTM D 4052 - 11	Density @ 15°C (kg/L)	0.775	0.840	0.781	
ASTM D 5972 - 05e1	Freezing Point (°C)		-47	-60	
ASTM D 976 - 06 (2011)	Cetane Index, Calculated	Report Only		50	
ASTM D 1322 - 12e1	Smoke Point (mm)	25.0		28.0	
ASTM D 130 - 12	Copper Strip Corrosion (2 h @ 100°C)		1 (Max)	1a	
ASTM D 3241 - 13	Thermal Stability @ 260°C				
	Tube Deposit Rating, Visual		<3 (Max)	1	
	Change in Pressure (mmHg)		25	0	
ASTM D 381 - 12	Existent Gum (mg/100 mL)		7.0	<1	
ASTM D 1094 - 07 (2013)	Water Reaction Interface Rating		1b (Max)	1	
ASTM D 7224 - 13	WSIM	70		85	
ASTM D 5006 - 11	FSII (% vol)	Report Only		0.04	
ASTM D 2624 - 09	Conductivity (pS/m)	150	600	68	X
ASTM D 5001 - 10	Lubricity Test (BOCLE) Wear Scar (mm)	Report Only		0.62	
ASTM D 4809 - 13	Net Heat of Combustion (MJ/kg)	42.8		43.6	
ASTM D 1319 - 13	Olefins (% vol)	Report Only		0.7	
ASTM D 445 - 12	Viscosity @ -20°C (mm^2/s)		8.0	4.7	
ASTM D 7171 - 05	Hydrogen Content by NMR (% mass)			14.2	

Dispositions:
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** Date as provided by customer

| Report Generated: 09/23/13 15:25*

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B.3.2 Fuel Injection System Stanadyne:

Rotary distributor fuel injection pumps are fuel lubricated, thus sensitive to fuel lubricity. Highly refined, low sulfur and low aromatic fuels can cause substantial performance degradation with these pumps. Wear seen in the Stanadyne pumps could be interpolated to rotary distributor pumps of other manufacturers.

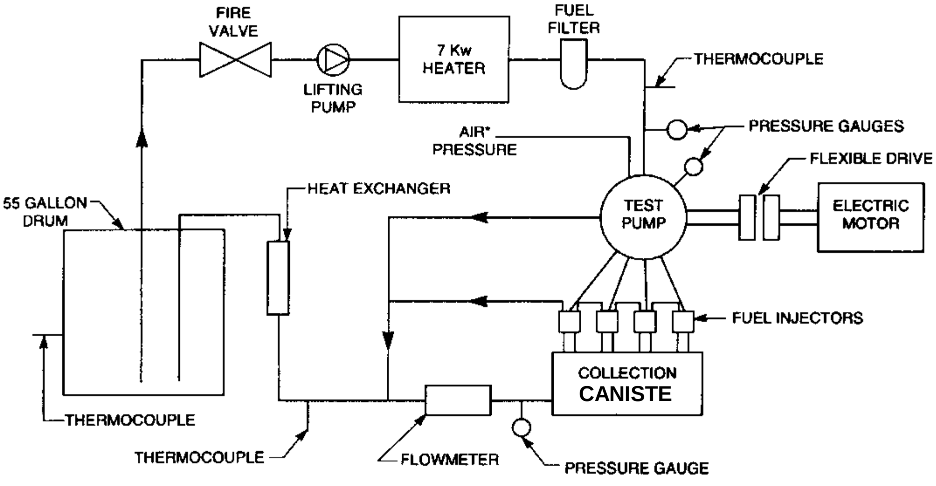
B.3.3 Pump Test Procedure

Full-scale equipment tests were performed using new fuel injection pumps and fuel injectors with each test fuel. The pump tests were performed in duplicate in order to obtain average wear results. Two fifty-five gallon drums of the appropriate test fuel are normally required for each 500-hour pump tests. The 500-hour tests were performed under steady state conditions at maximum fuel delivery for the test pump, as summarized in Table B-10. The tests will be occasionally halted and restarted as necessary due to scheduling requirements or technical reasons. The pumps were started gradually to prevent seizure due to thermal shock. To further reduce the risk of seizure due to differential expansion, the fuel was not preheated prior to starting the pumps.

Table B-10. Pump Operating Conditions

Parameter:	Value:
Duration, hrs	500
Speed, RPM	1800
Fuel Inlet Temperature, °C	77/40
Throttle position	Full
Fuel-drum temperature, °C	<30

The test stand includes injection flow and pump return pipes, lift pumps, filters, flow meters, a fuel pre-heater and a heat exchanger to reduce the temperature of the fuel before returning to the storage tank. A schematic diagram of the fuel supply system proposed for the pump stand is shown in Figure B-1. The temperature of the incoming fuel to each pump will be controlled to 77°C or 40°C depending on the test requirement.



* Not necessary for all pumps

Figure B-1. Schematic Diagram of Fuel Delivery System

The high-pressure outlets from the pumps will be connected to fuel injectors assembled in a collection canister.

B.3.4 Laboratory Scale Wear Tests

Stanadyne has indicated the lubricity of the test fuel should be determined prior to testing. Stanadyne has recommended the test fuel be changed at 250-hour intervals. The laboratory scale wear performed on the test fuels was the Ball on Cylinder Lubricity Evaluator procedure described in ASTM D-5001, because that procedure is called out for aviation kerosene fuels and additives. The ASTM D-6079 High Frequency Reciprocating Rig (HFRR) wear tests were also performed on the test fuels.

B.3.5 Evaluation of the Pumps Using a Calibrated Test Stand

Prior to and following each 500-hour pump test, the performance of the Stanadyne pumps were evaluated using a calibrated test stand. The objective of the calibration stand evaluation is to define the effect of the durability testing on pump performance. The calibration stand evaluations were performed at an authorized pump distributor. No adjustments were made to any of the pumps to achieve the manufacturer’s specifications, either before, during, or following the 500-hour pump stand tests.

The appropriate inspection and test procedures for determining fuel injector performance were followed prior to, and after each fuel evaluation.

B.3.6 Pump Disassembly and Wear Evaluation

The fuel injection pumps and fuel injectors were disassembled at SwRI® following completion of the 500-hour durability test and the subsequent evaluation using the calibrated test stand. A SwRI disassembly and rating procedure was originally developed for the U.S. Army for use with Stanadyne equipment. Each sliding contact within the pump is rated on a scale from 0 to 5, with 0 corresponding to no wear and 5 corresponding to severe wear and failure. The wear scars on components throughout the pump are evaluated visually and quantitative measurements of wear volume were made on the critical pump components. The SwRI procedure looks at all wear contacts within the fuel injection pump, which are lubricated by the fuel.

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B.4.0 PUMP TEST STAND EVALUATIONS

B.4.1 Rotary Pump Test Procedure

The Stanadyne arctic pumps used for this program are opposed-piston, inlet-metered, positive-displacement, rotary-distributor, fuel-lubricated injection pumps, model DB2831-5209, for a General Engine Products 6.5L engine application. The arctic pump is equipped with hardened transfer pump blades, transfer pump liner, governor thrust washer, and drive shaft tang to reduce wear in these critical areas of the pump. A schematic diagram of the principal pump components is provided in Figure B-2.

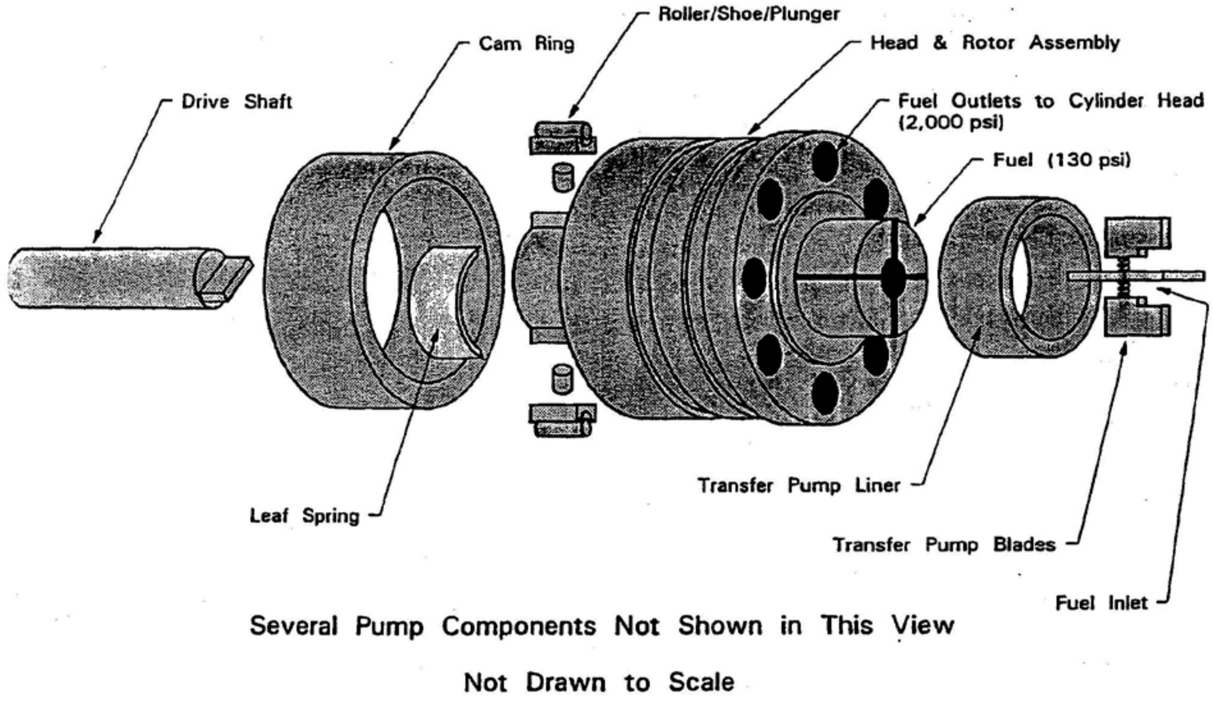

Figure B-2. Schematic Diagram of Principal Pump Components

The new pumps were disassembled, and pre-test roller-to-roller dimensions and transfer pump blade heights were obtained. Roller-to-roller dimensions were set per Stanadyne Diesel Systems Injection Pump Specifications for the DB2831-5209 model. The specification calls for a roller-to-roller dimension setting of 1.962 inches ± .001 inches. All pumps were set prior to testing with instructions that the roller-to-roller dimension not be adjusted during pre- and post-performance evaluations so that wear in these components could be accurately measured. Although there are not any min-max specifications other than initial assembly values, wear calculation from the roller-to-roller dimension is an excellent benchmark for the effects of fuel lubricity.

The pumps were reassembled and pre-test performance evaluations were conducted. The pumps were then mounted on the test stand and operated at 1800-RPM, with the fuel levers in the wide open throttle position (WOT) for targeted 500-hour increments (or less). Fuel flow, fuel inlet and outlet temperatures, transfer pump, pump housing pressures, and RPM were tracked and recorded. Flow meter readings reflect the injected fuel from the eight fuel injectors in each collection canister. Any wear in the fuel injection pump metering section was reflected as an increased or reduced flow reading. For these sets of tests the fuel inlet temperature control target was either 77°C or 40°C. Fuel inlet temperature variations directly can affect the fuel return temperature; the fuel return temperature is a function of accelerated pump wear. The transfer pump pressure is the regulated pressure the metal blade transfer pump supplies to the pump metering section. With low lubricity fuels, wear is likely to occur in the transfer pump blades, blade slot, and eccentric liner. Wear in these areas generally causes the transfer pump pressure to decrease. However, because the transfer pump has a pressure regulator, significant wear needs to occur in the transfer pump before the fuel pressure drops to below the operating range allowed in the pump specification. The housing pressure is the regulated pressure in the pump body that affects fuel metering and timing. With low lubricity fuel, wear occurs in high fuel pressure generating opposed plungers and bores, and between the hydraulic head and rotor. Leakage from the increased diametrical clearances of the plunger bores and the hydraulic head and rotor, results in increased housing pressures. Increased housing pressure reduces metered fuel and retards injection timing.

B.4.2 Pump Test Stand

The rotary pumps were tested on a drive stand with a common fuel supply. To insure a realistic test environment, the mounting arrangement and drive gear duplicate that of the 6.5L engine. The fuel was maintained in a 55-gallon drum and continuously recirculated throughout the duration of each test. A gear pump provided a positive head of 3 psig at the inlet to the test pumps. A cartridge filter rated at 2 microns was used to remove wear debris and particulate contamination. Finally, a 7-kW Chromalox explosion-resistant circulation heater produced the required fuel inlet temperature.

The high-pressure outlets from the pumps were connected to eight Bosch Model O432217104 fuel injectors for a 6.5L engine and assembled in a collection canister. Fuel from both canisters was then returned to the 55-gallon drum. A separate line was used to return excess fuel from the governor housing to the fuel supply. Fuel-to-water heat exchangers on both the return lines from the injector canisters and the governor housing were used to cool the fuel. The test stand with pumps mounted is shown in Figure B-3.

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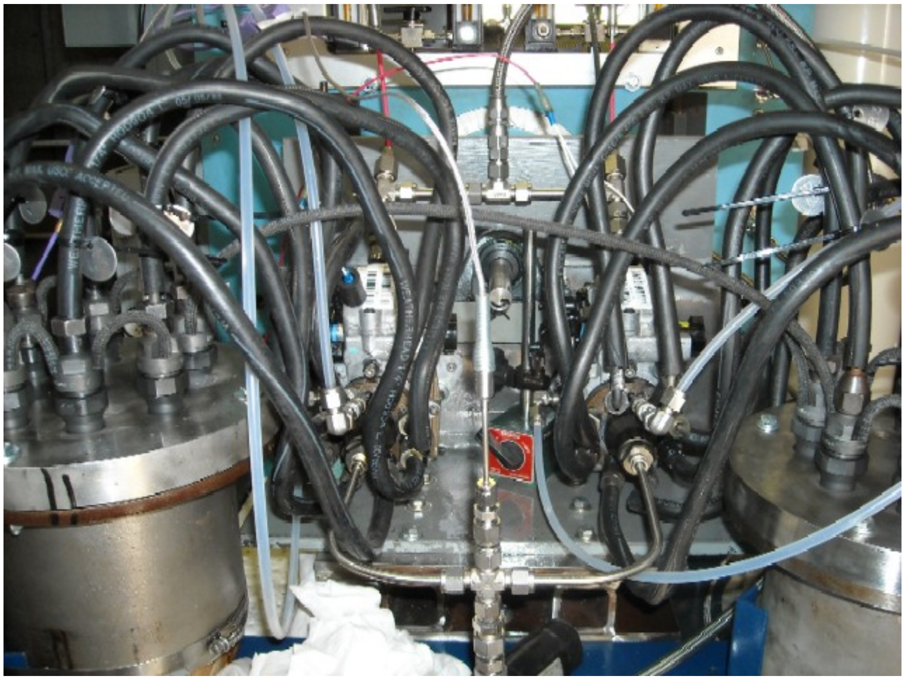

Figure B-3. Dual Stanadyne Rotary Fuel Injection Pumps Mounted on Stand with Fuel Injectors

A data acquisition and control system recorded pump stand RPM, fuel inlet pressure, fuel inlet and return temperature, transfer pump pressures, pump housing pressures, and fuel flow readings. The entire rig was equipped with safety shutdowns that would turn off the drive motor in the event of low fluid level in the supply drum, high inlet and return fuel temperature (70ºC or 100 ºC), or low or high transfer pump and housing pressure. Since high-return fuel temperature is a precursor of accelerated wear, this fail-safe feature reduces the possibility of head and rotor seizure.

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B.5.0 ROTARY FUEL INJECTION PUMP EVALUATIONS AND RESULTS

B.5.1 Rotary Fuel Injection Pumps with Elevated Temperature JP-8 Fuel

B.5.1.1 JP-8 Fuel at 77 °C

The Stanadyne model DB2831-5209 rotary fuel injection pumps were received from a supplier and the pumps appeared to be in good condition. The fuel injection pumps were installed on the test stand and the pumps were operated for an hour to validate their operation and to run-in the components with a good lubricity calibration fluid. The pumps were run for 30-minutes at 1200-RPM pump speed, with a half-rack fuel flow setting. For the final 30-minutes of the run-in the pumps were operated at the test condition of 1800-RPM pump speed, with a full-rack fuel flow setting.

The test bench and pumps were flushed with isooctane to attempt to remove any remaining run-in fluid. The isooctane was forced through the fuel injection pumps with pressure; the pumps were not run with isooctane in them. Following the isooctane flush, the treated JP-8 was introduced into the test stand and the stand was operated at an idle condition until 2L of fuel was flushed through each set of eight injectors.

The testing with the as received JP-8 fuel was initiated and the fuel injection pumps and stand control system appeared to function properly. The operating summaries for the respective fuel injection pumps are shown in Table B-11, averaged over the operating interval for each pump, 35-hours for pump SN:16393232 and 139-hours for pump SN: 16393231.

Table B-11. JP-8 Pump Operating Summary

Parameter	Unit	Average	Std. Dev.
Pump Speed	RPM	1800	0.3
Fuel Inlet Pressure	psig	3.02	0.17
Fuel Inlet Temperature	°C	77.3	2.6
Housing Pressure, SN:16393232	psig	15.11	0.57
Housing Pressure, SN:16393231	psig	14.44	0.74
Transfer Pump Pressure, SN:16393232	psig	77.22	1.00
Transfer Pump Pressure, SN:16393231	psig	79.08	2.62
Pump Fuel Return Temperature, SN:16393232	°C	87.6	2.3
Pump Fuel Return Temperature, SN:16393231	°C	86.7	3.7
Injected Flow Rate, SN:16393232	ml/min	527.0	38.0
Injected Flow Rate, SN:16393231	ml/min	577.7	37.0

The first rotary fuel injection pump test was initiated with the JP-8 fuel at 77°C fuel inlet temperature. The fuel injection pump installed on the right side of the stand, SN: 16393232, exhibited a 25% reduction in injection delivery at 35-hours of operation at 77°C. The top cover of pump SN: 16393232 was removed for inspection and metallic wear debris was evident in the housing as shown in Figure B-4. Also evident is a light brown staining of the housing surfaces. Testing was halted with the right pump, as experience indicates further operation could cause pump seizure.

Testing was continued with the pump installed on the left side of the test stand. The fuel injection pump installed on the left side of the stand, SN: 16393231, exhibited a 25% reduction in injection delivery at 139-hours of operation at 77°C. The top cover of pump SN: 16393231 was removed for inspection and metallic wear debris, along with brown staining, was evident in the housing as shown in Figure B-5.

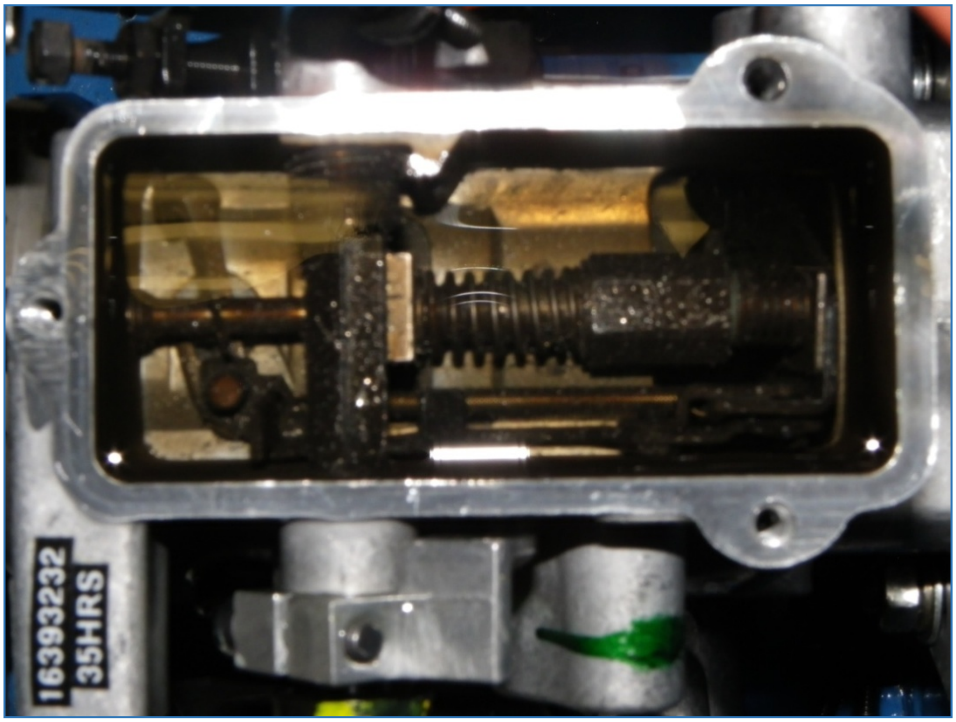

Figure B-4. Pump SN: 16393232 Showing Wear Debris at 35-hours with JP-8 Fuel at 77°C Inlet Temperature

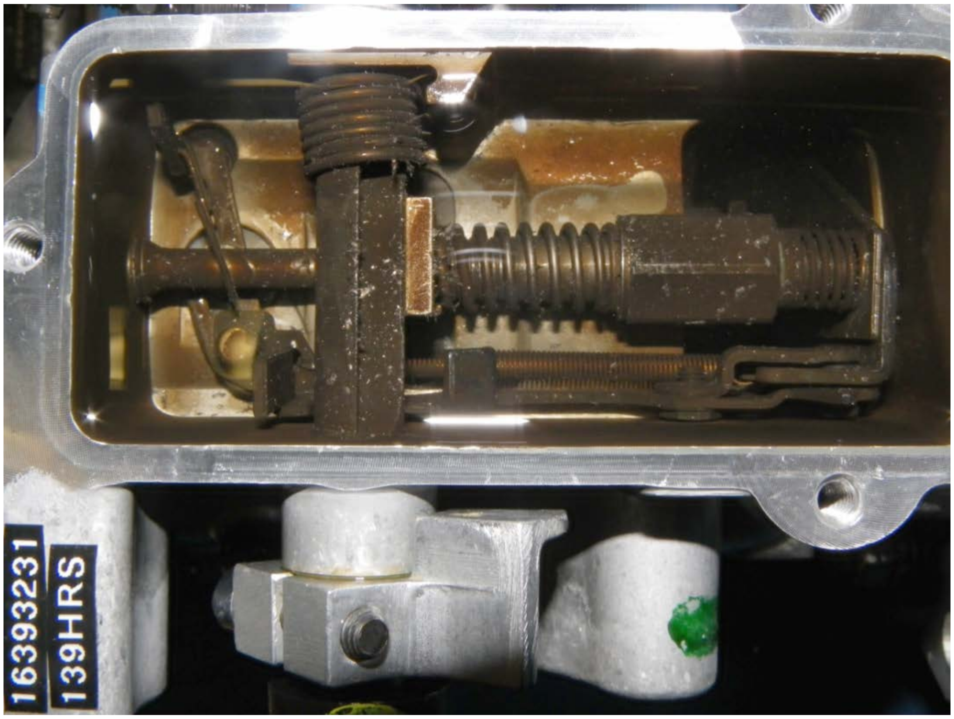

Figure B-5. Pump SN: 16393231 Showing Wear Debris at 139-hours with JP-8 Fuel at 77°C Inlet Temperature

The fuel injection pump delivery histories are shown in Figure B-6 for both fuel injection pumps for operation on JP-8 fuel at 77°C fuel inlet temperature. Both injection pumps revealed slightly erratic delivery characteristics. Erratic delivery in these pumps could be due to metering valve wear or governor linkage wear. The reductions of the injected fuel delivery for the respective pump EOT times are evident in Figure B-6.

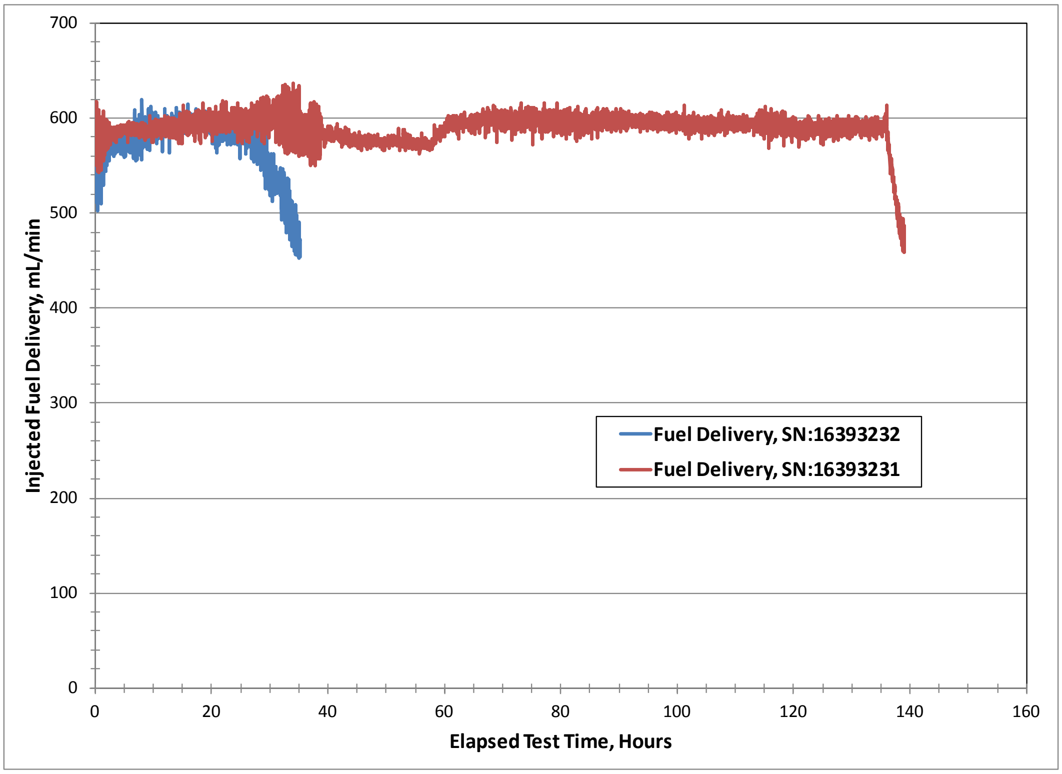

Figure B-6. Fuel Flow Rate Histories for JP-8 Fuel at Elevated Temperature

The fuel injection pump temperature histories are shown in Figure B-7 for both fuel injection pumps for operation on JP-8 fuel at 77°C fuel inlet temperature. The test stand was converted to single pump operation with the removal of pump SN: 16393232. The fuel inlet temperature controller had a difficult time maintaining the fuel inlet temperature. The controller was re-tuned, after which a consistent fuel inlet temperature was maintained. It is possible the swings in fuel inlet temperature may have hastened the wear with pump SN: 16393231 after the 35-hour re-start, as the housing fuel return temperature settled at an elevated value after re-tuning the temperature controller. Prior to the test termination with either fuel injection pump, the housing fuel return temperatures are seen to increase, due to increased internal friction in the fuel injection pumps.

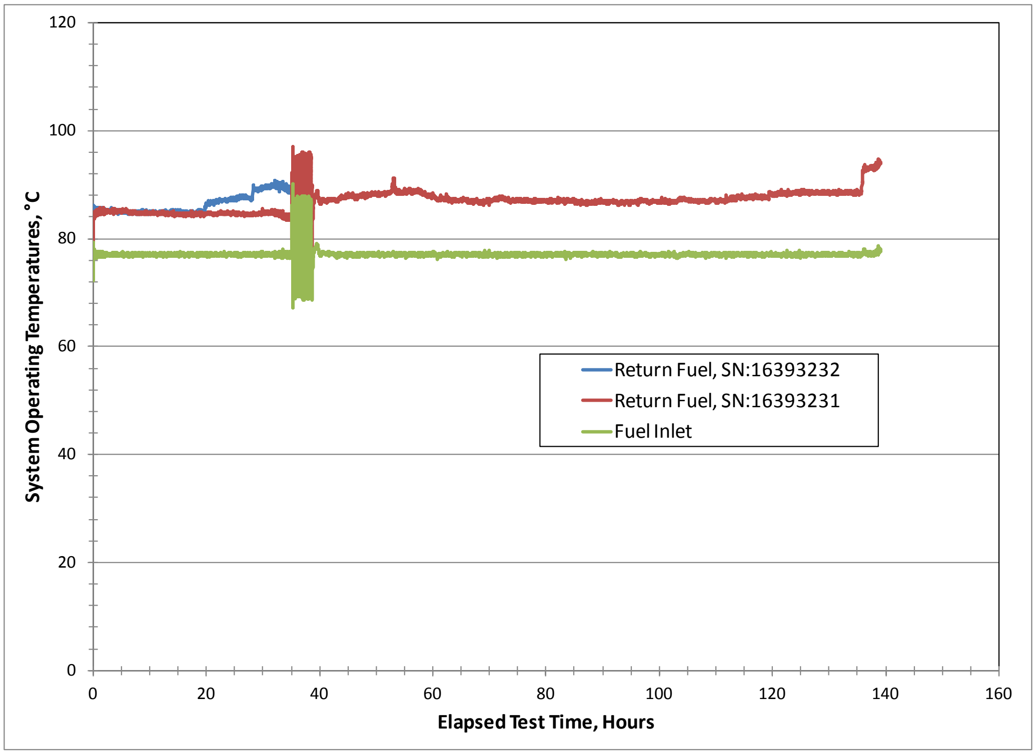

Figure B-7. Fuel Inlet and Fuel Return Temperatures for JP-8 Fuel at Elevated Temperature

Shown in Figure B-8 are the pressure histories for the elevated temperature JP-8 fuel testing. Fuel injection pump SN: 16393231 revealed a slight decrease in fuel delivery with a slight increase in housing pressure towards the end of testing. Housing pressure usually increases in these pumps when an excessive amount of high-pressure fuel leaks past the pumping plungers, indicating an increase of the plunger-to-bore clearance. The transfer pump pressure histories for both pumps indicate wear in the transfer pump and transfer pump regulator led to some erratic pressure histories, with pump SN: 16393231 being more erratic.

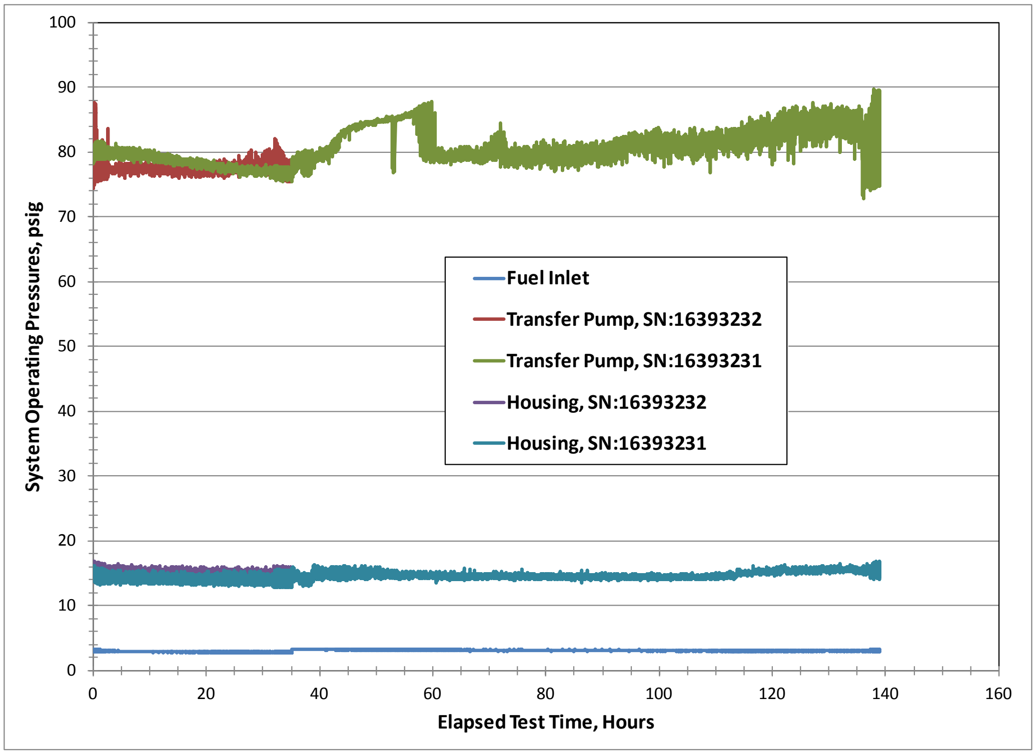

Figure B-8. Fuel Inlet, Fuel Transfer Pump, and Housing Pressure Histories for JP-8 Fuel at Elevated Temperature

B.5.1.2 50/50 ATJ/JP-8 Fuel Blend at 40 °C

Two Stanadyne model DB2831-5209 fuel injection pumps were installed on the test stand and the pumps were operated for an hour to validate their operation and to run-in the components with a good lubricity calibration fluid. The pumps were run for 30-minutes at 1200-RPM pump speed, with a half-rack fuel flow setting. For the final 30-minutes of the run-in the pumps were operated at the test condition of 1800-RPM pump speed, with a full-rack fuel flow setting.

The test bench and pumps were flushed with isooctane to attempt to remove any remaining run-in fluid. The isooctane was forced through the fuel injection pumps with pressure; the pumps were not run with isooctane in them. Following the isooctane flush, the treated ATJ/JP-8 fuel was introduced into the test stand and the stand was operated at an idle condition until 2L of fuel was flushed through each set of eight injectors.

The testing with the ATJ/JP-8 fuel was initiated and the fuel injection pumps and stand control system functioned normally. The operating summaries for the respective fuel injection pumps are shown in Table B-12, averaged over the 500-hour operating interval for each fuel injection pump.

Table B-12. ATJ/JP-8 Pump Operating Summary

Parameter	Unit	Average	Std. Dev.
Pump Speed	RPM	1800	0.1
Fuel Inlet Pressure	psig	3.34	0.19
Fuel Inlet Temperature	°C	40.0	0.4
Housing Pressure, SN:16393230	psig	12.63	0.46
Housing Pressure, SN:16393229	psig	13.26	0.33
Transfer Pump Pressure, SN:16393230	psig	83.70	1.62
Transfer Pump Pressure, SN:16393229	psig	78.89	2.99
Pump Fuel Return Temperature, SN:16393230	°C	52.4	0.9
Pump Fuel Return Temperature, SN:16393229	°C	51.4	0.9
Injected Flow Rate, SN:16393230	ml/min	677.8	33.6
Injected Flow Rate, SN:16393229	ml/min	663.7	28.4

The flow histories of the fuel injection pumps operating on the ATJ/JP-8 blend are shown in Figure B-9. From the onset of testing both fuel injection pumps exhibited an increase in fuel delivery. Pump SN: 16393230 increased injected delivery that eventually stabilized after 150-hours of operation. Pump SN: 16393229 exhibited more erratic delivery, with delivery rising and falling during testing. However both fuel injection pumps appeared to be operating normally on the ATJ/JP-8 blend at the conclusion of the 500-hours of operation.

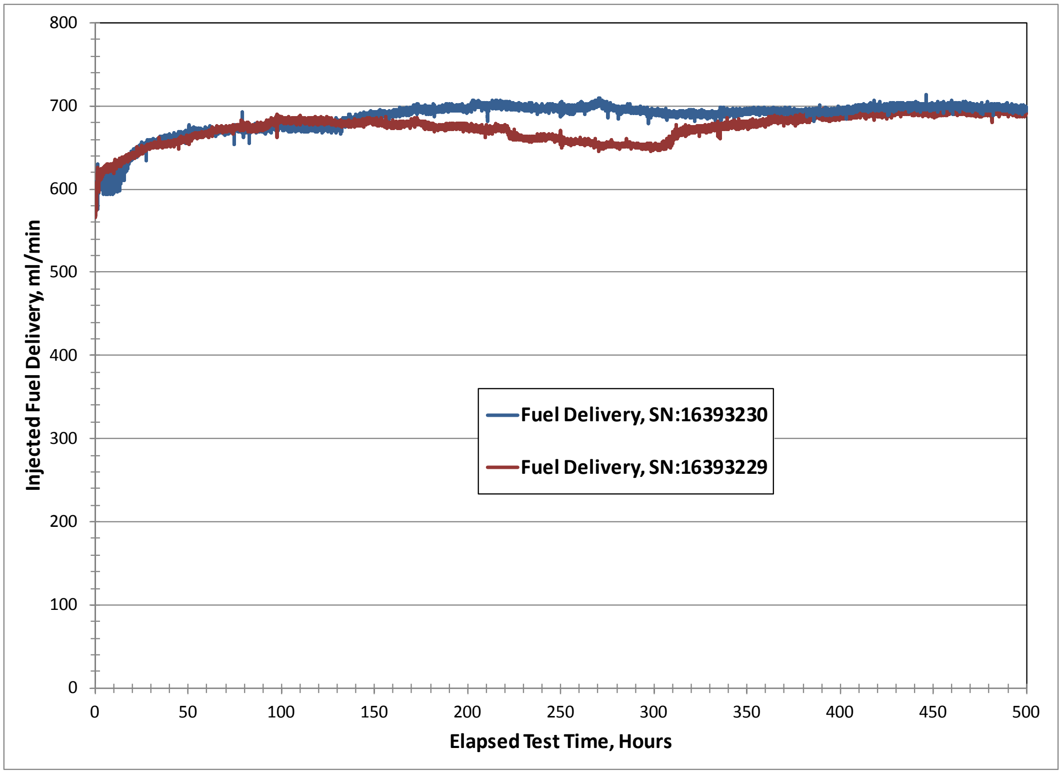

Figure B-9. Injection Pump Delivery Histories for ATJ/JP-8 Evaluation

The temperature histories of the fuel injection pumps are shown in Figure B-10. From the onset of testing both fuel injection pumps exhibited some form of erratic fuel return temperature behavior. For pump SN: 16393230 the return fuel temperature increased, usually a sign of increased internal friction, then decreased and increased again towards mid-test. Pump SN: 16393229 exhibited steady initial fuel return temperature that increased about mid-test indicating increased internal friction. Unusual wear in the pumps usually result in increases and variability of the fuel return temperatures. The fuel inlet temperature to both pumps was very consistent throughout testing.

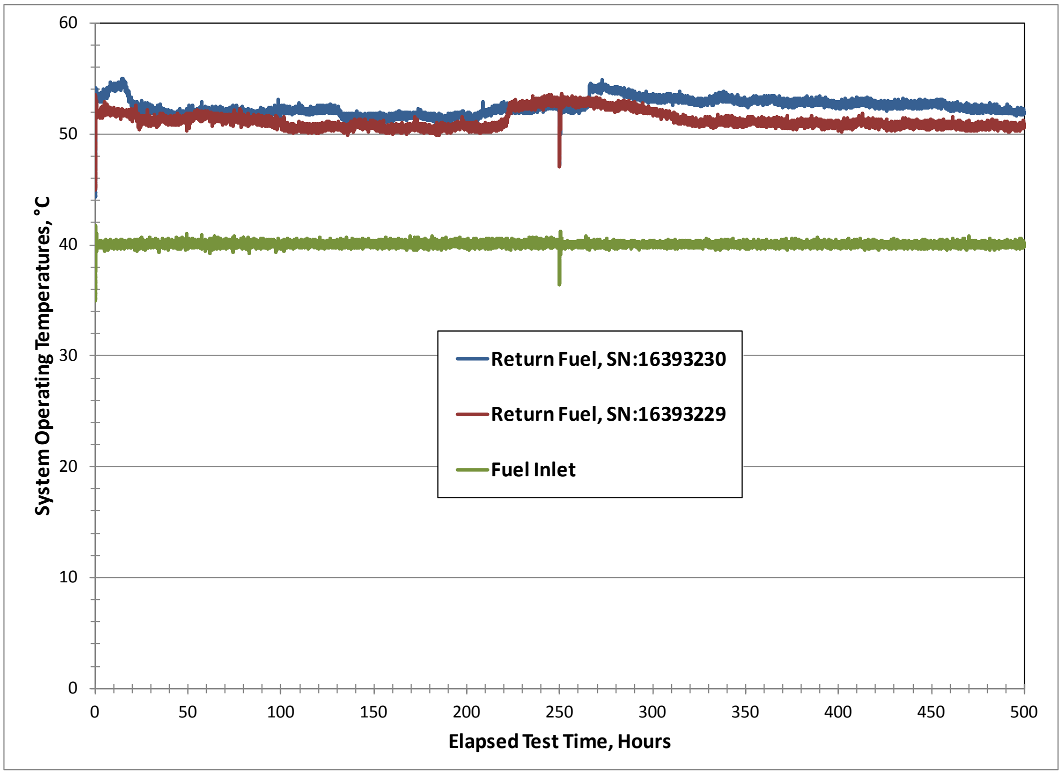

Figure B-10. Injection Pump Temperature Histories for ATJ/JP-8 Evaluation

Figure B-11 shows the fuel pressure histories for the test with the ATJ/JP-8 fuel. The fuel inlet and housing pressures for pumps SN: 16393229 and SN: 16393230 maintained a consistent level throughout the 500-Hours of operation. The transfer pump pressure for pump SN: 16393229 revealed a steady pressure for the first 200-hours, exhibited a sharp increase, followed by significant variability, then a decrease towards the end of the test. Pump SN: 16393230 reveals an initial transfer pump pressure spike, a stabilization, an increase again at mid-test, then stabilized pressure to the end of the test. The erratic pressure excursions of the transfer pump indicate pump liner, pump blade, and pump regulator wear. At 500-hours of testing the tops of both fuel injection pumps were removed for inspection, and the pump housings were free of wear debris. The housing for pump SN: 16393229 is shown in Figure B-12 and the housing for pump SN: 16393230 is shown in Figure B-13. Also note in both figures the lack of brown staining of the housing components.

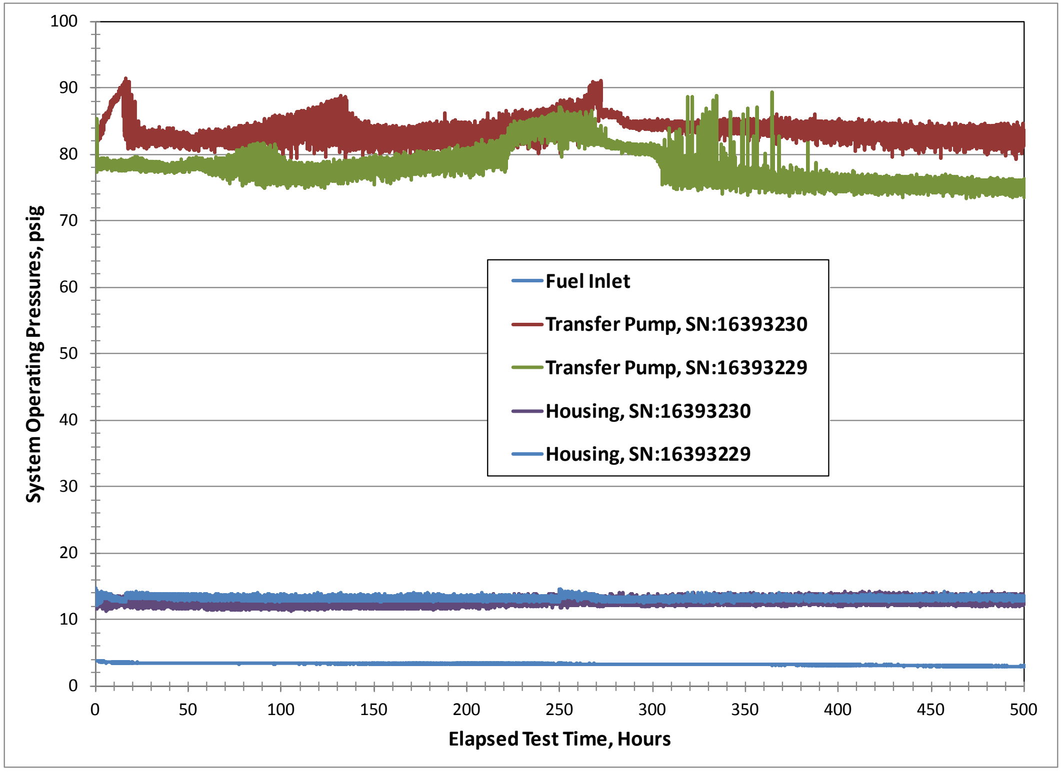

Figure B-11. Injection Pump Pressure Histories for ATJ/JP-8 Evaluation

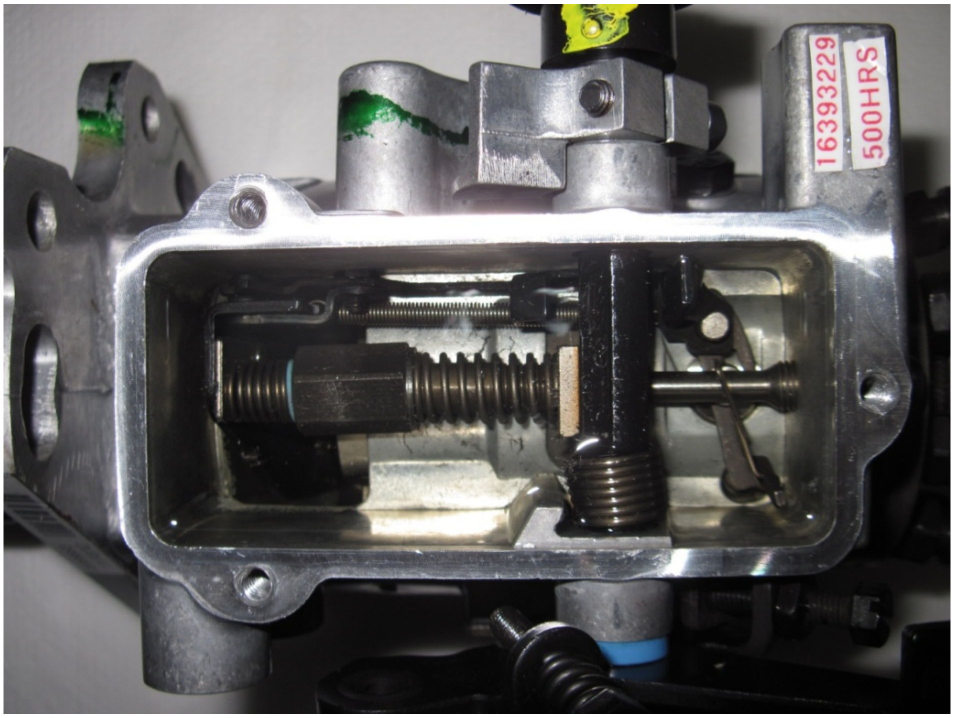

Figure B-12. Pump SN: 16393229 Governor Assembly with 500-Hours Testing with ATJ/JP-8 Fuel

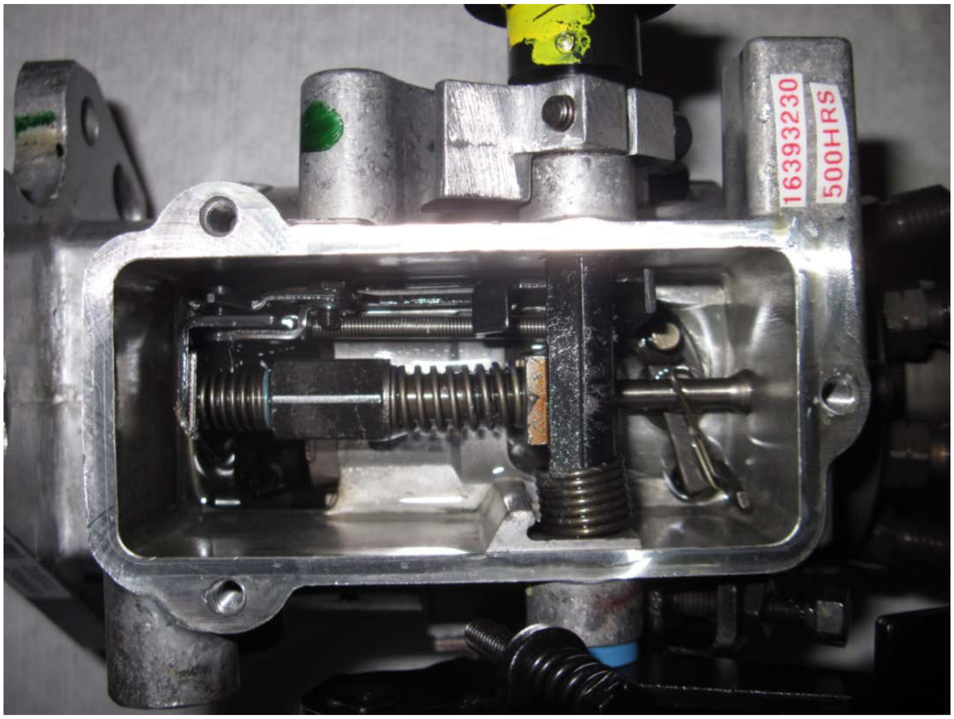

Figure B-13. Pump SN: 16393230 Governor Assembly with 500-Hours Testing with ATJ/JP-8 Fuel

B.5.2 Rotary Pump Performance Measurements

Prior to the durability testing all the fuel injection pumps were run on an injection pump calibration stand to verify their performance with respect to their model number and application specification sheet. Although the pumps come from the factory set to meet their designated specification, because SwRI disassembles the pumps to take transfer pump blade measurements and roller-to-roller dimensions the fuel injection pumps performance is validated by this pre-test calibration. At the conclusion of testing the fuel injection pumps are installed on the calibration stand and checked for performance changes due to the test fuel. There are not any adjustments made to the fuel injection pumps by the calibration personnel nor is the pump disassembled prior to completion of this calibration.

B.5.2.1 JP-8 Fuel at 77 °C

The Pre- and Post-Test performance curves for fuel injection pump SN: 16393231 are included as Table B-13. Items in shaded boxes in Table B-13 are values that fall outside of the specification for the fuel injection pump model. Red shading is for values above the specification maximums, blue shading for values below the specification minimums. At 1750-RPM and 1800-RPM the delivered quantity was out of specification which could lead to a reduction in engine peak power. The results at 2025-RPM suggest the governor operation was not compromised for the SN: 16393231 pump on JP-8 fuel. At 1600-RPM the timing advance is out of specification, which could affect engine efficiency. The minimum delivery values at 200-RPM and 75-RPM were not met; these conditions are significant for engine starting. The delivery at 75-RPM was low, indicating an engine would have trouble starting with pump SN: 16393231.

The Pre- and Post-Test performance curves for fuel injection pump SN: 16393232 are included as Table B-14. At 350-RPM the low idle delivery was zero, which indicates an engine would not idle with this pump installed. At 1750-RPM and 1800-RPM the delivered quantity was out of specification which could lead to a reduction in engine peak power. The results at 2025-RPM suggest the governor operation was not compromised for the SN: 16393232 pump on JP-8 fuel. The minimum delivery values at 200-RPM and 75-RPM were not met; these conditions are significant for engine starting. The delivery at 75-RPM was low, indicating an engine would have trouble starting with pump SN: 16393232.

Both pumps experienced operational issues as a result of operation with the JP-8 fuel at the elevated 77°C fuel inlet temperature. It can be concluded that the as received JP-8 fuel had insufficient lubricity for rotary fuel injection pump operation at elevated temperature. The fuel as received had a treatment rate of a CI/LI additive just slightly greater than the minimum specification level, whilst prior testing for the U.S. ARMY had indicated maximum CI/LI treatment in JP-8 can result in successful rotary fuel injection pump operation at 77°C. [B-5]

Table B-13. Injection Pump SN: 16393231 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-5209 (arctic)		**SN: 16393231**
Test condition :	**139 hours @ FIT 77°C and 1800 RPM**	**Test: C3JP8-77-500**
Fuel :	**JP-8, AF-8462**	

PUMP RPM	*Description*	*Spec.*	*Before*	*After*	*Change*
1000	Transfer pump psi.	60-62 psi	62 psi	62 psi	0 psi
	Return Fuel	225-375 cc	314 cc	274 cc	40 cc
	Fuel Delivery	51.5 cc Max.	51 cc	45 cc	6 cc
350	Low Idle	12-16 cc	14 cc	**6.0 cc**	8 cc
	Housing psi.	8-12 psi	12 psi	12.0 psi	0.0 psi
	Cold Advance Solenoid	0-1 deg.	0°	0°	0°
1750	Fuel Delivery	44.5-47.5 cc	45.0 cc	**40.0 cc**	5 cc
	Advance	3.75 - 4.75 deg.	4.27°	4.29°	-.02°
1900	Fuel Delivery	31.5 cc min.	37 cc	40 cc	-3 cc
1600	Face Cam Fuel delivery	21.5 - 23.5 cc	12 cc	24 cc	12
	Face Cam Advance	4 - 6 deg.	5.15°	**3.82°**	1.33°
1800	Fuel Delivery	44 cc min.	46 cc	**40 cc**	6 cc
	Transfer Pump psi	Record	90 psi	89 psi	1 psi
	Housing psi.	Record	13 psi	12 psi	1
2025	High Idle	15 cc max.	2.0 cc	11.0 cc	-9.0 cc
	Transfer pump psi.	125 psi max.	109 psi	100 psi	9 psi
200	WOT Fuel Delivery	40 cc min.	44 cc	**35 cc**	9 cc
	WOT Shut-Off	4 cc max.	0 cc	0 cc	0 cc
75	Low Idle Fuel Delivery	26 cc min.	28 cc	**20 cc**	8 cc
	Transfer pump psi.	16 psi min.	27 psi	22 psi	5 psi
	Air Timing	-1 deg.(+/-.5 deg)	-1.00°	-1.00°	.00°
	Fluid Temp. Deg. C		38	38	

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Table B-14. Injection Pump SN: 16393232 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-5209 (arctic)		**SN : 16393232**
Test condition :	**35 hours @ FIT 77°C and 1800 RPM**	**Test : C3JP8-77-500**
Fuel :	**JP-8, AF-8462**	

PUMP RPM	*Description*	*Spec.*	*Before*	*After*	*Change*
1000	Transfer pump psi.	60-62 psi	62 psi	61 psi	1 psi
	Return Fuel	225-375 cc	260 cc	228 cc	32 cc
	Fuel Delivery	51.5 cc Max.	51 cc	42 cc	9 cc
350	Low Idle	12-16 cc	13 cc	**0.0 cc**	13 cc
	Housing psi.	8-12 psi	12.5 psi	11.5 psi	1.0 psi
	Cold Advance Solenoid	0-1 deg.	0°	0°	0°
1750	Fuel Delivery	44.5-47.5 cc	46.5 cc	**39.0 cc**	8.0 cc
	Advance	3.75 - 4.75 deg.	4.22°	4.39°	-0.17°
1900	Fuel Delivery	31.5 cc min.	38 cc	39 cc	-1.0 cc
1600	Face Cam Fuel delivery	21.5 - 23.5 cc	22 cc	22 cc	0.0 cc
	Face Cam Advance	4 - 6 deg.	4.98°	4.79°	0.19°
1800	Fuel Delivery	44 cc min.	46 cc	**40 cc**	6 cc
	Transfer Pump psi	Record	90 psi	90 psi	0 psi
	Housing psi.	Record	13 psi	12 psi	1
2025	High Idle	15 cc max.	2.0 cc	0.0 cc	2.0 cc
	Transfer pump psi.	125 psi max.	109 psi	109 psi	0.0 psi
200	WOT Fuel Delivery	40 cc min.	44 cc	**35 cc**	9.0 cc
	WOT Shut-Off	4 cc max.	0 cc	0 cc	0 cc
75	Low Idle Fuel Delivery	26 cc min.	30 cc	**19 cc**	11 cc
	Transfer pump psi.	16 psi min.	21 psi	20 psi	1 psi
	Air Timing	-1 deg.(+/-.5 deg)	-1.00°	-1.00°	0.0°
	Fluid Temp. Deg. C		38	38	

B.5.2.2 50/50 ATJ/JP-8 Fuel Blend at 40 °C

The Pre- and Post-Test performance curves for fuel injection pump SN: 16393229 are included as Table B-15. Items in shaded boxes in Table B-15 are values that fall outside of the specification for the fuel injection pump model. Red shading is for values above the specification maximums, blue shading for values below the specification minimums. At 1000-RPM the delivery volume was above specification, the delivery characteristics at 1000-RPM would likely impact the peak torque of the engine, and with this pump an engine would exhibit increased black smoke. At low idle, 350-RPM, pump SN: 16393229 was above the maximum delivery value that could result in a fast engine idle. At 1750-RPM the delivered quantity was out of specification which could lead to an increase in engine power, at the cost of increased fuel consumption, increased black smoke and increased engine temperatures. The results at 2025-RPM suggest the governor operation had not been compromised for the SN: 16393229 pump on the ATJ/JP-8 fuel blend. The minimum delivery values at 200-RPM and 75-RPM were met, so engine starting with this pump would not be an issue.

The Pre- and Post-Test performance curves for fuel injection pump SN: 16393230 are included as Table B-16. Items in shaded boxes in Table B-16 are values that fall outside of the specification for the fuel injection pump model. At low idle, 350-RPM, pump SN: 16393230 was below the minimum delivery value that may result in a rough engine idle. At 1750-RPM the delivered quantity was out of specification which could lead to an increase in engine power, at the cost of increased fuel consumption, increased black smoke and increased engine temperatures. The 1600-RPM calibration criteria suggest the pump would slightly over-fuel at an advanced injection timing that could affect economy and emissions. The 2025-RPM delivery result suggests the governor action is compromised for the SN: 16393230 pump that could lead to engine over speed. The minimum delivery values that are critical for starting at 200-RPM and 75-RPM were within specification.

Both fuel injection pumps completed 500-Hours of operation with the ATJ/JP-8 fuel, with a 0.63-mm BOCLE value. Both pumps exhibited some performance degradation with respect to their calibration performance criterion that would have impacted engine operability, mostly from over-fuelling.

Table B-15. Injection Pump SN: 16393229 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-5209 (arctic)		**SN: 16393229**
Test condition :	**500 hours @ FIT 40°C and 1800 RPM**	**Test: AF8596-C3ATJ-40-500**
Fuel :	**ATJ/JP8, AF-8596**	

PUMP RPM	*Description*	*Spec.*	*Before*	*After*	*Change*
1000	Transfer pump psi.	60-62 psi	62 psi	62 psi	0 psi
	Return Fuel	225-375 cc	320 cc	350 cc	-30 cc
	Fuel Delivery	51.5 cc Max.	50 cc	**54 cc**	-4.0 cc
350	Low Idle	12-16 cc	15 cc	**28.0 cc**	-13 cc
	Housing psi.	8-12 psi	12.5 psi	11.5 psi	1.0 psi
	Cold Advance Solenoid	0-1 deg.	0°	0°	0°
1750	Fuel Delivery	44.5-47.5 cc	44.5 cc	**49.0 cc**	-5.0 cc
	Advance	3.75 - 4.75 deg.	4.21°	4.25°	-0.04°
1900	Fuel Delivery	31.5 cc min.	38.0 cc	48.0 cc	-10.0 cc
1600	Face Cam Fuel delivery	21.5 - 23.5 cc	21.0 cc	22.0 cc	1.0
	Face Cam Advance	4.0 – 6.0 deg.	5.27°	5.75°	-0.48°
1800	Fuel Delivery	44 cc min.	44 cc	49 cc	-5 cc
	Transfer Pump psi	Record	88 psi	88 psi	0 psi
	Housing psi.	Record	13 psi	13 psi	0 psi
2025	High Idle	15 cc max.	1.0 cc	0.0 cc	1.0 cc
	Transfer pump psi.	125 psi max.	105 psi	100 psi	5 psi
200	WOT Fuel Delivery	40 cc min.	40 cc	42 cc	-2 cc
	WOT Shut-Off	4 cc max.	0 cc	0 cc	0 cc
75	Low Idle Fuel Delivery	26 cc min.	25 cc	25 cc	0 cc
	Transfer pump psi.	16 psi min.	22 psi	25 psi	-3 psi
	Air Timing	-1 deg.(+/-.5 deg)	-1.0°	-1.0°	0.0°
	Fluid Temp. Deg. C		38	38	

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Table B-16. Injection Pump SN: 16393230 Performance Specifications

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-5209 (arctic)		**SN : 16393230**
Test condition :	**500 hours @ FIT 40°C and 1800 RPM**	**Test : AF8596-C3ATJ-40-500**
Fuel :	**ATJ/JP8, AF-8596**	

PUMP RPM	***Description***	***Spec.***	***Before***	***After***	***Change***
1000	Transfer pump psi.	60-62 psi	62 psi	61 psi	1 psi
	Return Fuel	225-375 cc	292 cc	310 cc	-18 cc
	Fuel Delivery	51.5 cc Max.	49.0 cc	50.0 cc	-1.0 cc
350	Low Idle	12-16 cc	14 cc	**8.0 cc**	6 cc
	Housing psi.	8-12 psi	12 psi	12 psi	0.0 psi
	Cold Advance Solenoid	0-1 deg.	0°	0°	0°
1750	Fuel Delivery	44.5-47.5 cc	44.5 cc	**50.0 cc**	-6.0 cc
	Advance	3.75 - 4.75 deg.	4.30°	4.00°	0.30°
1900	Fuel Delivery	31.5 cc min.	37.0 cc	50.0 cc	-13.0 cc
1600	Face Cam Fuel delivery	21.5 - 23.5 cc	22.0 cc	**24.0 cc**	2.0
	Face Cam Advance	4.0 – 6.0 deg.	4.96°	**7.50°**	-2.54°
1800	Fuel Delivery	44 cc min.	44 cc	50 cc	-6 cc
	Transfer Pump psi	Record	87 psi	88 psi	-1 psi
	Housing psi.	Record	13 psi	13 psi	0 psi
2025	High Idle	15.0 cc max.	1.5 cc	**22.0 cc**	-20.5 cc
	Transfer pump psi.	125 psi max.	104 psi	98 psi	6 psi
200	WOT Fuel Delivery	40 cc min.	41.5 cc	48 cc	-7 cc
	WOT Shut-Off	4 cc max.	0 cc	0 cc	0 cc
75	Low Idle Fuel Delivery	26 cc min.	28 cc	30 cc	-2 cc
	Transfer pump psi.	16 psi min.	28 psi	26 psi	2 psi
	Air Timing	-1 deg.(+/-.5 deg)	-1.0°	-1.0°	0.0°
	Fluid Temp. Deg. C		38	38	

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B.5.3 Rotary Pump Wear Measurements

The transfer pump and plunger assemblies are integral to the fuel-metering system in the Stanadyne rotary pump, and by function are the most affected by low lubricity fuel. Accelerated wear in either the transfer pump blades or the roller-to-roller dimension results in a change of fueling condition that jeopardizes the quantity of fuel injected into the hydraulic head assembly. Wear in the transfer pump blades limits the amount of pressure necessary to maintain the proper amount of fuel in the chamber where opposing plungers, actuated by the rollers and cam, inject the metered fuel into the hydraulic head assembly. Roller-to-roller dimension variations alter the travel distance of the plungers, effectively changing metered fuel, injection pressure, and injection timing.

B.5.3.1 JP-8 Fuel at 77 °C

Table B-17 and Table B-18 present the transfer pump blade and roller-to-roller dimension measurement results for the two fuel injection pumps that operated on JP-8 fuel at elevated temperature. There were not any out-of-specification transfer blade measurements based on the dimension length C for either pump SN: 16393231 or SN: 16393232. The width of the blades did not change dramatically, nor did the blade’s thicknesses decrease much due to the shortened test durations. Both pump roller-to-roller dimensions changes were less than the ± 0.127-mm assembly specification tolerance. However the roller-to-roller dimensions did slightly decrease for both pumps, as reflected in the decreased delivery seen for both pumps. The roller-to-roller eccentricity specification is 0.2032-mm maximum, which both pumps met for testing with the JP-8 fuel at elevated temperature. In general all transfer pump blades were in fair condition, and the roller-to-roller dimensions changes reflect some of the performance changes seen on the calibration stand.

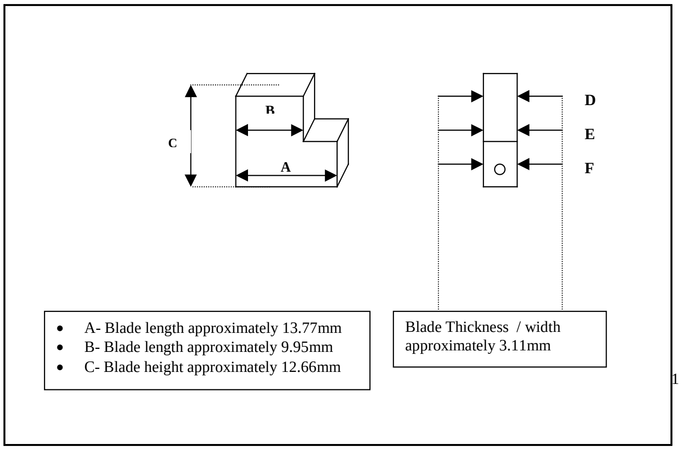
Table B-17. Pump SN: 16393231 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-5209	**SN: 16393231**	**Test Number : C3JP8-77-500**
Fuel description : JP-8, AF-8462		

	Date:	1/10/2013	3/2/2013	
Dimensional Measurements (mm)		***0 hrs.***	***139 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.6462	13.6411	-0.0051
	Dimension B	9.9657	9.9606	-0.0051
	Dimension C	12.6683	12.6683	0.0000
	Dimension D	3.1191	3.1128	-0.0064
	Dimension E	3.1179	3.1166	-0.0013
	Dimension F	3.1179	3.1166	-0.0013
Transfer Pump Blade 2	Dimension A	13.6716	13.6665	-0.0051
	Dimension B	10.0140	10.0063	-0.0076
	Dimension C	12.6721	12.6721	0.0000
	Dimension D	3.1255	3.1204	-0.0051
	Dimension E	3.1255	3.1242	-0.0013
	Dimension F	3.1255	3.1242	-0.0013
Transfer Pump Blade 3	Dimension A	13.6563	13.6538	-0.0025
	Dimension B	9.9835	9.9784	-0.0051
	Dimension C	12.6695	12.6683	-0.0013
	Dimension D	3.1280	3.1255	-0.0025
	Dimension E	3.1280	3.1267	-0.0013
	Dimension F	3.1280	3.1255	-0.0025
Transfer Pump Blade 4	Dimension A	13.6550	13.6525	-0.0025
	Dimension B	9.9962	9.9911	-0.0051
	Dimension C	12.6746	12.6721	-0.0025
	Dimension D	3.1217	3.1204	-0.0013
	Dimension E	3.1217	3.1217	0.0000
	Dimension F	3.1217	3.1217	0.0000
	Roller to Roller (mm)	49.8373	49.8069	-0.0305
	Eccentricity (mm)	0.0508	0.0762	0.0254
	Drive Backlash (mm)	0.1016	0.4826	0.3810

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



- A- Blade length approximately 13.77mm
- B- Blade length approximately 9.95mm
- C- Blade height approximately 12.66mm

Blade Thickness / width approximately 3.11mm

1

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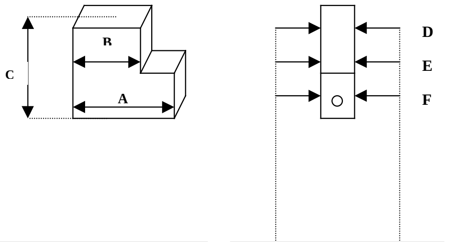
Table B-18. Pump SN: 16393232 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-5209	**SN: 16393232**	**Test Number : C3JP8-77-500**
Fuel description : JP-8, AF-8462		

	Date:	1/10/2013	3/2/2013	
Dimensional Measurements (mm)		***0 hrs.***	***35 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.6728	13.6703	-0.0025
	Dimension B	10.0495	10.0457	-0.0038
	Dimension C	12.6771	12.6759	-0.0013
	Dimension D	3.1306	3.1293	-0.0013
	Dimension E	3.1293	3.1267	-0.0025
	Dimension F	3.1280	3.1280	0.0000
Transfer Pump Blade 2	Dimension A	13.6474	13.6462	-0.0013
	Dimension B	9.9568	9.9543	-0.0025
	Dimension C	12.6708	12.6695	-0.0013
	Dimension D	3.1267	3.1255	-0.0013
	Dimension E	3.1267	3.1267	0.0000
	Dimension F	3.1267	3.1255	-0.0013
Transfer Pump Blade 3	Dimension A	13.6652	13.6652	0.0000
	Dimension B	10.0025	10.0013	-0.0013
	Dimension C	12.6721	12.6708	-0.0013
	Dimension D	3.1318	3.1306	-0.0013
	Dimension E	3.1318	3.1306	-0.0013
	Dimension F	3.1318	3.1318	0.0000
Transfer Pump Blade 4	Dimension A	13.6601	13.6589	-0.0013
	Dimension B	9.9860	9.9835	-0.0025
	Dimension C	12.6721	12.6708	-0.0013
	Dimension D	3.1267	3.1255	-0.0013
	Dimension E	3.1267	3.1267	0.0000
	Dimension F	3.1267	3.1267	0.0000
	Roller to Roller (mm)	49.8348	49.8043	-0.0305
	Eccentricity (mm)	0.0762	0.1524	0.0762
	Drive Backlash (mm)	0.1270	0.1778	0.0508

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



- A- Blade length approximately 13.77mm
- B- Blade length approximately 9.95mm
- C- Blade height approximately 12.66mm

Blade Thickness / width approximately 3.11mm

B.5.3.2 50/50 ATJ/JP-8 Fuel Blend at 40 °C

Table B-19 and Table B-20 present the transfer pump blade and roller-to-roller dimension measurement results for the two fuel injection pumps that operated on the ATJ/JP-8 fuel blend. There were not any out-of-specification transfer blade measurements based on the dimension length C for either pump SN: 16393229 or SN: 16393230. The width of the blades did not change dramatically, nor did the blade's thicknesses decrease much. Both pump SN: 16393229 and SN: 16393230 roller-to-roller dimensions increased, changing slightly more than the ± 0.127-mm assembly specification tolerance. The roller-to-roller dimensions increase for both pumps is reflected in the slightly increased delivery seen for both pumps. The roller-to-roller eccentricity specification is 0.2032-mm maximum, which neither pump exceeded after 500-Hours testing with the ATJ/JP-8 fuel blend. In general all transfer pump blades were in fair condition, and the roller-to-roller dimensions changes reflected the performance changes seen on the calibration stand.

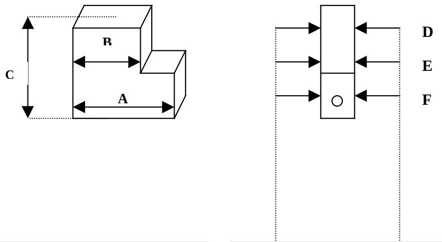
Table B-19. Pump SN: 16393229 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-5209	**SN: 16393229**	**Test Number : AF8596-C3ATJ-40-500**
Fuel description : ATJ/JP8, AF-8596		

	Date:	1/9/2013	8/22/2013	
Dimensional Measurements (mm)		***0 hrs.***	***500 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.6728	13.6703	-0.0025
	Dimension B	10.0330	10.0241	-0.0089
	Dimension C	12.6721	12.6721	0.0000
	Dimension D	3.1318	3.1293	-0.0025
	Dimension E	3.1318	3.1293	-0.0025
	Dimension F	3.1318	3.1280	-0.0038
Transfer Pump Blade 2	Dimension A	13.6703	13.6538	-0.0165
	Dimension B	9.9911	9.9886	-0.0025
	Dimension C	12.6683	12.6721	0.0038
	Dimension D	3.1306	3.1280	-0.0025
	Dimension E	3.1318	3.1293	-0.0025
	Dimension F	3.1318	3.1293	-0.0025
Transfer Pump Blade 3	Dimension A	13.6716	13.6601	-0.0114
	Dimension B	9.9936	9.9924	-0.0013
	Dimension C	12.6784	12.6746	-0.0038
	Dimension D	3.1306	3.1267	-0.0038
	Dimension E	3.1318	3.1267	-0.0051
	Dimension F	3.1318	3.1255	-0.0063
Transfer Pump Blade 4	Dimension A	13.6703	13.6627	-0.0076
	Dimension B	10.0025	9.9974	-0.0051
	Dimension C	12.6746	12.6721	-0.0025
	Dimension D	3.1306	3.1250	-0.0056
	Dimension E	3.1318	3.1255	-0.0063
	Dimension F	3.1318	3.1267	-0.0051
	Roller to Roller (mm)	49.8373	49.9669	0.1295
	Eccentricity (mm)	0.2286	0.1524	-0.0762
	Drive Backlash (mm)	0.1016	0.4826	0.3810

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



- A- Blade length approximately 13.77mm
- B- Blade length approximately 9.95mm
- C- Blade height approximately 12.66mm

Blade Thickness / width approximately 3.11mm

1

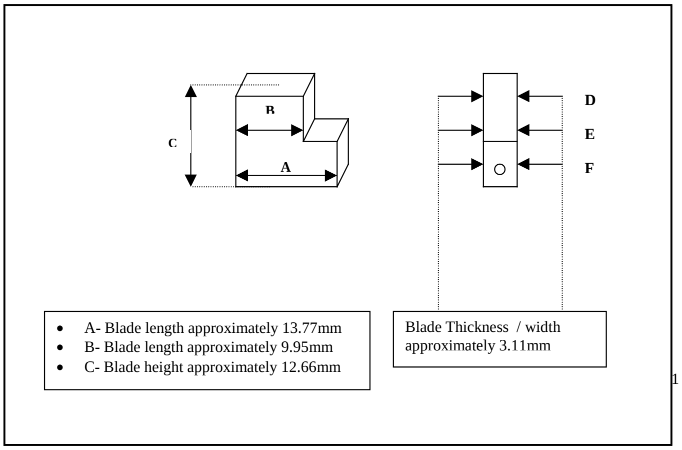
Table B-20. Pump SN: 16393230 Blade Size Measurements

Blade & Roller-To-Roller Measurements

Pump Type : DB2831-5209	**SN: 16393230**	**Test Number : AF8596-C3ATJ-40-500**
Fuel description : ATJ/JP8, AF-8596		

	Date:	1/9/2013	8/27/2013	
Dimensional Measurements (mm)		***0 hrs.***	***500 hrs.***	***Change***
Transfer Pump Blade 1	Dimension A	13.6550	13.6525	-0.0025
	Dimension B	9.9581	9.9555	-0.0025
	Dimension C	12.6784	12.6771	-0.0013
	Dimension D	3.1267	3.1255	-0.0013
	Dimension E	3.1293	3.1255	-0.0038
	Dimension F	3.1293	3.1267	-0.0025
Transfer Pump Blade 2	Dimension A	13.6614	13.6576	-0.0038
	Dimension B	9.9720	9.9708	-0.0013
	Dimension C	12.6771	12.6759	-0.0013
	Dimension D	3.1280	3.1250	-0.0030
	Dimension E	3.1280	3.1267	-0.0013
	Dimension F	3.1293	3.1280	-0.0013
Transfer Pump Blade 3	Dimension A	13.6335	13.6246	-0.0089
	Dimension B	9.9403	9.9314	-0.0089
	Dimension C	12.6746	12.6746	0.0000
	Dimension D	3.1255	3.1199	-0.0056
	Dimension E	3.1242	3.1199	-0.0043
	Dimension F	3.1242	3.1217	-0.0025
Transfer Pump Blade 4	Dimension A	13.6500	13.6474	-0.0025
	Dimension B	9.9924	9.9873	-0.0051
	Dimension C	12.6721	12.6721	0.0000
	Dimension D	3.1280	3.1242	-0.0038
	Dimension E	3.1280	3.1255	-0.0025
	Dimension F	3.1293	3.1280	-0.0013
	Roller to Roller (mm)	49.8373	50.0253	0.1880
	Eccentricity (mm)	0.1016	0.1016	0.0000
	Drive Backlash (mm)	0.1016	0.4064	0.3048

	MIN - HEIGHT (C)	MAX - HEIGHT (C)
Inches	0.4986	0.4993
Millimeters	12.66444	12.68222



- A- Blade length approximately 13.77mm
- B- Blade length approximately 9.95mm
- C- Blade height approximately 12.66mm

Blade Thickness / width approximately 3.11mm

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B.5.4 Fuel Injector Results

Fuel injector nozzle tests were performed in accordance with procedures set forth in an approved 6.5L diesel engine manual using diesel nozzle tester J 29075 – B. Nozzle testing is comprised of the following checks:

- Nozzle Opening Pressure
- Leakage
- Chatter
- Spray Pattern

Each test is considered independent of the others, and if any one of the tests is not satisfied, the injector should be replaced.

The normal opening pressure specification for these injectors is 1500 psig minimum. The specified nozzle leakage test involves pressurizing the injector nozzle to 1400 psig and holding for 10 seconds – no fuel droplets should separate from the injector tip. The chatter and spray pattern evaluations are subjective. A sharp audible chatter from the injector and a finely misted spray cone are required.

New Bosch Model O432217104 injectors were used for both of the fuels tests. The injector performance tests and rating results are shown in Table B-21 for the JP-8 test at elevated temperature. All sixteen fuel injectors passed the post-test opening pressure evaluations after the shortened testing intervals. All sixteen fuel injectors passed the injector tip leakage, chatter, and spray pattern checks.

The injector performance tests and rating results are shown in Table B-22 for the ATJ/JP-8 fuel blend test. All sixteen fuel injectors met the minimum nozzle opening pressure after 500-hours of operation. With the ATJ/JP-8 fuel blend, all sixteen fuel injectors passed the injector tip leakage, chatter, and spray pattern evaluations after 500-hours of operation.

Table B-21. Fuel Injector Performance Evaluations after 500-Hours JP-8 CI/LI Fuel Usage

Stanadyne Rotary Pump Lubricity Evaluation

6.2L/6.5L Fuel Injector Test Inspection

Test No.	Inj. Pump ID No.	Fuel	Inj. ID No.	Opening Pressure (pre-test)	Opening Pressure (post-test)	Tip Leakage (pre-test)	Tip Leakage (post-test)	Chatter (pre-test)	Chatter (post-test)	Spray pattern (pre-test)	Spray pattern (post-test)	Date (pre-test)	Date (post-test)	Test Hours	Tech.
C3JP8-77-500	SN : 16393232	JP-8, AF-8462	JP8-9	1925	1850	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	35	REG
			JP8-10	1925	1775	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	35	REG
			JP8-11	1900	1850	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	35	REG
			JP8-12	1900	1825	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	35	REG
			JP8-13	1975	1825	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	35	REG
			JP8-14	1900	1800	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	35	REG
			JP8-15	1925	1825	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	35	REG
			JP8-16	1975	1825	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	35	REG
C3JP8-77-500	SN : 16393231	JP-8, AF-8462	JP8-1	1925	1700	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	139	REG
			JP8-2	1925	1725	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	139	REG
			JP8-3	1925	1725	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	139	REG
			JP8-4	1925	1700	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	139	REG
			JP8-5	1975	1775	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	139	REG
			JP8-6	1925	1775	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	139	REG
			JP8-7	1875	1700	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	139	REG
			JP8-8	1875	1690	pass	pass	pass	pass	pass	pass	12/12/2012	3/5/2013	139	REG
			Spec. :	1500psig min	1500psig min	no drop off in 10 sec. @ 1400 psi	no drop off in 10 sec. @ 1400 psi	chatter	chatter	fine mist	fine mist				

Comments :

Table B-22. Fuel Injector Performance Evaluations after 500-Hours ATJ/JP-8 CI/LI Fuel Usage

Stanadyne Rotary Pump Lubricity Evaluation

6.2L/6.5L Fuel Injector Test Inspection

Test No.	Inj. Pump ID No.	Fuel	Inj. ID No.	Opening Pressure (pre-test)	Opening Pressure (post-test)	Tip Leakage (pre-test)	Tip Leakage (post-test)	Chatter (pre-test)	Chatter (post-test)	Spray pattern (pre-test)	Spray pattern (post-test)	Date (pre-test)	Date (post-test)	Test Hours	Tech.
AF8596-C3ATJ-40-500	SN : 16393230	ATJ/JP8, AF-8596	ATJ-9	1925	1600	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-10	1925	1600	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-11	1875	1600	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-12	1975	1600	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-13	1900	1625	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-14	1975	1675	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-15	1975	1600	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-16	2000	1650	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
AF8596-C3ATJ-40-500	SN : 16393229	ATJ/JP8, AF-8596	ATJ-1	1975	1575	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-2	1950	1650	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-3	1900	1575	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-4	1900	1600	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-5	1975	1650	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-6	1900	1625	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-7	1900	1550	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			ATJ-8	1950	1675	pass	pass	pass	pass	pass	pass	12/12/2012	8/12/2013	500	REG
			Spec. :	1500psig min	1500psig min	no drop off in 10 sec. @ 1400 psi	no drop off in 10 sec. @ 1400 psi	chatter	chatter	fine mist	fine mist				

Comments :

B.5.5 Rotary Pump Component Wear Evaluations

After the fuel injection pump calibration and functional performance checks, the fuel injection pumps were disassembled and the components critical to pump operation were evaluated for parts conditions. A technician with over twenty years experience rebuilding, servicing, and testing Stanadyne fuel injection pumps performed the subjective wear ratings.

B.5.5.1 JP-8 Fuel at 77°C – Pump SN: 16393231

The parts conditions and subjective wear ratings for fuel injection pump SN: 16393231 are summarized in Table B-23. Images of the wear seen on the components of fuel injection pump SN: 16393231 are shown in Figure B-14 through Figure B-31. Figure B-14 and Figure B-15 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure B-14 and Figure B-15 reveals very little distress at the rotor discharge ports due to the shortened 139-hour test duration with the JP-8 fuel at 77°C.

Figure B-16 and Figure B-17 are the Pre-Test and Post-Test conditions of the fuel injection pump SN: 16393231 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure B-16. Figure B-17 reveals a wear scar on the roller shoe from the leaf spring contact, heavy burnishing of the rollers, and chipping and scoring of the rollers. The rollers tend to discolor when combination rolling-sliding action occurs as the rollers follow the injection cam profile. Figure B-18 and Figure B-19 show the relatively small wear scar due to 139-hours operation on the roller shoe plunger contact. The injection pump cam ring shown in Figure B-20 and Figure B-21 reveals heavy distress, with evidence of sliding contact, and heavy lobe wear, flattened cam lobes, from 139-hours operation with the JP-8 fuel at elevated temperature. The excessive cam lobe wear likely contributed to the wear seen on the rollers.

The governor thrust washer condition before and after 139-hours are shown in Figure B-22 and Figure B-23. The polishing wear seen on the thrust washer in Figure B-23 is excessive for 139-hours of injection pump operation. Scoring wear seen on the advance piston suggests the fuel pressure may have been fluctuating in that area of the fuel injection pumps housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The wear on these components is greater than normal considering the 139-hour duration of testing. The wear on the thrust washer, the advance piston wear, and the metering valve may have affected fuel injection pump operation as evidenced on the calibration stand.

Table B-23. Pump SN: 16393231 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-5209	**SN : 16393231**
Test condition : 139 hours @ FIT 77°C and 1800 RPM	**TEST : C3JP8-77-500**
Fuel : JP-8, AF-8462	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Wear at rotor slots and liner contact	2.5
BLADE SPRINGS	No wear	0
LINER	80% Scoring wear	3.5
TRANSFER PUMP REGULATOR	Polishing wear from blade contact	2
REGULATOR PISTON	Polishing wear and light scoring	2
ROTOR	Wear marks at inlet and distributor ports	3
ROTOR RETAINERS	Wear from rotor contact	2.5
DELIVERY VALVE	Polishing wear, light scoring	2.5
PLUNGERS	Polishing wear, light scoring	2.5
SHOES	Heavy scoring from roller contact	4.5
ROLLERS	Heavy chipping and scoring	5
LEAF SPRING	Wear from shoe contact	2.5
CAM RING	Lobes worn down and chipped	4.5
THRUST WASHER	Polishing wear from weights	1.5
THRUST SLEEVE	Metal inserts missing. Wear from governor weights and pivot fingers	3.5
GOVORNER WEIGHTS	Wear at heel and thrust washer contact	2.5
LINK HOOK	Finger bably worn. Dimple at pivot point	3.5
METERING VAVLE	Polishing wear	1.5
DRIVE SHAFT TANG	Fretting wear	4
DRIVE SHAFT SEALS	Normal	1
CAM PIN	.002" out of round. Flat spot from piston	4
ADVANCE PISTON	Scoring wear	3
HOUSING	Dark brown stains, mostly in governor top area	1
	AVERAGE DEMERIT RATINGS	2.72

Figure B-24 and Figure B-25 illustrate the level of wear seen in the transfer pump section of fuel injection pump SN: 16393231. Figure B-24 shows the surface condition of the transfer pump liner prior to testing and Figure B-25 shows the surface with scoring wear after 139-hours of operation on the JP-8 fuel at elevated temperature. Also illustrative of the transfer pump section wear are the transfer pump blade conditions shown in Figure B-26 through Figure B-29. The edge wear shown in Figure B-26 and Figure B-27 corresponds to the surface on the transfer pump blades that contact and slide on the transfer pump liner, separated by a film of fuel. The blade edge conditions in Figure B-27 reflect the scoring seen on the transfer pump liner, excessive for 139-hours operation. The side polishing shown in Figure B-28 and Figure B-29 reflect wear from the transfer pump blade slots on the injection pump rotor, and is relatively mild. The wear seen on the transfer pump components is excessive considering the testing duration for pump SN: 16393231.

Figure B-30 and Figure B-31 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure B-30 and Figure B-31 reveal a wear scar that indicates backlash and timing were likely altered with the JP-8 fuel at elevated temperature after 139-hours.

Figure B-14. Pump SN: 16393231 Distributor Rotor before Testing with JP-8 Fuel

Figure B-15. Pump SN: 16393231 Distributor Rotor with 139-Hours Testing with JP-8 Fuel

Figure B-16. Pump SN: 16393231 Rollers and Shoe before Testing with JP-8 Fuel

Figure B-17. Pump SN: 16393231 Rollers and Shoe with 139-Hours Testing with JP-8 Fuel

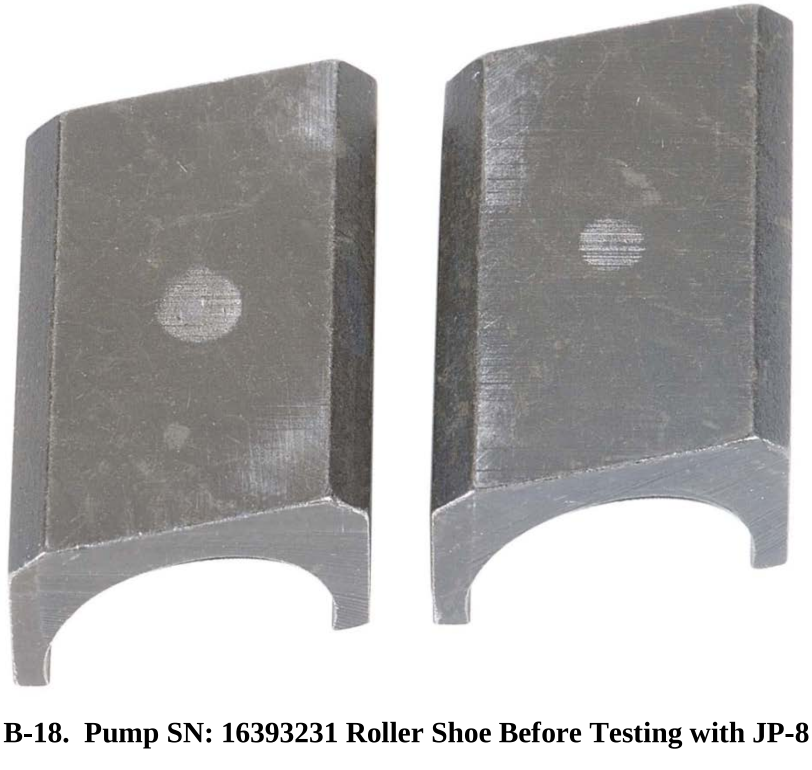

Figure B-18. Pump SN: 16393231 Roller Shoe Before Testing with JP-8 Fuel

Figure B-19. Pump SN: 16393231 Roller Shoe with 139-Hours Testing with JP-8 Fuel

Figure B-20. Pump SN: 16393231 Cam Ring before Testing with JP-8 Fuel

Figure B-21. Pump SN: 16393231 Cam Ring with 139-Hours Testing with JP-8 Fuel

Figure B-22. Pump SN: 16393231 Thrust Washer Before Testing with JP-8 Fuel

Figure B-23. Pump SN: 16393231 Thrust Washer with 139-Hours Testing with JP-8 Fuel

Figure B-24. Pump SN: 16393231 Transfer Pump Liner Before Testing with JP-8 Fuel

Figure B-25. Pump SN: 16393231 Transfer Pump Liner with 139-Hours Testing with JP-8 Fuel

Figure B-26. Pump SN: 16393231 Transfer Pump Blade Edges Before Testing with JP-8 Fuel

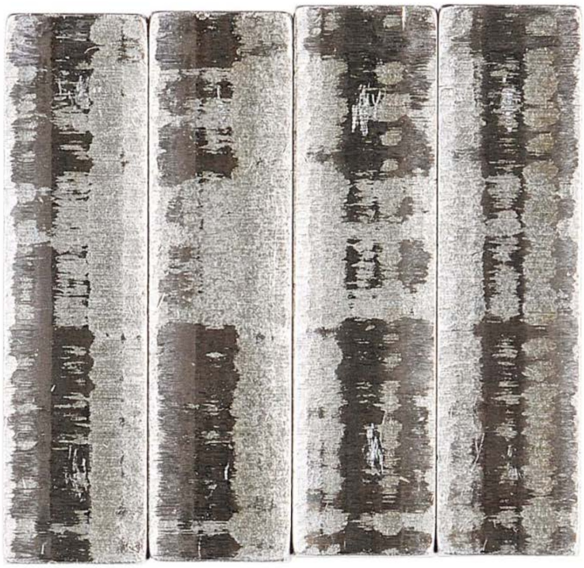

Figure B-27. Pump SN: 16393231 Transfer Pump Blade Edges with 139-Hours Testing with JP-8 Fuel

Figure B-28. Pump SN: 16393231 Transfer Pump Blade Sides Before Testing with JP-8 Fuel

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Figure B-29. Pump SN: 16393231 Transfer Pump Blade Sides with 139-Hours Testing with JP-8 Fuel

Figure B-30. Pump SN: 16393231 Driveshaft Drive Tang Before Testing with JP-8 Fuel

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Figure B-31. Pump SN: 16393231 Driveshaft Drive Tang with 139-Hours Testing with JP-8 Fuel

B.5.5.2 JP-8 Fuel at 77°C – Pump SN: 16393232

The parts conditions and subjective wear ratings for fuel injection pump SN: 16393232 are summarized in Table B-24. Images of the wear seen on the components of fuel injection pump SN: 16393232 are shown in Figure B-32 through Figure B-49. Figure B-32 and Figure B-33 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure B-33 reveal the very light scratches at the rotor discharge ports, usually from wear debris, after the 35-hours.

Figure B-34 and Figure B-35 are the Pre-Test and Post-Test conditions of the fuel injection pump SN: 16393232 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure B-34. Figure B-35 reveals only light polishing wear on the roller shoe from the leaf spring contact. Figure B-35 shows the Rollers and Roller Shoes with extreme wear and one of the roller shoes being split. Figure B-36 and Figure B-37 show the wear scar due to 35-hours operation on the roller shoe plunger contact. The injection pump cam ring conditions are shown in Figure B-38 and Figure B-39. The cam ring the rollers ride on exhibited flattened cam lobes as seen in Figure B-39. The split roller shoe or the flattened cam lobes have not been seen with JP-8 fuels before, the extreme wear is attributed to the elevated test temperature operation with the JP-8 fuel.

The governor thrust washer condition before and after 35-hours is seen in Figure B-40 and Figure B-41. The polishing wear seen on the thrust washer in Figure B-41 is excessive for only 35-hours of injection pump operation. Scoring wear seen on the advance piston suggests the fuel pressure may have been fluctuating in that area of the fuel injection pumps housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly

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polished area shows at one location on the helix. The wear on these components is greater than normal considering the 35-hour duration of testing. The wear on the thrust washer, the advance piston wear, and the metering valve had an effect on pump operation.

Figure B-42 and Figure B-43 illustrates the level of wear seen in the transfer pump section of fuel injection pump SN: 16393232. Figure B-42 shows the surface condition of the transfer pump liner prior to testing and Figure B-43 shows the surface with moderate scoring after 35-hours of operation on the elevated temperature JP-8 fuel. Also illustrative of wear in the transfer pump section are the transfer pump blade conditions shown in Figure B-44 through Figure B-47. The edge wear shown in Figure B-44 and Figure B-45 corresponds to the surface on the transfer pump blades that contact the transfer pump liner. The blade edge conditions in Figure B-45 reflect the scoring seen on the transfer pump liner, excessive for 35-hours operation. The light side polishing shown in Figure B-46 and Figure B-47 reflect wear from the transfer pump blade slots on the injection pump rotor. The wear seen on the transfer pump components is excessive considering the testing duration for pump SN: 16393232.

Figure B-48 and Figure B-49 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure B-49 reveals a mild wear scar that indicates backlash was starting to occur due to cam and cam roller wear with the JP-8 fuel after 35-hours. For both pumps that utilized the JP-8 fuel at elevated temperature, the significant wear of the cam and cam rollers likely contributed to the fuel injection pump performance degradation. The cumulative effect of all the worn components also contributed to the degradation with the JP-8 fuel at 77°C fuel inlet temperature.

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Table B-24. Pump SN: 16393232 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-5209	**SN : 16393232**
Test condition : 35 hours @ FIT 77°C and 1800 RPM	**TEST : C3JP8-77-500**
Fuel : JP-8, AF-8462	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Wear at rotor slots and liner contact	2.5
BLADE SPRINGS	Light rubbing wear	0.5
LINER	80% Scoring wear	3.5
TRANSFER PUMP REGULATOR	Polishing wear. Small groove from blades	2.5
REGULATOR PISTON	Polishing wear.	2
ROTOR	Wear at distributor ports	2
ROTOR RETAINERS	Wear from rotor	2.5
DELIVERY VALVE	Polishing wear	2
PLUNGERS	Polishing wear. Light scoring	2.5
SHOES	Right shoe split in half. Scoring from rollers	5
ROLLERS	Heavy chipping and scoring	5
LEAF SPRING	Wear from shoe contact	2.5
CAM RING	Lobes worn down	4.5
THRUST WASHER	Polishing wear from weights	2
THRUST SLEEVE	Metal inserts missing and wear from weights and fingers	3
GOVORNER WEIGHTS	Wear at heels and thrust washer contact	2.5
LINK HOOK	Wear on fingers and pivot	2.5
METERING VAVLE	Polishing wear	1
DRIVE SHAFT TANG	Fretting wear	2.5
DRIVE SHAFT SEALS	Normal	1
CAM PIN	.001" out of round. Wear from piston	3
ADVANCE PISTON	Scoring wear	3
HOUSING	Dark Brown stains	1
	AVERAGE DEMERIT RATINGS	2.54

Figure B-32. Pump SN: 16393232 Distributor Rotor Before Testing with JP-8 Fuel

Figure B-33. Pump SN: 16393232 Distributor Rotor with 35-Hours Testing with JP-8 Fuel

Figure B-34. Pump SN: 16393232 Rollers and Shoe Condition Before Testing with JP-8 Fuel

Figure B-35. Pump SN: 16393232 Rollers and Shoe with 35-Hours Testing with JP-8 Fuel

Figure B-36. Pump SN: 16393232 Roller Shoe Condition Before Testing with JP-8 Fuel

Figure B-37. Pump SN: 16393232 Roller Shoe with 35-Hours Testing with JP-8 Fuel

Figure B-38. Pump SN: 16393232 Cam Ring Before Testing with JP-8 Fuel

Figure B-39. Pump SN: 16393232 Cam Ring with 35-Hours Testing with JP-8 Fuel

Figure B-40. Pump SN: 16393232 Thrust Washer Before Testing with JP-8 Fuel

Figure B-41. Pump SN: 16393232 Thrust Washer with 35-Hours Testing with JP-8 Fuel

Figure B-42. Pump SN: 16393232 Transfer Pump Liner Before Testing with JP-8 Fuel

Figure B-43. Pump SN: 16393232 Transfer Pump Liner with 35-Hours Testing with JP-8 Fuel

Figure B-44. Pump SN: 16393232 Transfer Pump Blade Edges Before Testing with JP-8 Fuel

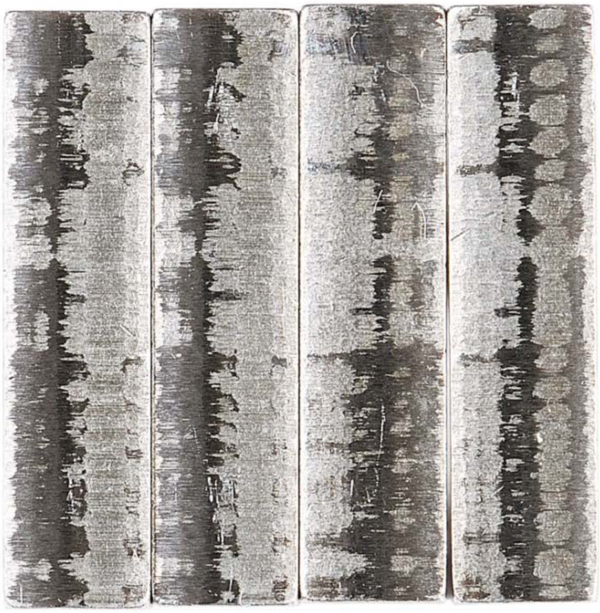

Figure B-45. Pump SN: 16393232 Transfer Pump Blade Edges with 35-Hours Testing with JP-8 Fuel

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Figure B-46. Pump SN: 16393232 Transfer Pump Blade Sides Before Testing with JP-8 Fuel

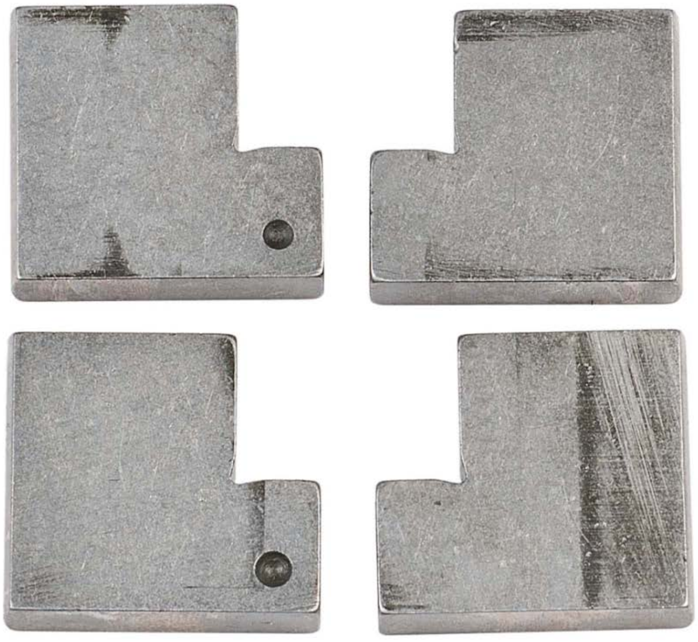

Figure B-47. Pump SN: 16393232 Transfer Pump Blade Sides with 35-Hours Testing with JP-8 Fuel

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Figure B-48. Pump SN: 16393232 Driveshaft Drive Tang Before Testing with JP-8 Fuel

Figure B-49. Pump SN: 16393232 Driveshaft Drive Tang with 35-Hours Testing with JP-8 Fuel

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B.5.5.3 50/50 ATJ/JP-8 Fuel Blend at 40 °C – Pump SN: 16393229

The parts conditions and subjective wear ratings for fuel injection pump SN: 16393229 are summarized in Table B-25. Images of the wear seen on the components of fuel injection pump SN: 16393229 are shown in Figure B-50 through Figure B-67. Figure B-50 and Figure B-51 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure B-51 shows the discharge ports and rotor are in fair condition, with light scratching from wear debris after 500-Hours. The rotor condition with the ATJ/JP-8 blend is comparable to the rotor condition seen with JP-8 at 500-hours at 40°C fuel inlet temperature.

Figure B-52 and Figure B-53 is the Pre-Test and Post-Test conditions of the fuel injection pump SN: 16393229 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure B-52. Figure B-53 reveals mild wear scars on the roller shoe from the leaf spring contact, and heavy burnishing of the rollers. The rollers tend to discolor when combination rolling-sliding action occurs as the rollers follow the injection cam profile. Figure B-54 and Figure B-55 show the relatively mild wear scar due to 500-hours operation on the roller shoe plunger contact. The injection pump cam ring shown in Figure B-56 and Figure B-57 reveals some polishing wear on the cam lobes with the ATJ/JP-8 fuel blend that is comparable to 500-hours operation with JP-8.

The governor thrust washer condition before and after 500-hours is seen in Figure B-58 and Figure B-59. The polishing wear seen on the thrust washer in Figure B-59 is typical for the 500-hour operating interval. Polishing and light scoring wear seen on the advance piston suggests the fuel pressure fluctuations in that area of the fuel injection pump housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The light wear on these components is normal considering the 500-hour duration of testing. The wear on the thrust washer, the advance piston wear, and the metering valve did not have an effect on pump operation.

Figure B-60 and Figure B-61 illustrates the level of wear seen in the transfer pump section of fuel injection pump SN: 16393229. Figure B-60 shows the surface condition of the transfer pump liner prior to testing and Figure B-61 shows the surface with moderate circumferential scoring after 500-hours of operation on the ATJ/JP-8 fuel. Also illustrative of the transfer pump section wear are the transfer pump blade conditions shown in Figure B-62 through Figure B-65. The edge wear shown in Figure B-62 and Figure B-63 corresponds to the surface on the transfer pump blades that contact the transfer pump liner. The side polishing shown in Figure B-64 and Figure B-65 reflect wear from the transfer pump blade slots on the injection pump rotor. The wear seen on the transfer pump components of pump SN: 16393229 is similar to the elevated temperature JP-8 test, but the wear was spread out over the 500-hour duration. The transfer pump component conditions suggest the test fuel has marginal fuel lubricity.

Figure B-66 and Figure B-67 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure B-67 reveals a heavy wear scar that indicates backlash and timing were likely altered with the ATJ/JP-8 fuel blend after 500-hours.

Table B-25. Pump SN: 16393229 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-5209	**SN : 16393229**
Test condition : 500 hours @ FIT 40°C and 1800 RPM	**TEST : AF8596-C3ATJ-40-500**
Fuel : ATJ/JP8, AF-8596	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Wear at rotor slots and liner contact	2.5
BLADE SPRINGS	No wear	0
LINER	80% Wear	3
TRANSFER PUMP REGULATOR	Polishing wear from blades and rotor	2
REGULATOR PISTON	Polishing wear	2
ROTOR	Wear at distributor ports	2
ROTOR RETAINERS	Wear from rotor	2
DELIVERY VALVE	Polishing wear	2
PLUNGERS	Polishing wear	1.5
SHOES	Scoring from roller weight. Light wear from leaf spring contact	2.5
ROLLERS	Discolored and some scoring	3
LEAF SPRING	Wear from shoe contact	3
CAM RING	Polishing wear from rollers	2
THRUST WASHER	Polishing from weights	1
THRUST SLEEVE	Normal	1
GOVORNER WEIGHTS	Light wear fromthrust washer contact. Cage is loose	1.5
LINK HOOK	Polishing wear	1.5
METERING VAVLE	Polishing wear	1
DRIVE SHAFT TANG	Fretting wear	3.5
DRIVE SHAFT SEALS	Normal	1
CAM PIN	Out of round. Less than .001	2.5
ADVANCE PISTON	Scoring wear	3
HOUSING	Normal	1
	AVERAGE DEMERIT RATINGS	1.93

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Figure B-50. Pump SN: 16393229 Distributor Rotor Before Testing with ATJ/JP-8 Fuel

Figure B-51. Pump SN: 16393229 Distributor Rotor with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-52. Pump SN: 16393229 Rollers and Shoe Before Testing with ATJ/JP-8 Fuel

Figure B-53. Pump SN: 16393229 Rollers and Shoe with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-54. Pump SN: 16393229 Roller Shoe Before Testing with ATJ/JP-8 Fuel

Figure B-55. Pump SN: 16393229 Roller Shoe with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-56. Pump SN: 16393229 Cam Ring Before Testing with ATJ/JP-8 Fuel

Figure B-57. Pump SN: 16393229 Cam Ring with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-58. Pump SN: 16393229 Thrust Washer Before Testing with ATJ/JP-8 Fuel

Figure B-59. Pump SN: 16393229 Thrust Washer with 500-Hours Testing with ATJ/JP-8 Fuel

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Figure B-60. Pump SN: 16393229 Transfer Pump Liner Before Testing with ATJ/JP-8 Fuel

Figure B-61. Pump SN: 16393229 Transfer Pump Liner with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-62. Pump SN: 16393229 Transfer Pump Blade Edges Before Testing with ATJ/JP-8 Fuel

Figure B-63. Pump SN: 16393229 Transfer Pump Blade Edges with 500-Hours Testing with ATJ/JP-8 Fuel

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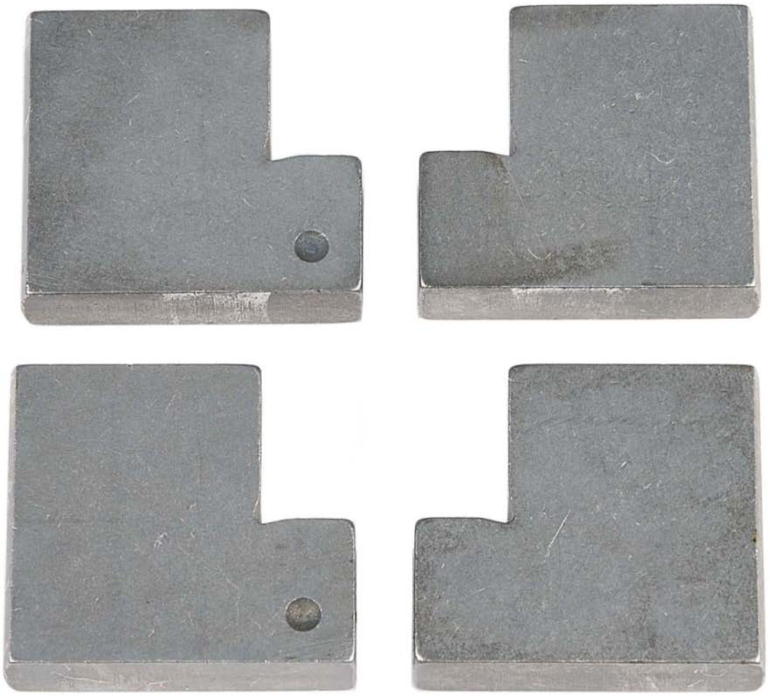

Figure B-64. Pump SN: 16393229 Transfer Pump Blade Sides Before Testing with ATJ/JP-8 Fuel

Figure B-65. Pump SN: 16393229 Transfer Pump Blade Sides with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-66. Pump SN: 16393229 Driveshaft Drive Tang Sides Before Testing with ATJ/JP-8 Fuel

Figure B-67. Pump SN: 16393229 Driveshaft Drive Tang with 500-Hours Testing with ATJ/JP-8 Fuel

B.5.5.4 50/50 ATJ/JP-8 Fuel Blend at 40 °C – Pump SN: 16393230

The parts conditions and subjective wear ratings for fuel injection pump SN: 16393230 are summarized in Table B-26. Images of the wear seen on the components of fuel injection pump SN: 16393230 are shown in Figure B-68 through Figure B-85. Figure B-68 and Figure B-69 show the condition of the injection pump rotor that carries the plungers and distributes the compressed fuel. Figure B-69 shows the discharge ports and rotor with scratches and wear near all the rotor discharge ports, usually from wear debris, after the 500-hours of operation. The rotor condition with the ATJ/JP-8 blend is more distress than the rotor condition seen with JP-8 at 500-hours.

Figure B-70 and Figure B-71 is the Pre-Test and Post-Test conditions of fuel injection pump SN: 16393230 roller shoe and roller conditions. Of note is the lack of a wear scar at the roller shoe leaf spring contact and the shiny, bright rollers shown in Figure B-70. Figure B-71 reveals light wear scars on the roller shoe from the leaf spring contact; moderate burnishing of the rollers, and pitting/chipping on roller ends. The rollers tend to discolor when combination rolling-sliding action occurs as the rollers follow the injection cam profile. Figure B-72 and Figure B-73 show the relatively moderate wear scar due to 500-hours operation at the roller shoe plunger contact. The wear seen in Figure B-73 is typical for a good lubricity fuel. The combination of leaf spring contact wear on the roller shoe, wear on the roller, and plunger contact wear on the roller shoe, can result in increased fuel delivery. The injection pump cam ring shown in Figure B-74 and Figure B-75 does reveal some polishing and wear on the cam lobes from 500-hours operation with the ATJ/JP-8 fuel blend and some chipping from the distressed rollers. The roller distress with the ATJ/JP-8 blend is more severe than typically seen with JP-8 after 500-hours with 40°C fuel inlet temperature.

The governor thrust washer conditions before and after 500-hours are seen in Figure B-76 and Figure B-77. The polishing wear seen on the thrust washer in Figure B-77 appears typical for 500-hour operation with a nominal lubricity fuel. Polishing and light scoring wear seen on the advance piston suggests the fuel pressure fluctuations in that area of the fuel injection pump housing. The metering valve regulates the pressure to the rotor fill ports. The pressure is regulated by the action of the helix changing the outlet area of an orifice. Due to WOT operation a lightly polished area shows at one location on the helix. The light wear on these components is normal considering the 500-hour duration of testing. The wear on the thrust washer, the advance piston wear, and the metering valve may have affected the governor cut-off operation. The subjective ratings note the governor weight cage was cracked, which indicates backlash within the pump. Cracks in the governor weight cage have been related to excessive drive tang wear, that have been related to fuel lubricity.

Figure B-78 and Figure B-79 illustrate the level of wear seen in the transfer pump section of fuel injection pump SN: 16393230. Figure B-78 shows the surface condition of the transfer pump liner prior to testing and Figure B-79 shows the surface with moderate circumferential scoring after 500-hours of operation on the ATJ/JP-8 fuel. Also illustrative of the transfer pump section wear are the transfer pump blade conditions shown in Figure B-80 through Figure B-83. The edge wear shown in Figure B-80 and Figure B-81 corresponds to the surface on the transfer pump blades that contact the transfer pump liner and are typical for 500-hours operation with a marginal lubricity fuel. The side polishing shown in Figure B-82 and Figure B-83 reflect wear from the transfer pump blade slots on the injection pump rotor. The wear seen on the transfer pump components of pump SN: 16393230 is similar to the elevated temperature JP-8 test, but the wear was spread out over the 500-hour duration. The transfer pump component conditions suggest the test fuel has marginal fuel lubricity, also evidenced by the variation of transfer pump pressures noted during testing.

Figure B-84 and Figure B-85 show the condition of the injection pump drive shaft drive tang that transmits torque to the hydraulic section of the pump from the engine. Figure B-85 reveals a substantial wear scar that indicates backlash and timing were likely altered with the ATJ/JP-8 fuel blend after 500-hours. For both pumps that utilized the ATJ/JP-8 (0.60-mm BOCLE) fuel, the significantly worn components that impacted the injection pump performance degradation were the roller and cam contact and the transfer pump wear. Both pumps exhibited erratic transfer pump pressures, with pump SN: 16393229 exhibiting over-fuelling tendencies and pump SN: 16393230 having compromised governor action and low idle delivery.

Table B-26. Pump SN: 16393230 Component Wear Ratings

Stanadyne Pump Parts Evaluation

Pump Type : DB2831-5209	**SN : 16393230**
Test condition : 500 hours @ FIT 40°C and 1800 RPM	**TEST : AF8596-C3ATJ-40-500**
Fuel : ATJ/JP8, AF-8596	

Part Name	Condition of part	Rating 0 = New 5 = Failed
BLADES	Wear at rotor slots and liner contact	2.5
BLADE SPRINGS	No wear	0
LINER	80% Wear	3
TRANSFER PUMP REGULATOR	Polishing wear from blades and rotor	2
REGULATOR PISTON	Polishing wear	2.5
ROTOR	Wear at distributor ports	3
ROTOR RETAINERS	Wear from rotor	2
DELIVERY VALVE	Polishing wear	2
PLUNGERS	Polishing wear	1.5
SHOES	Heavier scoring from roller weight. Light wear from leaf spring contact	3
ROLLERS	Badly chipped on ends	4.5
LEAF SPRING	Wear from shoe contact	3
CAM RING	Chipping from shoes	4
THRUST WASHER	Polishing from weights	1
THRUST SLEEVE	Normal	1
GOVORNER WEIGHTS	Light wear fromthrust washer contact. Cage is cracked.	1.5
LINK HOOK	Polishing wear	2
METERING VAVLE	Polishing wear	1
DRIVE SHAFT TANG	Fretting wear	3.5
DRIVE SHAFT SEALS	Normal	1
CAM PIN	.002" out of round	4
ADVANCE PISTON	Scoring wear	2.5
HOUSING	Normal	1
	AVERAGE DEMERIT RATINGS	2.24

Figure B-68. Pump SN: 16393230 Distributor Rotor Before Testing with ATJ/JP-8 Fuel

Figure B-69. Pump SN: 16393230 Distributor Rotor with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-70. Pump SN: 16393230 Rollers and Shoe Before Testing with ATJ/JP-8 Fuel

Figure B-71. Pump SN: 16393230 Rollers and Shoe with 500-Hours Testing with ATJ/JP-8 Fuel

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Figure B-72. Pump SN: 16393230 Roller Shoe Before Testing with ATJ/JP-8 Fuel

Figure B-73. Pump SN: 16393230 Roller Shoe with 500-Hours Testing with ATJ/JP-8 Fuel

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Figure B-74. Pump SN: 16393230 Cam Ring Before Testing with ATJ/JP-8 Fuel

Figure B-75. Pump SN: 16393230 Cam Ring with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-76. Pump SN: 16393230 Thrust Washer Before Testing with ATJ/JP-8 Fuel

Figure B-77. Pump SN: 16393230 Thrust Washer with 500-Hours Testing with ATJ/JP-8 Fuel

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Figure B-78. Pump SN: 16393230 Transfer Pump Liner Before Testing with ATJ/JP-8 Fuel

Figure B-79. Pump SN: 16393230 Transfer Pump Liner with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-80. Pump SN: 16393230 Transfer Pump Blade Edges Before Testing with ATJ/JP-8 Fuel

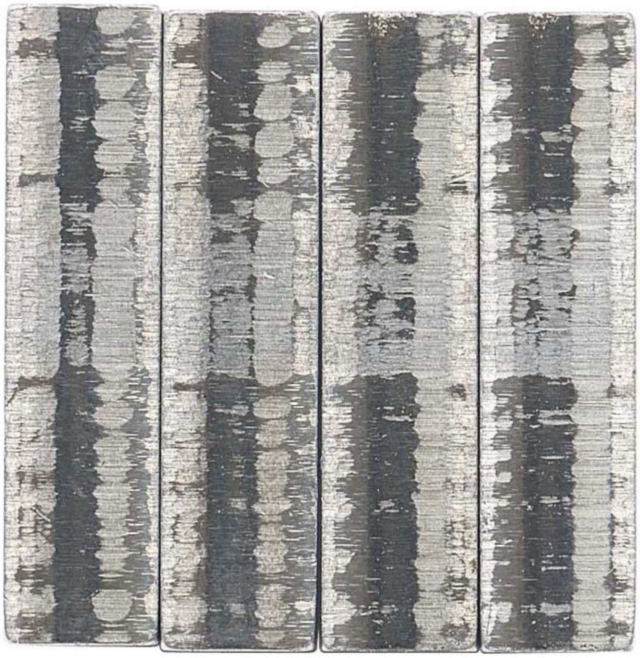

Figure B-81. Pump SN: 16393230 Transfer Pump Blade Edges with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-82. Pump SN: 16393230 Transfer Pump Blade Sides Before Testing with ATJ/JP-8 Fuel

Figure B-83. Pump SN: 16393230 Transfer Pump Blade Sides with 500-Hours Testing with ATJ/JP-8 Fuel

Figure B-84. Pump SN: 16393230 Driveshaft Drive Tang Before Testing with ATJ/JP-8 Fuel

Figure B-85. Pump SN: 16393230 Driveshaft Drive Tang with 500-Hours Testing with ATJ/JP-8 Fuel

B.6.0 DISCUSSION OF RESULTS

In a prior study [B-2] the effect of synthetic fuel on the durability of the Stanadyne arctic rotary fuel injection pump that contains hardened parts was examined. This fuel injection pump is found on the HMMWV. In conducting the pump stand test with neat synthetic fuel, it was found that the tests had to be stopped prematurely due to fuel injection performance issues that ultimately could affect the operation of an engine.

Comparison results from various synthetic fuel programs were reviewed. [B-2, B-3] The comparisons of synthetics fuels performance in rotary fuel injection pumps discussed suggested that synthetic kerosene fuels when utilized neat resulted in premature component wear. On a positive note, reference 3 also performed tests with CI/LI additives in synthetic fuel that showed a substantial improvement of rotary fuel injection pump durability with additive treated synthetic fuel.

A study [B-4] was performed to determine the impacts of a QPL-25017 CI/LI additive on fuel injection pump durability with synthetic fuel. A CI/LI additive was used at the maximum permitted 22.5-ppm concentration in a synthetic fuel and in a 50/50-percent blend of synthetic/Jet-A fuel. In conducting the pump stand tests with the two fuels, it was found that both tests had completed 500-hours of operation with minimal impact on the performance or durability of the diesel engine fuel injection systems that included the fuel injection pump and fuel injectors.

A recent study [B-5] was performed to determine the impact of minimal QPL-25017 CI/LI additive levels on fuel injection pump durability with a synthetic fuel. The minimal additive levels were determined by the additive concentration that resulted in an ASTM D 5001 BOCLE wear scar in the synthetic fuel of 0.75-mm (8.5-ppm CI/LI additive) and 0.83-mm (2.75-ppm CI/LI additive). Both additive concentrations evaluated were below the QPL-25017 minimum effective concentration for the CI/LI additive used. Both additive levels evaluated were considered inadequate for rotary fuel injection pump protection.

A US ARMY study looked at CI/LI additive concentrations in synthetic and petroleum aviation kerosene fuels at elevated temperatures. [B-1] Results concluded the maximum allowable level of CI/LI was required to maintain fuel injection pump durability at elevated temperature. One QPL-25017 CI/LI product appeared to result in improved component conditions over the other products evaluated. The study looked at only the addition of CI/LI in Jet-A or SPK fuel, and did not look at the other MIL-DTL-83133H additives that make JP-8.

The JP-8 chosen for the current study represented fuel that can be bought in the marketplace that included all the MIL-DTL-83133H additives. The concentration of the CI/LI additive used in the purchased fuel (14.2-g/m^3) was very near the QPL-25017 approved minimum effective concentration (12-g/m^3). It should be note the CI/LI effectiveness listed in QPL-25017 is for the protection of aviation fuel systems, not diesel engine fuel injection systems. The early time failure of the fuel injection pumps at elevated temperature operation with the purchased JP-8 was not anticipated. Prior testing [B-1] suggested the pumps with minimum concentration CI/LI additive would last the duration, but would not meet performance specifications at the end of test. It was postulated the low aromatic levels of the purchased JP-8 altered the CI/LI additive effectiveness. A brief fractional factorial study of CI/LI effectiveness with fuel aromatic levels suggested the additives are more effective in higher aromatic fuels.

The aromatic level of the JP-8 purchased was low (11.6-percent), such that a 50/50 blend of ATJ/JP-8 would fall below a minimum recommended fuel aromatic level of 8-perernt. The WP-AFRL identified a fuel blend that met the minimum aromatics with 50-percent ATJ fuel component. The ATJ/JP-8 blend had a ASTM D5001 lubricity of 0.60-mm as tested at SwRI. The type of additive, nor the additive concentration was known for the test fuel blend provided. A prior test with a 0.67-mm BOCLE fuel had previously lasted 500-hours pump stand hours, so the decision was made to not increase the level of CI/LI for the ATJ/JP-8 test performed at 40°C fuel temperature.

Although the 50/50 ATJ/JP-8 fuel blend permitted completion of the 500-hours in the rotary diesel fuel injection pump test, the fuel injection pumps did not meet performance specifications at the end of testing. One fuel injection pump would not allow idle operation if it was installed on an engine, and one pump would over fuel an engine. Component inspections suggest the transfer pump wear was excessive and the cam ring and roller interface wear was high for both pumps. As seen in previous work [B-1, B-3, B-4], the maximum effective concentration of CI/LI additive is suggested for synthetic fuel blends in order to offer adequate rotary diesel fuel injection pump wear protection.

B.7.0 CONCLUSIONS

The following conclusions can be made from the cumulative knowledge of utilizing JP-8 at elevated temperature and synthetic aviation kerosene fuel blends in diesel rotary fuel injection pumps:

1. For elevated fuel inlet temperature operation, even with petroleum JP-8 at 77°C, the maximum effective CI/LI concentration is required to provide adequate wear protection.
2. A 50/50 blend of ATJ/JP-8 operated at 40°C fuel inlet temperature will allow 500-hours of rotary pump operation. However the performance degradation of the fuel injection pumps at 500-hours would impact engine operation, and component inspections suggested excessive wear.

B.8.0 RECOMMENDATIONS

The technical feasibility of using JP-8 at elevated temperatures and using ATJ fuel in rotary fuel injection equipment when blended with a CI/LI additive and petroleum based commercial aviation kerosene has been investigated:

1. At elevated fuel inlet temperatures the maximum effective concentration of a QPL-25017 CI/LI should be utilized in JP-8.
2. It is recommended that blends of ATJ and JP-8 fuels include the addition of the maximum effective concentration of CI/LI for use in diesel rotary fuel injection equipment.

B.9.0 REFERENCES

[B-1] "Effectiveness Of Additives In Improving Fuel Lubricity And Preventing Pump Failure At High Temperature", Interim Report TFLRF No. 437, D.M. Yost, A.C. Brandt, and R.A. Alvarez, U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI), Southwest Research Institute, January 2013.

[B-2] Final Report for Southwest Research Institute® Project No. 08.13283.01.001, "Research of Renewable IPK Alternative Jet Fuel", G.R. Wilson III, December 19, 2008.

[B-3] "Synthetic Fuel Lubricity Evaluations", Interim Report TFLRF No. 367, E.A. Frame and R.A. Alvarez, U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI), Southwest Research Institute, September 2003, ADA 421822.

[B-4] Final Report for Southwest Research Institute® Project No. 08.14406.03,"R8 Rotary Fuel Injection Pump Wear Testing", G.R. Wilson III, and D. Yost, January 2010.

[B-5] Final Report for Southwest Research Institute® Project No. 08.16246.03, "Advanced Propulsion Fuels Research and Development Support to AFRL/RZPF Task Order 0011: Rapid Response Research and Development (R&R) for Propulsion Directorate", Bessee, et al, November 2012, Appendix C in AFRL-RQ-WP-TM-2013-0010.

Appendix C

Task 6A – Cetane Effects (ATJ Study)

EVALUATION OF THE EFFECTS OF CETANE IN THE FORD 6.7L HIGH PRESSURE COMMON RAIL DIESEL ENGINE AND THE GEP 6.5L TURBO DIESEL ENGINE

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San Antonio, TX

Prepared for

Universal Technology Corporation

July 2014

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Acronyms and Abbreviations

2-EHN	2-Ethylhexyl Nitrate
50MFB	50-Percent Mass Fraction Burned
ATDC	After Top Dead Center
BM	Bulk Modulus
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CA50	Crank Angle 50 Timing (or the crank angle at which the 50% MFB occurs)
CAD	Crank Angle Degrees
CN	Cetane Number
CO	Carbon Monoxide
DCN	Derived Cetane Number
ESC	European Stationary Cycle
FTDSA	Fischer Tropsch Diesel from South Africa
FTDSH	Fischer Tropsch Diesel from Shell
HC	Hydrocarbon
H/C	Hydrogen Atom to Carbon Atom Ratio
HCCI	Homogeneous Charge Compression Ignition
HRR	Heat Release Rate
IVC	Intake Valve Close
J/CAD	Joules per Crank Angle Degree
KVis	Kinematic Viscosity
LPP	Location of Peak Pressure
MFB	Mass Fraction Burned
MHRR	Maximum Heat Release Rate
NO_X	Oxides of Nitrogen (consisting of NO and NO_2)
PQIS	Petroleum Quality Information System
RPM	Revolutions Per Minute
SOI	Start of Injection
TDC	Top Dead Center
TFLRF	TARDEC Fuels and Lubricants Research Facility

Executive Summary

A fuel's cetane number is very important for the operation of modern diesel engines. The U.S. military currently uses petroleum-based jet fuels in diesel engine-powered ground vehicles and is studying the use of alternative jet fuels obtained from a variety of sources. Currently there is no cetane number specification for petroleum derived jet fuels as this property holds no significance for turbine engine operation. There does exist a minimum Derived Cetane Number of 40 for blended products, but it remains of interest to identify a window, or range, of cetane number which would be acceptable to ensure the reliable operation of diesel engine-powered military ground vehicles.

The TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute identified 3 candidate fuels with cetane numbers ranging from 30 to 51. The fuels selected were JP-8 and synthetic blends. The European Stationary Cycle 13 mode test, and a full load, 5 point power curve, were performed on a Ford 6.7L turbocharged V-8 diesel engine for each test fuel. Full engine instrumentation included in-cylinder pressure measurements. Engine operating parameters and exhaust gas emissions were recorded. For the Ford 6.7L engine with the range of fuels selected, there were not any observed major negative impacts on performance or emissions.

The two fuels with cetane numbers of 30 and 51 were also used for testing a GEP 6.5L turbocharged V-8 diesel engine operation in a cold box. This engine architecture is traditionally sensitive to cold start and was able to show large changes in operability between the two fuels. At a relatively warm 40°F, the low cetane fuel was unable to start in the engine without the aid of glow plugs. The low cetane fuel had two cylinders deactivate after ignition at only +20°F even with the glow plugs continuing to activate. At the -20°F condition, the low cetane fuel caused cylinders 4 and 6 to cease firing for 17 and 20 minutes respectively. The high cetane fuel did not experience any cylinders ceasing combustion after ignition until the temperature dropped to -20°F.

The results from this work should help the military integrate emerging and future fuels into the supply chain.

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C.1.0 INTRODUCTION

The goal of this program was to observe cetane-related performance trends and specifically measure power, combustion characteristics, exhaust gas emissions, and the ability to start in cold environments.

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C.2.0 EQUIPMENT

Two significantly different engines were used for the differing phases the program. For the cetane window study: a Ford 6.7L, V-8, turbocharged and intercooled diesel engine, with an electronically controlled high-pressure common rail fuel injection system, and utilizing a direct-injection combustion system. An Electronic Control Module (ECM) monitors engine speed, multiple sensors, and rack position to determine fuelling strategies such as injection timing, injection quantity, injection rate shaping, and turbocharger waste gate control for manifold pressure. Injection rate shaping is controlled by dividing the total injection quantity into multiple fuel injection events, that could include pilot, main, split main, and post injection events. The cetane window study was performed in this engine to determine if poor ignition quality fuel would negate the rate shaping strategies and lead to excessive combustion rates and increased engine emissions.

For the cold starts study: a GEP 6.5L, V-8, turbocharged diesel engine, with a mechanical rotary pump-line-nozzle fuel injection system, and utilizing an indirect-injection combustion system. Indirect injection diesel engines have a high surface to volume ratio for the combustion chamber, and high gas velocities during compression that results in high heat transfer rates during the fuel injection event. To offset the high heat transfer rates, glow plugs and an elevated engine compression ratio are utilized to add heat into the pre-chambers during the injection event to augment ignition. Except for a thermostatically controlled cold start advance, the mechanical fuel injection system does not have any sensor feedback to alter injection timing to stabilize combustion. Fuel ignition quality was expected to impact engine starting and the time to a consistent idle speed with this engine.

C.2.1 Maintenance

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

C.3.0 TEST CYCLES

C.3.1 European Stationary Cycle Load Steps

Each of the 13 modes of the ESC (see Figure C-1) are governed by a mathematical formula, as explained below, for calculating the engine speeds A, B, & C. Each operating point also has a weighting value assigned to it for calculating the cycle average emissions.

Ford 6.7L Engine Speeds
A = 1855 rpm
B = 2310 rpm
C = 2765 rpm

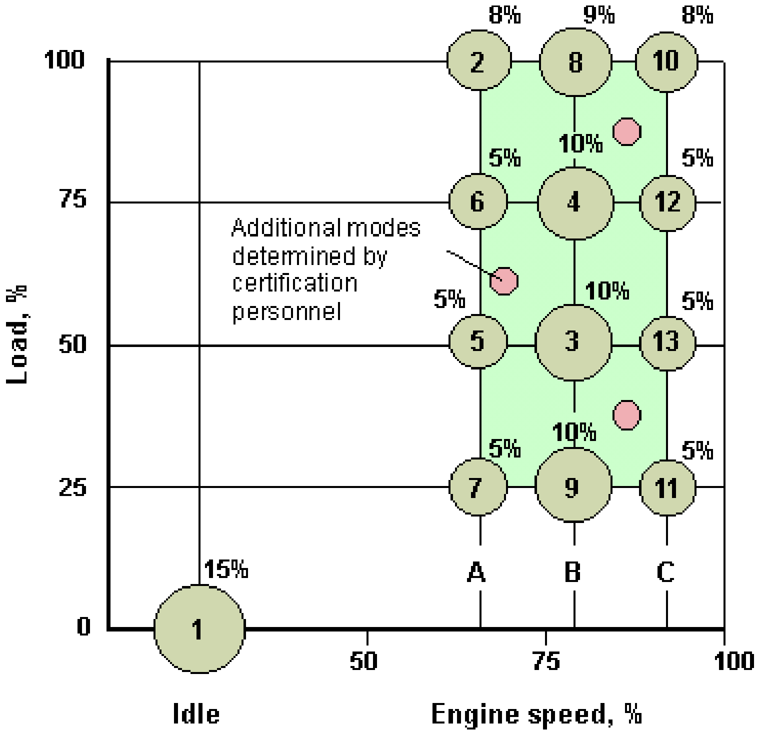

Figure C-1. ESC 13 Mode Cycle Description

The engine speeds are defined as follows:

1. The high speed n_{hi} is determined by calculating 70% of the declared maximum net power (310 Hp on JP-8). The highest engine speed where this power value occurs (i.e. above the rated speed) on the power curve is defined as n_{hi}.
2. The low speed n_{lo} is determined by calculating 50% of the declared maximum net power. The lowest engine speed where this power value occurs (i.e. below the rated speed) on the power curve is defined as n_{lo}.
3. The engine speeds A, B, and C to be used during the test are then calculated from the following formulas:

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

C.3.2 European Stationary Cycle Controls

On the Ford 6.7L engine, the coolant, oil, manifold, and fuel temperatures were closed loop controlled at fixed set points. The engine operating points for each ESC mode, and an additional 6 points to complete the power curve, can be seen in Table C-1. The full-rack power curve points will be noted as Mode 14 through Mode 18.

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Table C-1. Ford 6.7L Engine Operating Conditions

FORD 6.7							
		Speed	Load	Coolant Temp	Oil Temp	Inlet Air Temp	Fuel Temp
		RPM	Ft-Lb	°F	°F	°F	°F
ESC MODE	1	600	31	203	210	104	95
	2	1855	672		225		
	3	2310	338				
	4	2310	507				
	5	1855	348				
	6	1855	521				
	7	1855	174				
	8	2310	654				
	9	2310	169				
	10	2765	581				
	11	2765	153				
	12	2765	458				
	13	2765	306				
POWER CURVE MODE	14	1000	444				
	15	1400	580				
	16	1600	668				
	17	2000	680				
	18	2500	637				

C.3.3 Cold Start Method

The GEP 6.5L engine was operated on each fuel at 4 different temperatures: 40, 20, 0, and -20 degrees Fahrenheit. At each temperature, an attempt was made to start the engine without glow plugs. If that attempt was unsuccessful, the glow plugs were enabled for 10 seconds prior to cranking and then disabled. If that attempt was unsuccessful, the 10 second enable was followed by a 40% duty cycle controlled glow plug output, during cranking and running, that operated until a threshold coolant temperature had been achieved to ensure stable operation.

The GEP engine was connected to an electric drive motor with an overrunning clutch so constant starting speeds could be simulated without relying on the OEM starter or battery. Once the engine was firing and spinning above a threshold rpm, the drive motor would stop and allow the engine to continue un-aided.

C.4.0 INSTRUMENTATION

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

C.4.1 Engine Setups

The high speed instrumentation for the Ford 6.7L engine consisted of the following:

- Kistler Cylinder Pressure Transducer, 6056A
- Kistler 5018 Charge Amplifier
- BEI Shaft Encoder (0.2 CAD)
- PEM CWT Rogowski Current Waveform Transducer

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

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

The high speed data was recorded and post-processed by a SwRI High Speed DAQ. A SwRI PRISM DAQ system was used for engine control and data recording of the slow speed instrumentation. A Horiba MEXA 1600D emissions bench was also used on the Ford engine, (Figure C-2).

Figure C-2. Horiba MEXA 1600D Emissions Bench

The exhaust opacity measurements were made by a Wager Company 6500iL inline opacity meter. The device fits in line with the exhaust and consists of a light source and a detector. The output (0-100%) is sent to the PRISM data acquisition system.

C.5.0 TEST FUELS

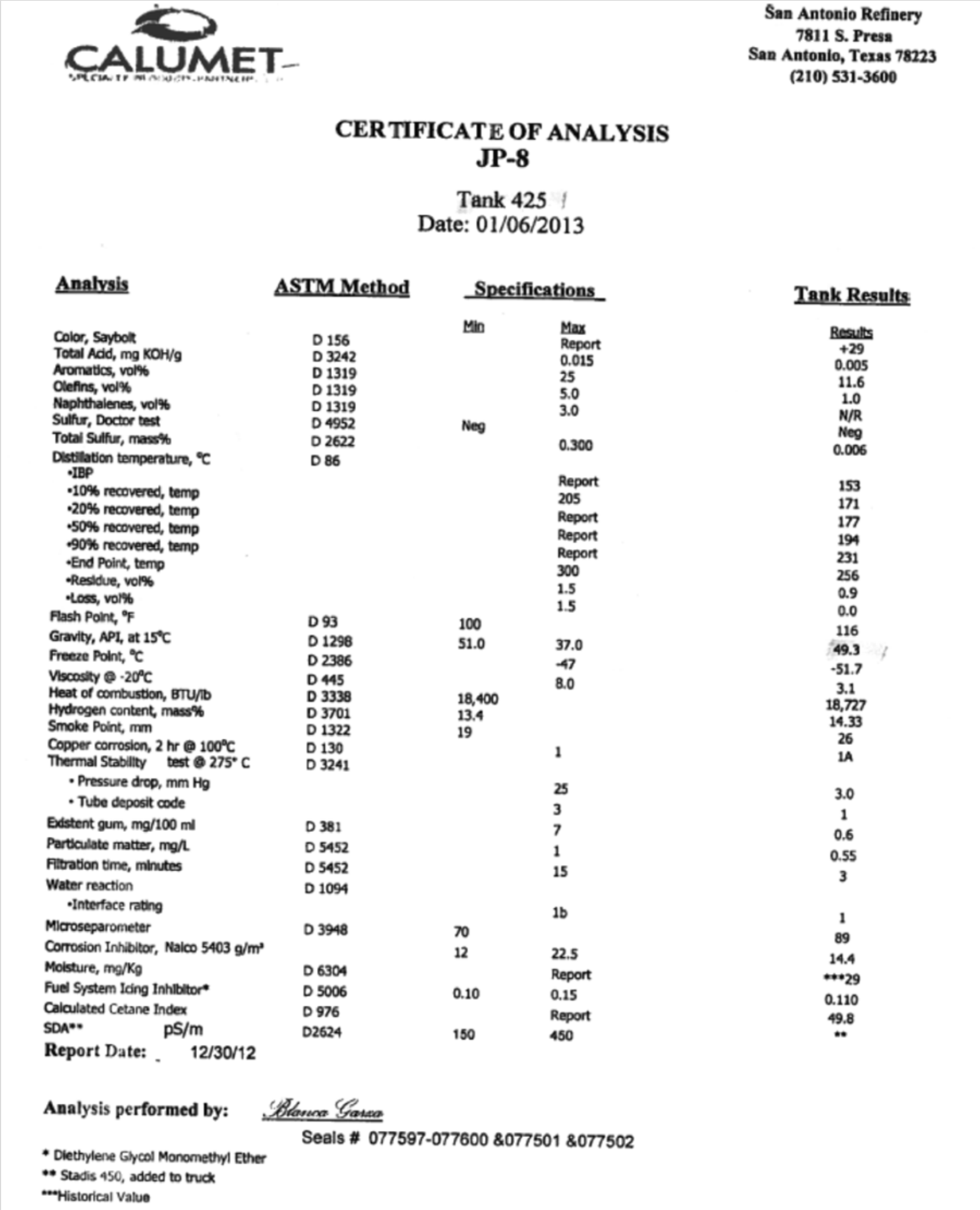
An ATJ fuel was supplied as GFE by WPAFB for blending at a 50/50 ratio by volume with JP-8. A JP-8 fuel meeting MIL-DTL-83133H was purchased from a local supplier. Table C-2 summarizes the critical properties of the locally sourced JP-8, coded AF-8462. The ASTM D613 cetane number was measured as 51.2 for the JP-8 fuel, which is higher than normally expected for JP-8.

A 50/50 JP-8/ATJ blend, coded AF-8504, was made using the locally sourced JP-8 and the WP-AFRL supplied ATJ fuels. The cetane number by ASTM D613 for the blend was 33.0. The AF-8504 fuel blend was evaluated for combustion performance in the FORD 6.7L engine before the decision was made to utilize a different fuel blend. The properties for fuel blend AF-8504 are shown in Table C-3.

Concerns were raised as to whether the batch of JP-8 fuel was representative due to the poor pump durability performance at elevated temperature in another phase of the test program. The JP-8 as purchased has a low CI/LI treatment rate, but still meets the BOCLE requirement. The fuel does have low aromatic levels (11.6%), that when blended 50-percent with a "zero"-aromatic synthetic fuel would fall below the minimum recommended aromatic levels (8.0%). A question was raised as to whether the resulting low aromatic level of the fuel blend could affect CI/LI additive effectiveness for diesel fuel injection pump protection. If the engine test was performed at low aromatics levels, it was felt an adverse engine durability result could possibly be misinterpreted.

A JP-8/ATJ blend that met the aromatics requirements, when aromatics are tested by ASTM D6379, was identified at WPAFB, and is shown in Table C-4. This fuel blend, coded AF-8596, was used as the target for the durability test blend. Three drums of the fuel were sent to SwRI and used for rotary pump testing, GEP 6.5LT cold start testing, and the FORD 6.7L engine combustion studies.

Table C-2. AF-8462 JP-8 Test Fuel Chemical and Physical Analysis



CALUMET

San Antonio Refinery
7811 S. Presa
San Antonio, Texas 78223
(210) 531-3600

CERTIFICATE OF ANALYSIS
JP-8

Tank 425
Date: 01/06/2013

Analysis	ASTM Method	Specifications Min	Specifications Max	Tank Results
Color, Saybolt	D 156		Report	+29
Total Acid, mg KOH/g	D 3242		0.015	0.005
Aromatics, vol%	D 1319		25	11.6
Olefins, vol%	D 1319		5.0	1.0
Naphthalenes, vol%	D 1319		3.0	N/R
Sulfur, Doctor test	D 4952	Neg		Neg
Total Sulfur, mass%	D 2622		0.300	0.006
Distillation temperature, °C	D 86			
•IBP			Report	153
•10% recovered, temp			205	171
•20% recovered, temp			Report	177
•50% recovered, temp			Report	194
•90% recovered, temp			Report	231
•End Point, temp			300	256
•Residue, vol%			1.5	0.9
•Loss, vol%			1.5	0.0
Flash Point, °F	D 93	100		116
Gravity, API, at 15°C	D 1298	51.0	37.0	49.3
Freeze Point, °C	D 2386		-47	-51.7
Viscosity @ -20°C	D 445		8.0	3.1
Heat of combustion, BTU/lb	D 3338	18,400		18,727
Hydrogen content, mass%	D 3701	13.4		14.33
Smoke Point, mm	D 1322	19		26
Copper corrosion, 2 hr @ 100°C	D 130		1	1A
Thermal Stability test @ 275° C	D 3241			
• Pressure drop, mm Hg			25	3.0
• Tube deposit code			3	1
Existent gum, mg/100 ml	D 381		7	0.6
Particulate matter, mg/L	D 5452		1	0.55
Filtration time, minutes	D 5452		15	3
Water reaction	D 1094			
•Interface rating			1b	1
Microseparometer	D 3948	70		89
Corrosion Inhibitor, Nalco 5403 g/m³		12	22.5	14.4
Moisture, mg/Kg	D 6304		Report	***29
Fuel System Icing Inhibitor*	D 5006	0.10	0.15	0.110
Calculated Cetane Index	D 976		Report	49.8
SDA** pS/m	D2624	150	450	**

Report Date: 12/30/12

Analysis performed by: Blanca Garza

Seals # 077597-077600 &077501 &077502

* Diethylene Glycol Monomethyl Ether

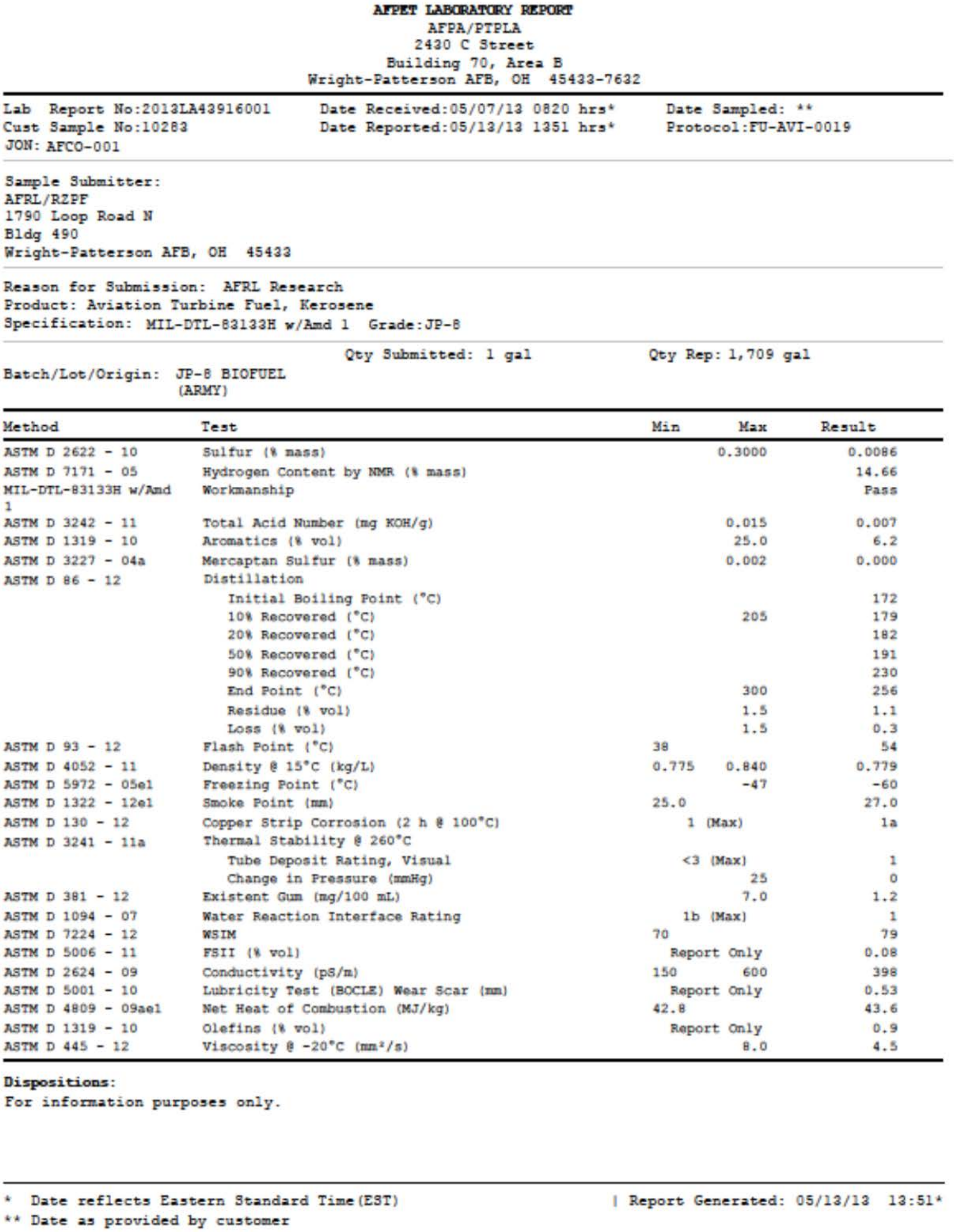
** Stadis 450, added to truck

***Historical Value

Table C-3. AF-8504: 50/50 Blend of ATJ and JP-8 (AF-8462)

Property	Units	ASTM Test No	Results
Density	g/mL	D1298	0.7699
Specific Gravity			0.7703
API Gravity	°API		52.2
Flashpoint	°C	D56	46
Freezing Point	°C	D2386	-56
Kinematic Viscosity @-20°C	cSt	D445LT	4.11
Kinematic Viscosity @40°C	cSt	D445	1.3
Kinematic Viscosity @76.7C	cSt	D445HT	0.85
Calculated Cetane Index	CI	D976	51.6
Cetane Number	CN	D613	33
Derrived Cetane Number	DCN	D6890	38.75
Heat of Combustion (Gross)	BTU/lb	D4809	20178
Copper Corrosion		D130	1A
Particulate Contamination	mg/L	D5452	1.45
Total Acid Number	mg KOH/g	D3242	0.008
Hydrocarbon Type (%vol)	Aromatics	D1319	5.7
	Olefins		1.5
	Saturates		92.8
Sulfur, Total	mass%	D2622	0.0036
Sulfur, Mercaptan	mass%	D3227	0.0004
Saybolt Color		D156	28
JFTOT		D3241	1
HFRR	mm	D6079	0.804
Scuffing Load BOCLE	g	D6078	2050
BOCLE	mm	D5001	0.58
Distillation	°C	D86	
	IBP		165.5
	0.1		174.9
	0.2		177.6
	0.5		187.3
	0.9		234.8
	End pt		256.9
Doctor Test		D4952	sweet
Net Heat of Combustion	MJ/kg	D4809	43.8
Hydrogen	mass%	D3701	14.69
Carbon	mass%	D5291	84.81
Hydrogen	mass%		14.8
Smoke Point	mm	D1322	29
Naphthalene Content	vol%	D1840	0.34
Gum Content	mg/100mL	D381	2
Water Reaction		D1094	1
MSEP		D3948	79
FSII Content	vol%	D5006	0.06
Electrical Conductivity	pS/m	D2624	6

Table C-4. AF-8596: WP-AFRL Fuel Used for Combustion and Cold Start Engine Testing



AFPET LABORATORY REPORT
AFPA/PTPLA
2430 C Street
Building 70, Area B
Wright-Patterson AFB, OH 45433-7632

Lab Report No:2013LA43916001	Date Received:05/07/13 0820 hrs*	Date Sampled: **
Cust Sample No:10283	Date Reported:05/13/13 1351 hrs*	Protocol:FU-AVI-0019
JON: AFCO-001		

Sample Submitter:
AFRL/RZPF
1790 Loop Road N
Bldg 490
Wright-Patterson AFB, OH 45433

Reason for Submission: AFRL Research
Product: Aviation Turbine Fuel, Kerosene
Specification: MIL-DTL-83133H w/Amd 1 Grade:JP-8

Qty Submitted: 1 gal
Qty Rep: 1,709 gal
Batch/Lot/Origin: JP-8 BIOFUEL (ARMY)

Method	Test	Min	Max	Result
ASTM D 2622 - 10	Sulfur (% mass)		0.3000	0.0086
ASTM D 7171 - 05	Hydrogen Content by NMR (% mass)			14.66
MIL-DTL-83133H w/Amd 1	Workmanship			Pass
ASTM D 3242 - 11	Total Acid Number (mg KOH/g)		0.015	0.007
ASTM D 1319 - 10	Aromatics (% vol)		25.0	6.2
ASTM D 3227 - 04a	Mercaptan Sulfur (% mass)		0.002	0.000
ASTM D 86 - 12	Distillation			
	Initial Boiling Point (°C)			172
	10% Recovered (°C)		205	179
	20% Recovered (°C)			182
	50% Recovered (°C)			191
	90% Recovered (°C)			230
	End Point (°C)		300	256
	Residue (% vol)		1.5	1.1
	Loss (% vol)		1.5	0.3
ASTM D 93 - 12	Flash Point (°C)	38		54
ASTM D 4052 - 11	Density @ 15°C (kg/L)	0.775	0.840	0.779
ASTM D 5972 - 05e1	Freezing Point (°C)		-47	-60
ASTM D 1322 - 12e1	Smoke Point (mm)	25.0		27.0
ASTM D 130 - 12	Copper Strip Corrosion (2 h @ 100°C)		1 (Max)	1a
ASTM D 3241 - 11a	Thermal Stability @ 260°C			
	Tube Deposit Rating, Visual		<3 (Max)	1
	Change in Pressure (mmHg)		25	0
ASTM D 381 - 12	Existent Gum (mg/100 mL)		7.0	1.2
ASTM D 1094 - 07	Water Reaction Interface Rating		1b (Max)	1
ASTM D 7224 - 12	WSIM	70		79
ASTM D 5006 - 11	FSII (% vol)	Report Only		0.08
ASTM D 2624 - 09	Conductivity (pS/m)	150	600	398
ASTM D 5001 - 10	Lubricity Test (BOCLE) Wear Scar (mm)	Report Only		0.53
ASTM D 4809 - 09ae1	Net Heat of Combustion (MJ/kg)	42.8		43.6
ASTM D 1319 - 10	Olefins (% vol)	Report Only		0.9
ASTM D 445 - 12	Viscosity @ -20°C (mm²/s)		8.0	4.5

Dispositions:
For information purposes only.

* Date reflects Eastern Standard Time(EST) | Report Generated: 05/13/13 13:51*
** Date as provided by customer

SwRI tested a sample from one of the drums of fuel received from AFRL. Tests performed were the ASTM D5001 BOCLE, D6079 HFRR, D613 Cetane Number, and D6890 Derived Cetane Number (DCN). Table C-5 shows the test results. The BOCLE test was repeated because the SwRI result differed from the AFRL analysis for the fuel. The AFRL result for BOCLE was 0.53-mm, outside the reproducibility of the ASTM method. The two SwRI results fall within the repeatability of the test method.

Table C-5. AFRL Test Fuel Results

ASTM Method	Result	Units
D5001 BOCLE	0.61/0.59	mm
D6079 HFRR	799	microns
D613 Cetane Number	30.8	CN
D6890 DCN	37.02/36.97	DCN

For the test fuel received from AFRL, the ASTM D613 cetane number results look reasonable, considering the low CN value for the ATJ blend component. However the ASTM D6890 DCN results appear high. Usually the CN and DCN results are closer than 7 numbers. A repeat DCN determination result repeated well with the earlier result, and was also high at 36.97.

C.6.0 FORD POWER CURVES

While the three fuels did not have a large impact (total difference between the three fuels was less than 4 HP) on the shape of the torque curve as seen in Figure C-3, there was a trend of increasing power with increasing fuel density as seen in Figure C-4. When compared with previous testing at TFLRF, the Ford 6.7 power output does not appear as sensitive to cetane number in the range of fuels tested.

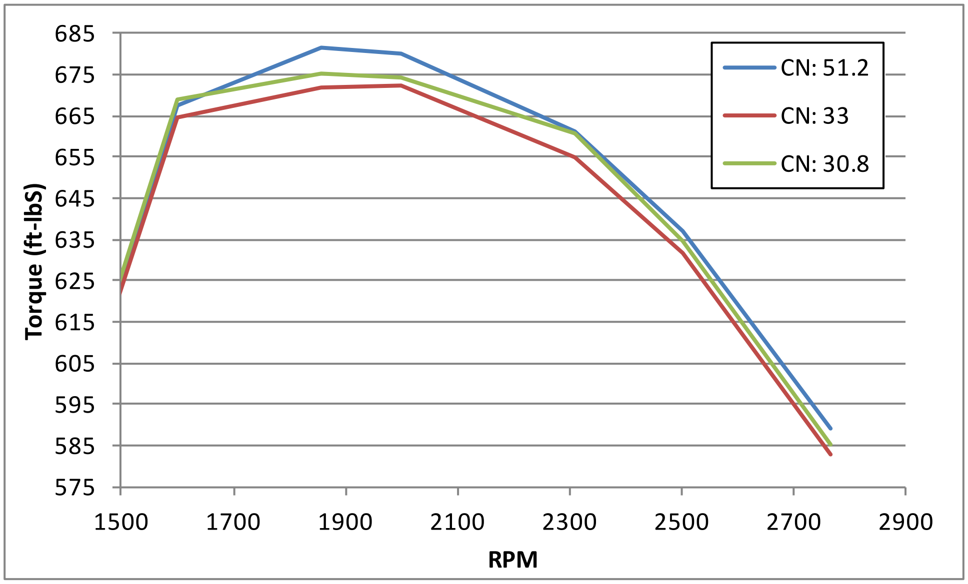


Figure C-3. Engine Torque Curve

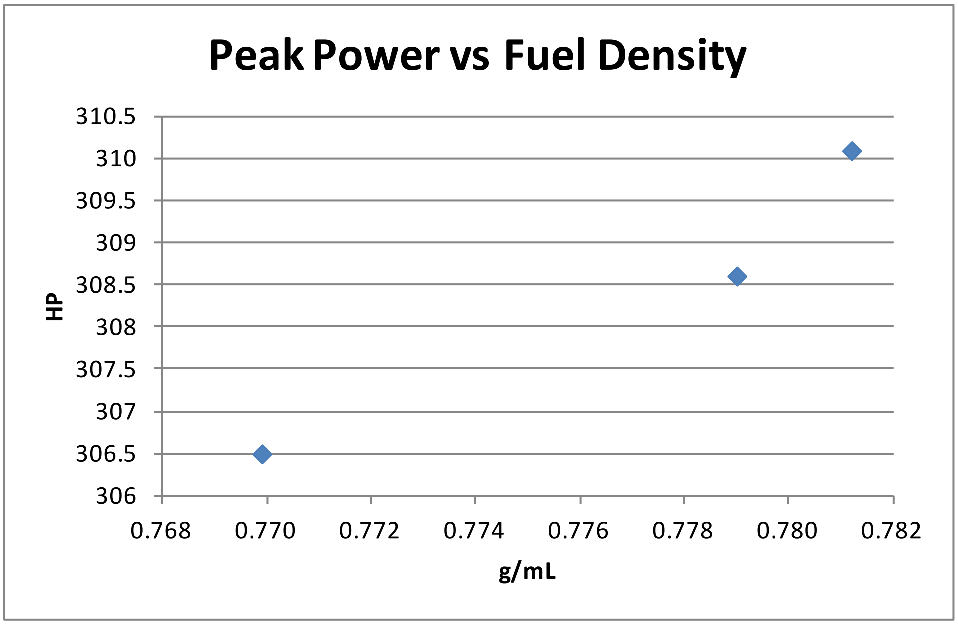


Figure C-4. Engine Peak Power versus Fuel Density

There was no direct correlation between power output and cetane number for the fuels tested, as seen in Figure C-5.

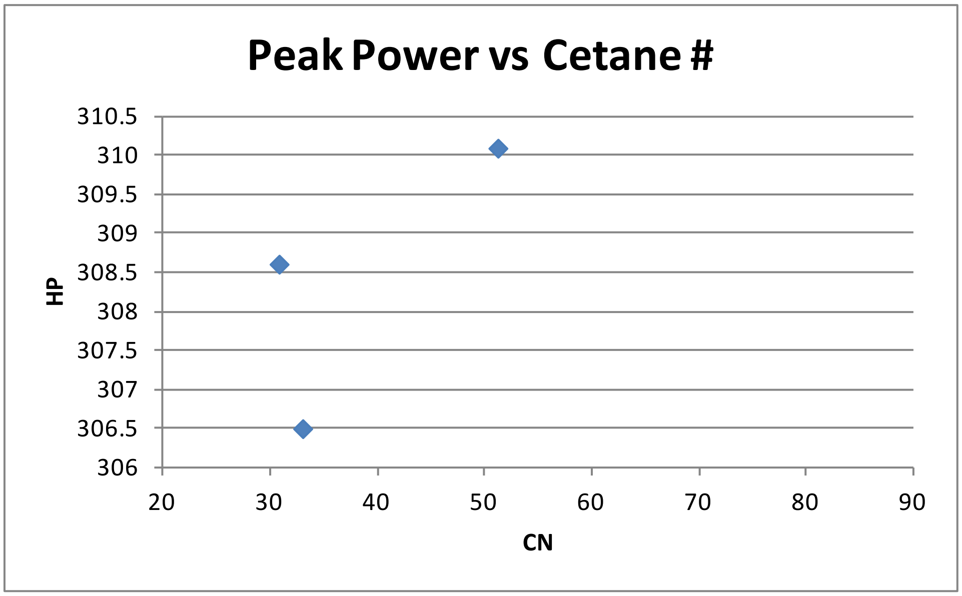


Figure C-5. Engine Peak Power versus Cetane Number

C.7.0 FORD EMISSIONS

The emissions number as presented for each fuel, is calculated from a corrected and weighted average of all thirteen data points in the European Stationary Cycle. These numbers are plotted versus the cetane value for each fuel as seen in Figure C-6. Although carbon monoxide decreases and oxides of nitrogen decrease with increasing cetane, the trends are much smaller in comparison with previous testing done on other engines at TFLRF. The results indicate that the Ford 6.7L engine out emissions are not sensitive to changing cetane number in the range of fuels tested.

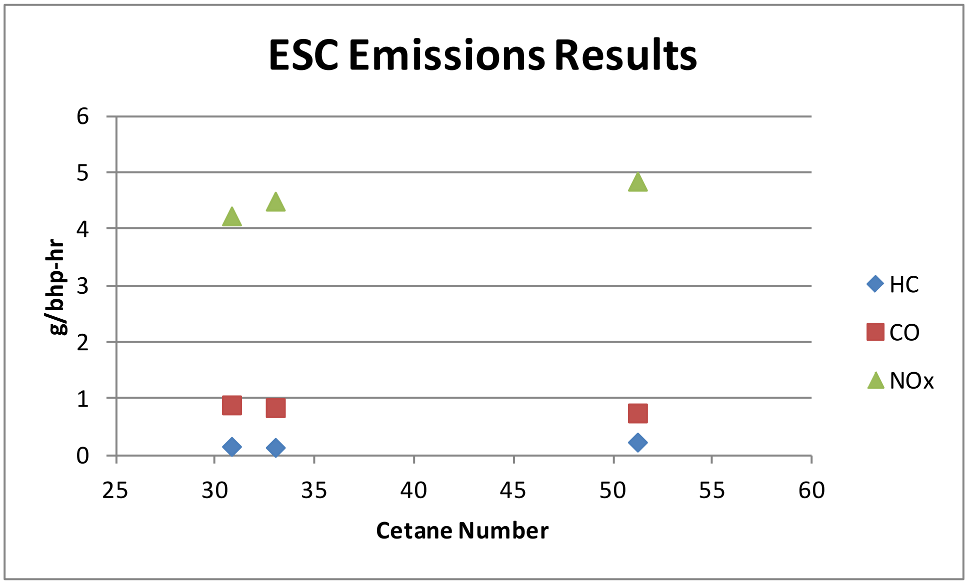


Figure C-6. Engine Emissions Results

C.8.0 FORD IGNITION DELAY

In order to better understand how cetane might affect ignition delay in the Ford 6.7L engine, a scatter plot was made (Figure C-7). The Arrhenius temperatures as plotted on the x-axis, were calculated from the manifold conditions at IVC, and the position of the piston at SOI. The ignition delay values were measured from the start of injection to the start of combustion. Unfortunately no clear trends emerge, either in the light, medium, or high load conditions for the three fuels tested.

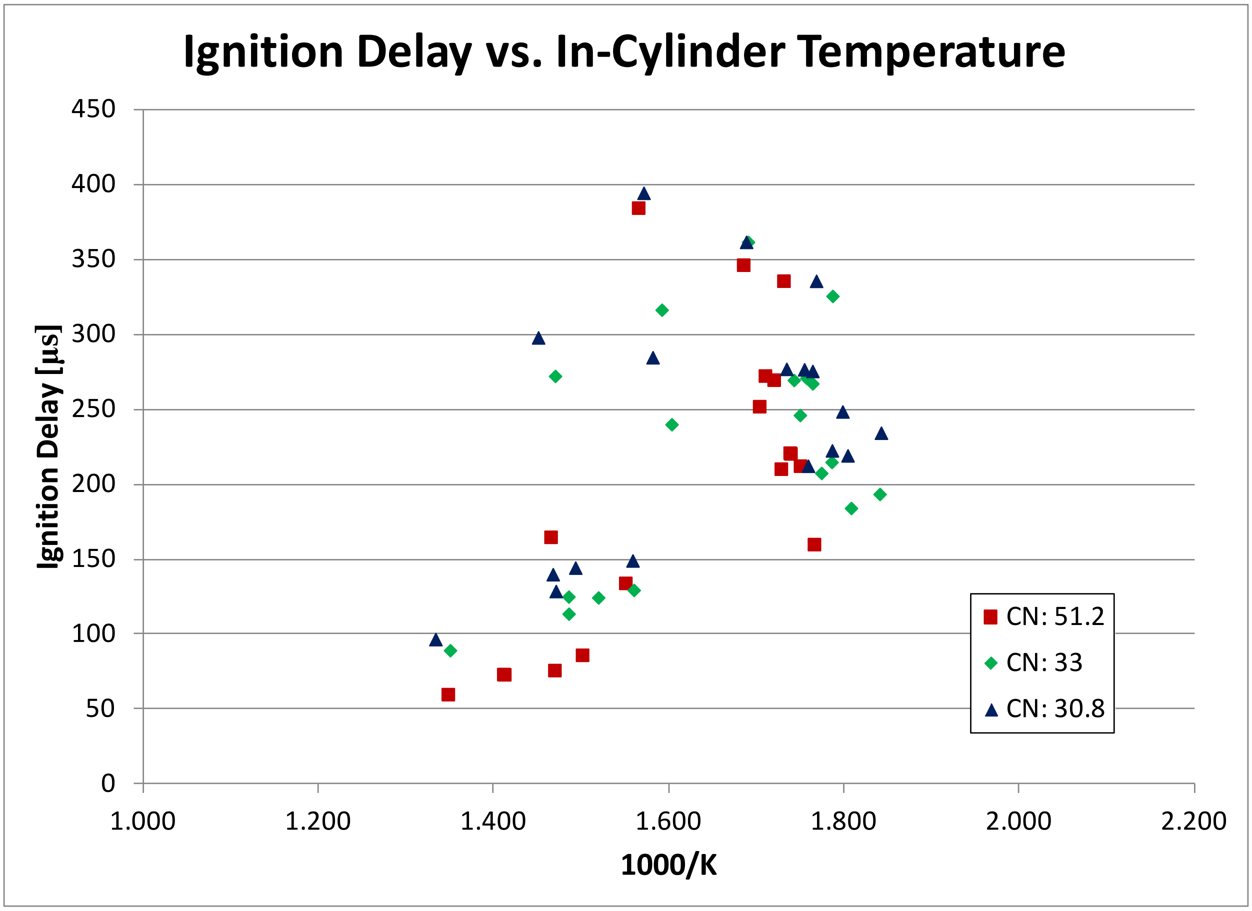


Figure C-7. Ignition Delay versus In-Cylinder Temperature at the Time of Injection

C.9.0 FORD COMBUSTION CHARACTERISTICS

In this section four of the eighteen (thirteen for the ESC, and five for the power curve) heat release plots are presented as a broad representation of the general combustion characteristics of the Ford 6.7L engine. It may be noted that there was no noticeable change in injection timing for any of the multiple injection strategies across all operating conditions.

Mode 1 (Figure C-8) is the idle condition. The high cetane fuel exhibits a large initial heat release event starting at minus 14° ATDC where the lower cetane fuels exhibit a moderate initial heat release event starting at minus 11° ATDC. The main events around TDC for all fuels are approximately equal in timing and magnitude.

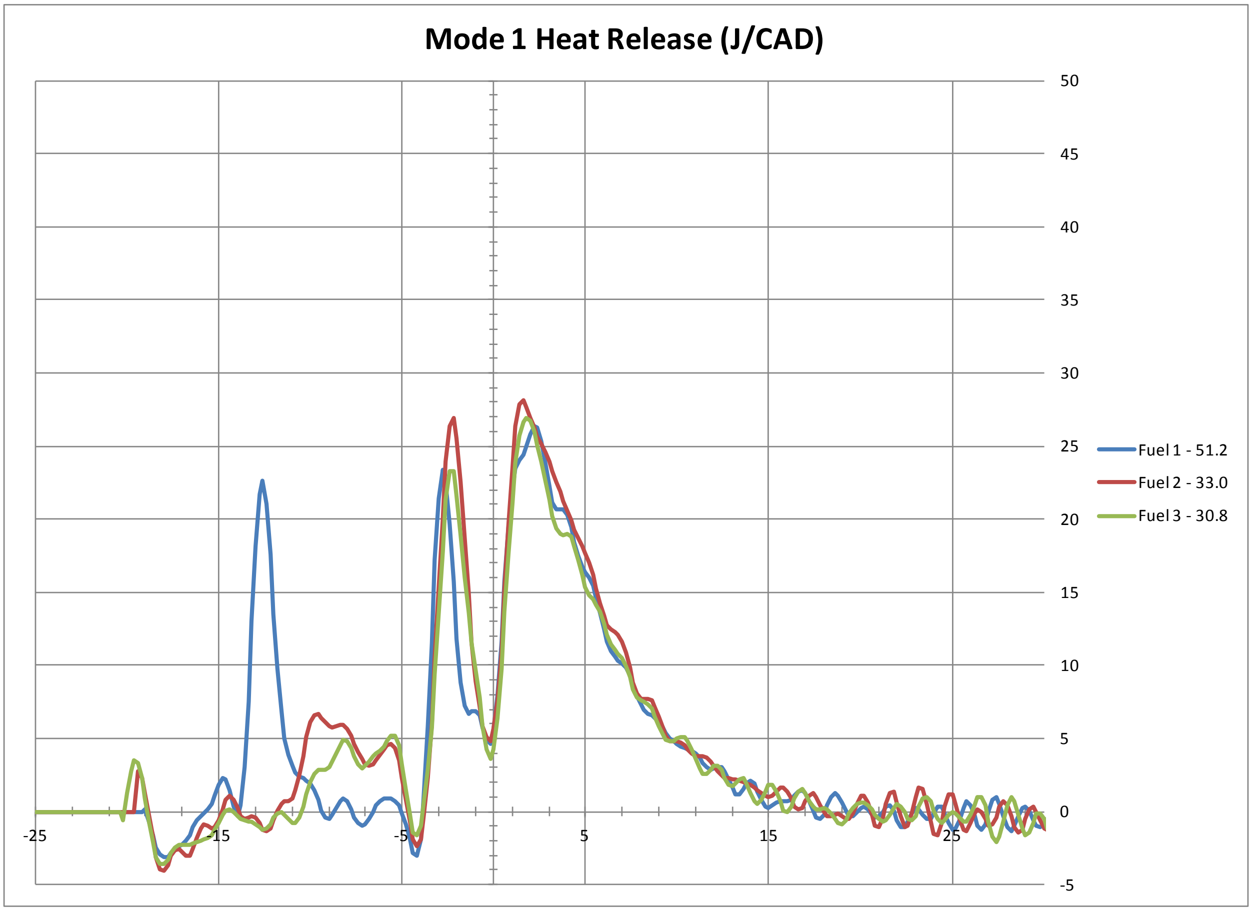


Figure C-8. Mode 1 Heat Release

Mode 2 (Figure C-9) is the condition closest to peak torque. The pre-injection event, as seen in the inset at -35° ATDC, is not noticeable in the heat release plots, and the main body of the heat release for all fuels is approximately equal in timing and magnitude. The engine controller utilizes multiple injection events to control the heat release rate and emissions. Fuel introduced during the pre-injection event is typically only 5-10% of the total fuel injection quantity. Modern engine control strategies appear to control the location and slope rate of the main injection quantity heat release rate event.

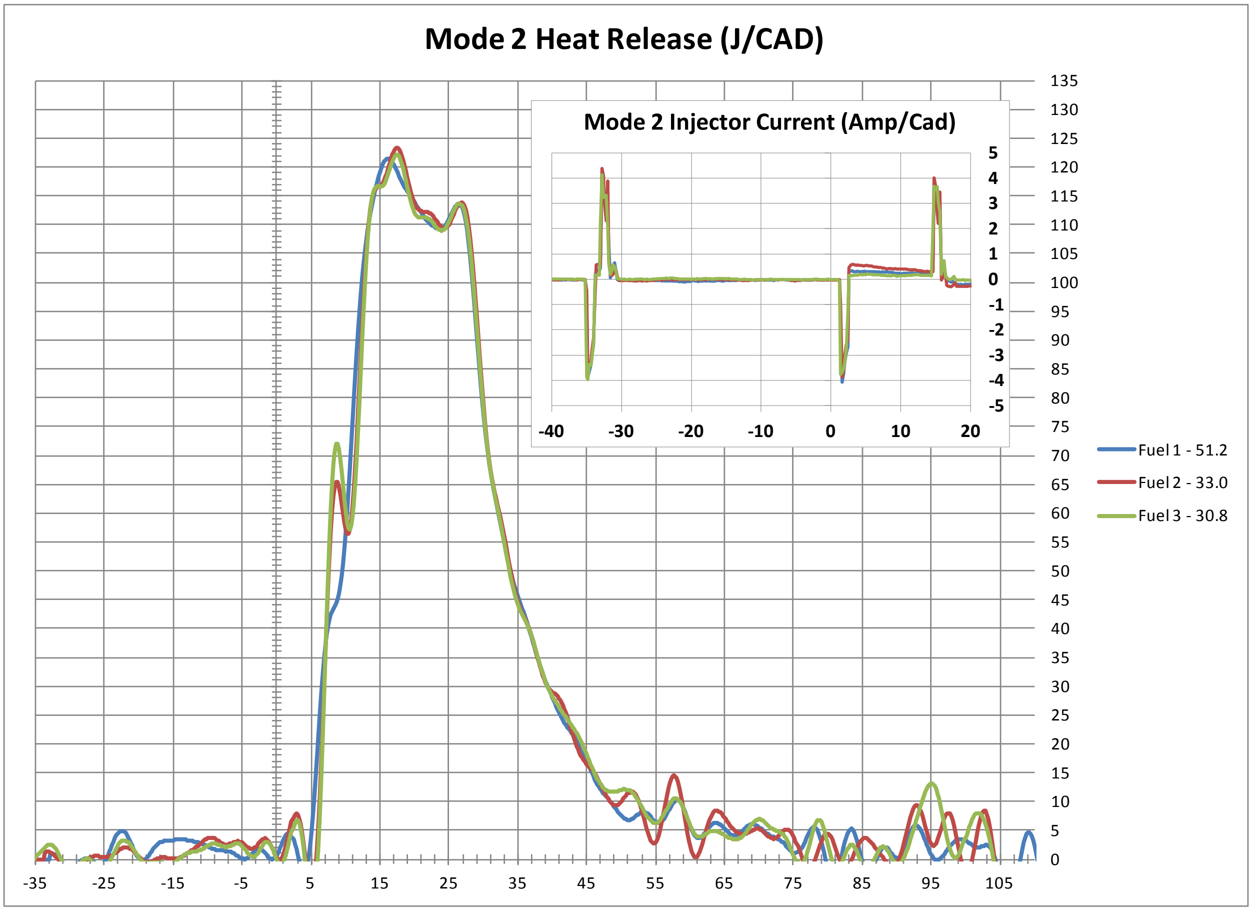


Figure C-9. Mode 2 Heat Release with Injector Current (Inset)

Mode 9 (Figure C-10) is closest to rated speed, but the load condition is light at 25%. Typically cetane has the most noticeable impact during light load conditions, and in the heat release plot, not only are the pre-injection events different in timing and magnitude, but the main events are as well. The high cetane fuel ignites at approximately minus 15° ATDC where the lower cetane fuels are closer to TDC by 5 and 6 degrees. The main heat release for the high cetane fuel is also a few degrees earlier. The lowest cetane fuel experiences a higher peak heat release than the other two.

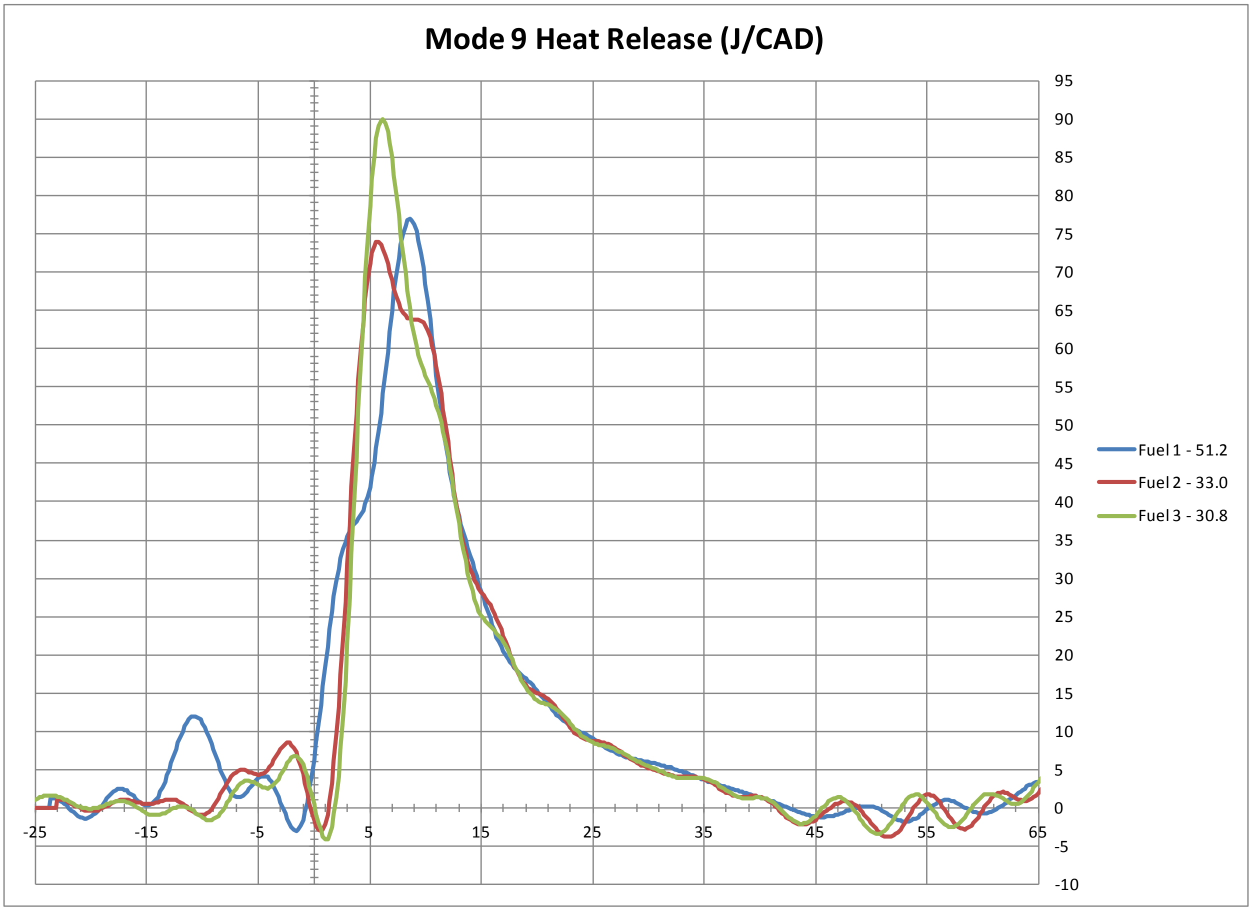


Figure C-10. Mode 9 Heat Release

Mode 14 (Figure C-11) is the lowest speed (1000 rpm) step for the power curve points, so the load is 100%. This mode shows the main heat releases are only separated by about 1 degree of timing, and their magnitudes are within 4% of each other. The pre-injection heat release events are very similar for the lower cetane fuels, and close in magnitude for the high cetane fuel, but the timings vary by 2 degrees.

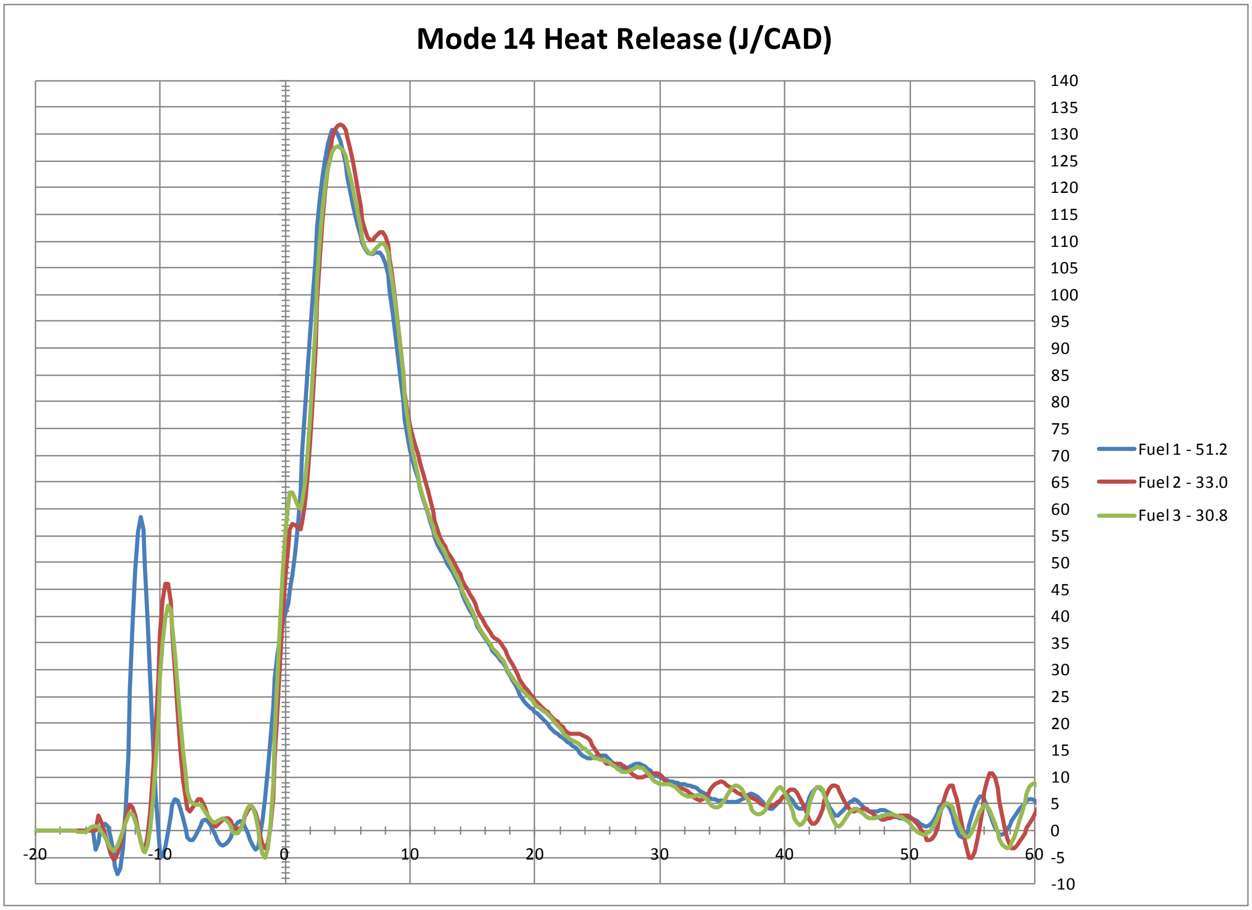


Figure C-11. Mode 14 Heat Release

C.10.0 GEP COLD START ON HIGH CETANE FUEL

At 40 degrees Fahrenheit, the engine was able to start without the aid of glow plugs. However, as seen in Figure C-12, the engine was firing intermittently on 4 cylinders before fully starting. A few seconds after starting, the engine was able to achieve a steady rpm. Cylinders 7 and 8 were the last to fire continuously, and the opacity decreased rapidly to zero once combustion stabilized.

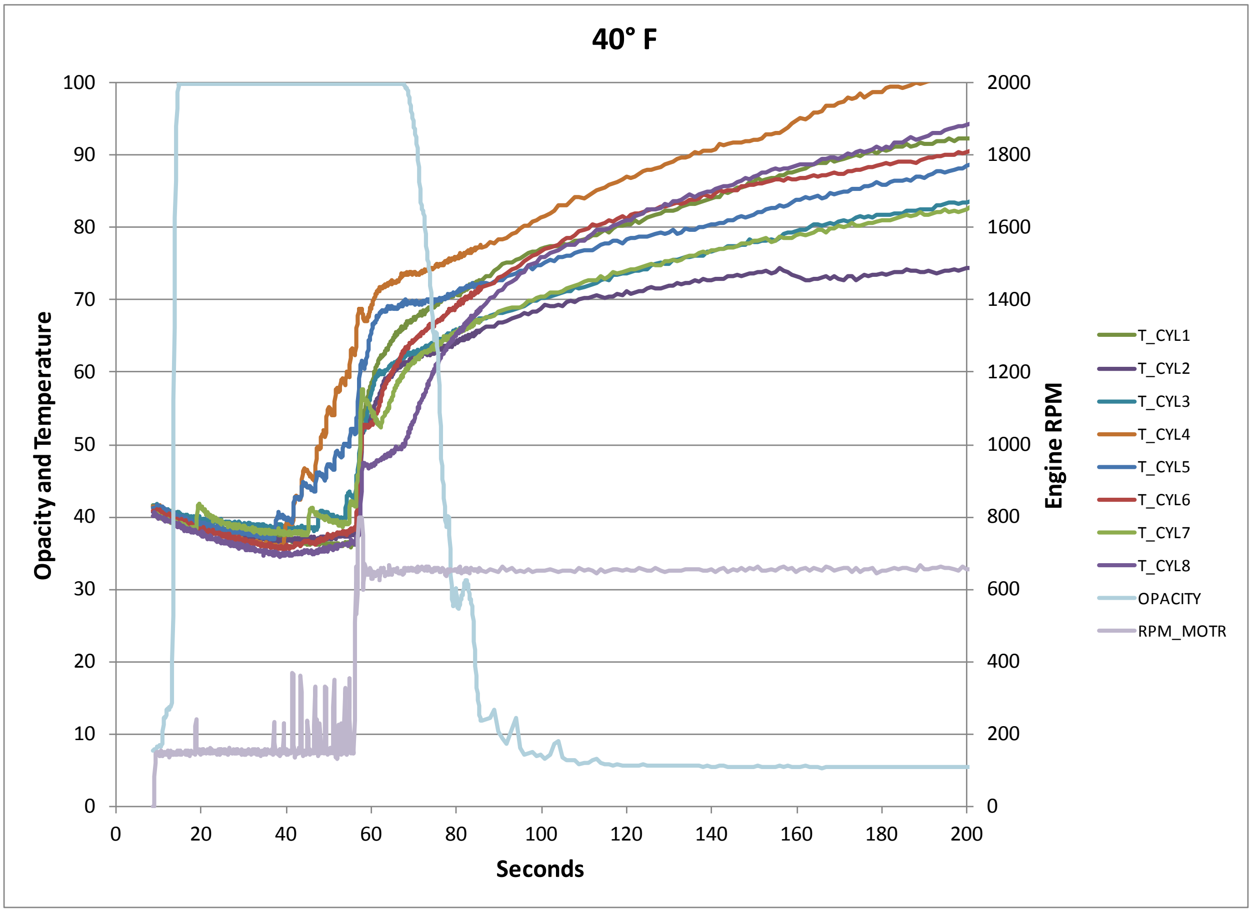


Figure C-12. High Cetane Cold Start at 40 °F

Approved for public release; distribution unlimited.

At 20 degrees Fahrenheit, the engine was unable to start without the use of glow plugs. As seen in Figure C-13, the engine started immediately with no hesitation, firing on all cylinders. The opacity took about a minute to drop below 10 percent as the individual cylinders continued to warm up.

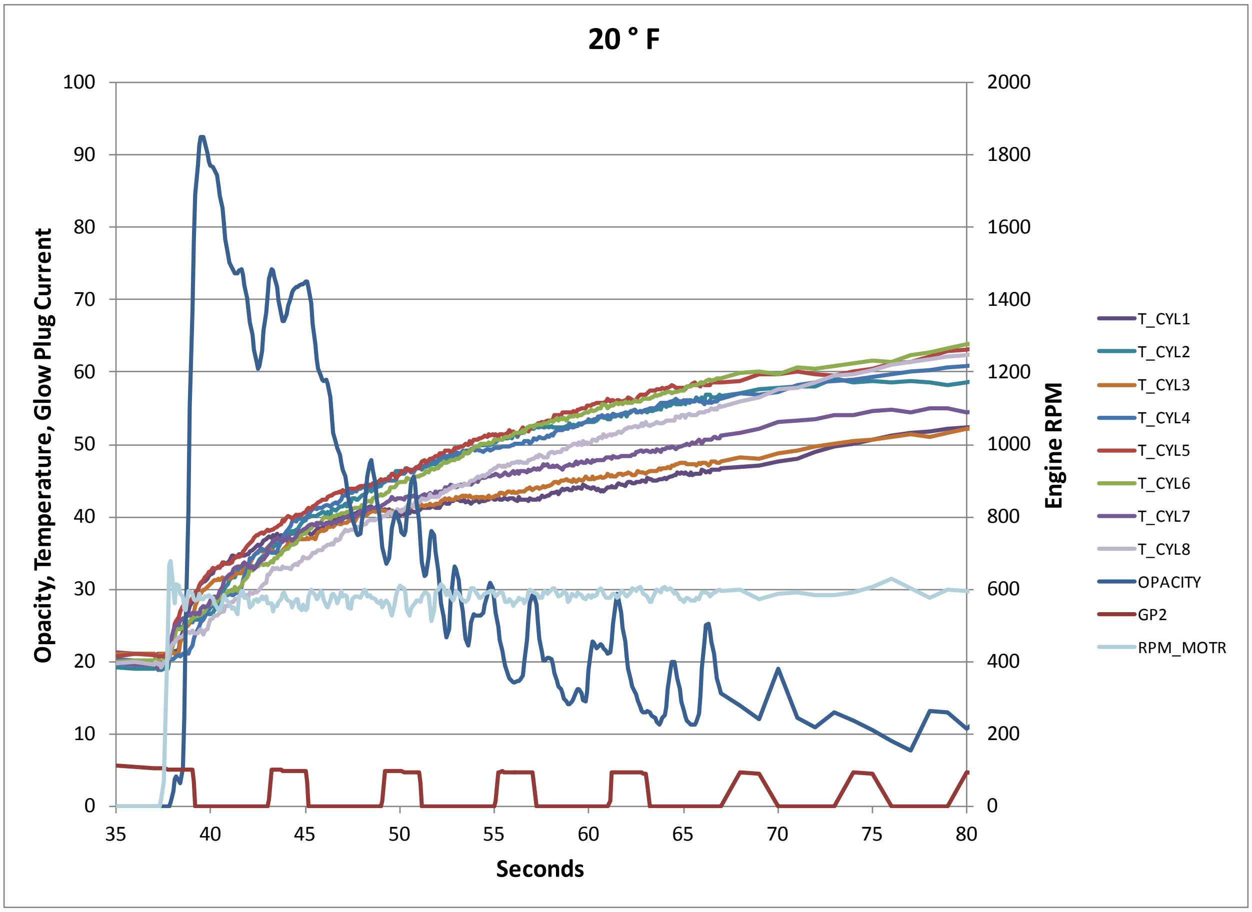


Figure C-13. High Cetane Cold Start at 20 °F

At 0 degrees Fahrenheit, the engine was again unable to start without the use of glow plugs. As seen in Figure C-14, the engine started immediately with no hesitation, firing on all cylinders. The opacity took about 10 seconds to drop below 10 percent as the individual cylinders continued to warm up. The rpm started a bit lower due to the increased engine friction of the viscous oil, but as the temperatures came up, so did the speed. It is surmised that the engine warms up faster at lower temperatures due to the increased viscosity of the fuel. The fuel's viscosity directly impacts the delivered volume. This is a result of the internal design of the rotary injection pump.

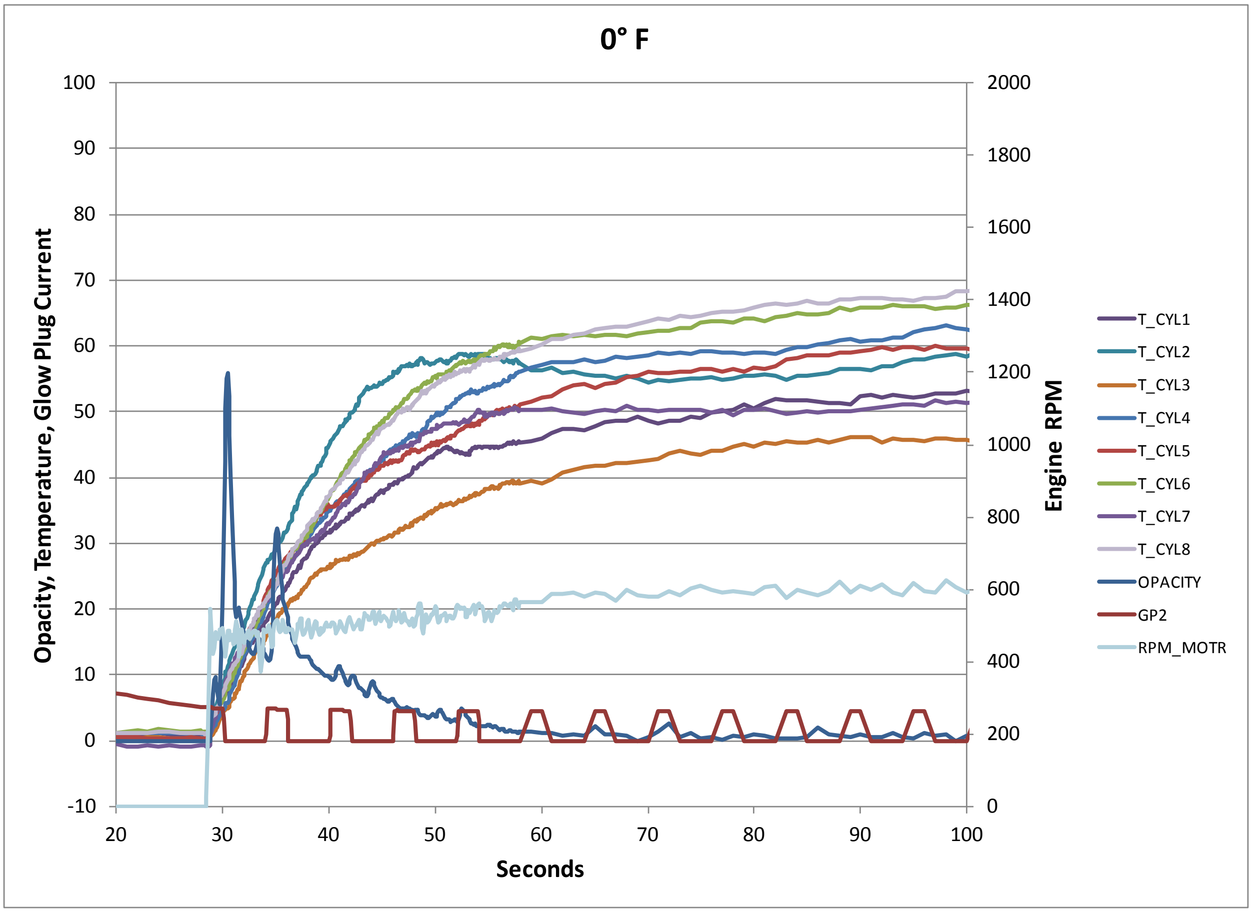


Figure C-14. High Cetane Cold Start at 0 °F

At -20 degrees Fahrenheit, the engine was again unable to start without the use of glow plugs. As seen in Figure C-15, the engine started immediately with no hesitation, firing on all cylinders. The opacity took about 1 minute to drop below 10 percent as the individual cylinders continued to warm up. The rpm started even lower than before due to the increased engine friction of the viscous oil, but as the temperatures came up, so did the speed. At this run condition, however cylinder 7 stopped firing after 2.5 minutes and did not re-ignite for another 2.5 minutes even with the glow plugs engaged on their duty cycle timer. After stable combustion on all 8 cylinders, the idle rpm was just over 600.

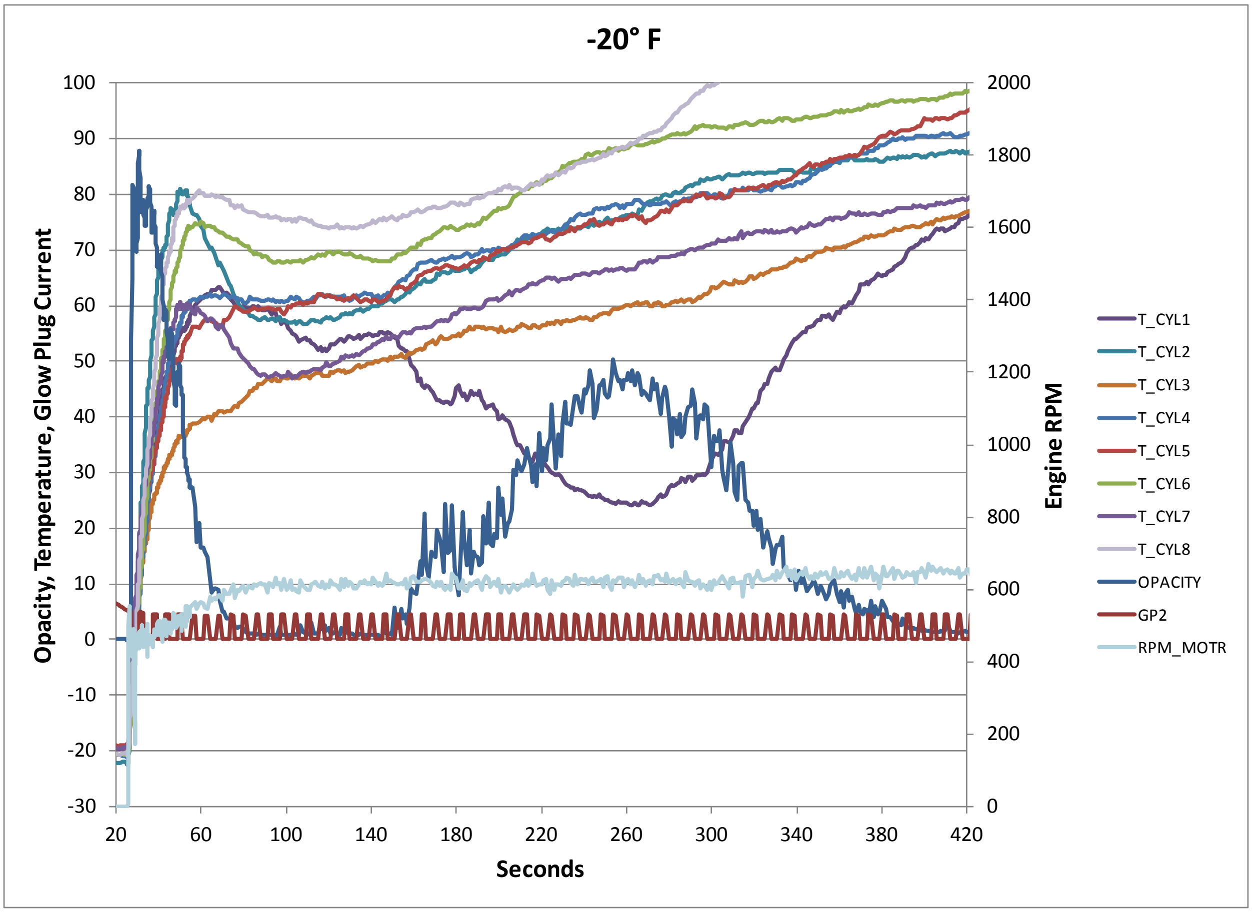


Figure C-15. High Cetane Cold Start at -20 °F

For this particular engine installation, it is not unexpected for a cylinder to stop firing at low temperatures. As mentioned previously, diesel engines with pre-chamber architecture are particularly sensitive to cold start regimes. Over all of the cold start tests performed, cylinders 1, 2, 4, 6, 7, and 8 all took turns discontinuing combustion after the initial start event. In addition, this particular engine installation is likely more sensitive to cold running operation due to the lack of accessory drive loads that are typically present in an actual vehicle.

C.11.0 GEP COLD START ON LOW CETAINE FUEL

At 40 degrees Fahrenheit, the engine was not able to start without the aid of glow plugs. The glow plugs were enabled for 10 seconds prior to ignition, and disabled after. The engine was able to start, but 3 of the cylinders immediately quit firing. As seen in Figure C-16, cylinder 2 was the first to relight, followed 30 seconds later by cylinder 7, and after another 30 seconds cylinder 8 reignited. Although the temperature of cylinder 2 does not increase with time as the other cylinders, combustion was occurring as indicated by the low opacity values.

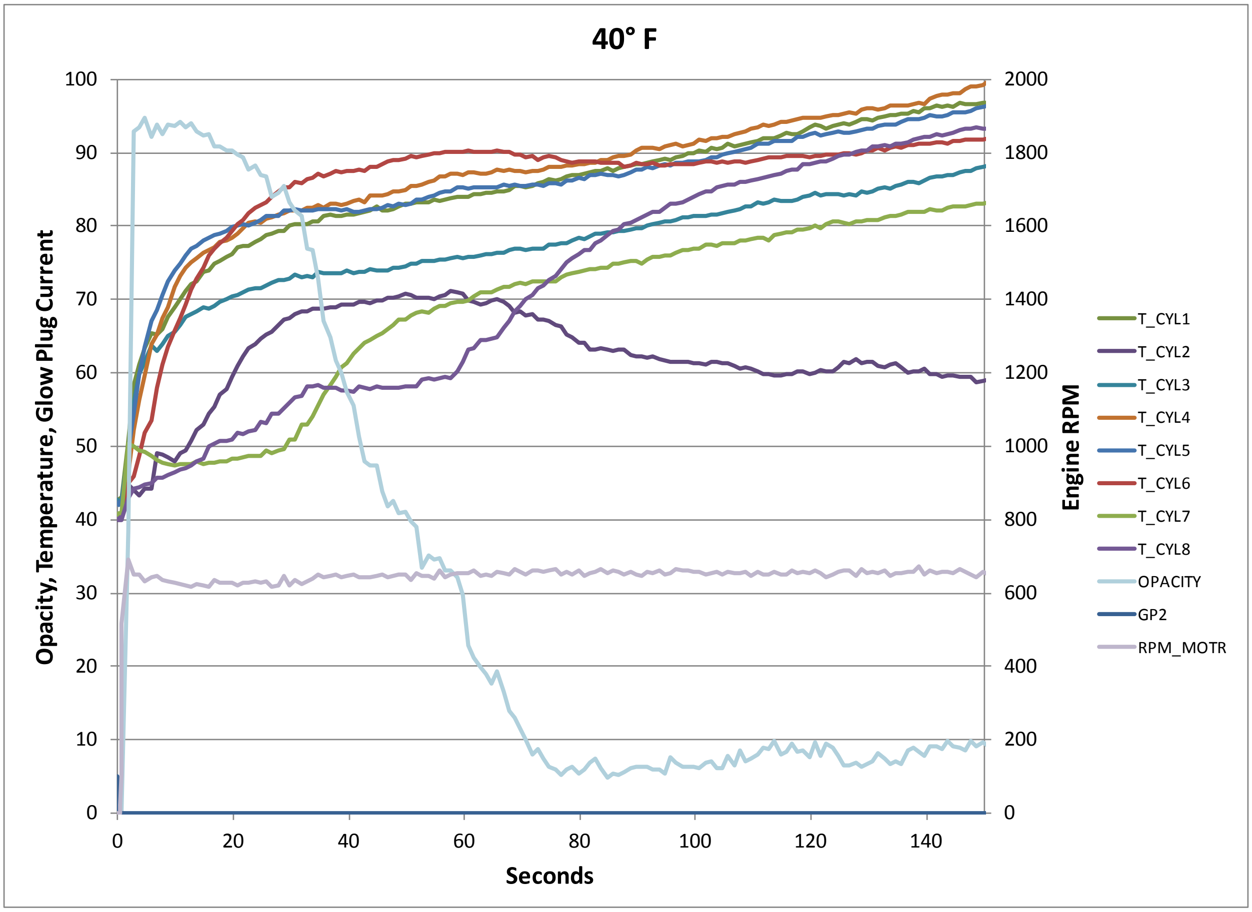


Figure C-16. Low Cetane Cold Start at 40 °F

At 20 degrees Fahrenheit, the engine was unable to start without the use of glow plugs. As seen in Figure C-17, the engine started immediately with no hesitation, firing on all cylinders. However, cylinder 4 stopped firing a few seconds after ignition, then resumed about the time cylinder 6 stopped firing. Cylinder 6 fired intermittently until full relight around 300 seconds.

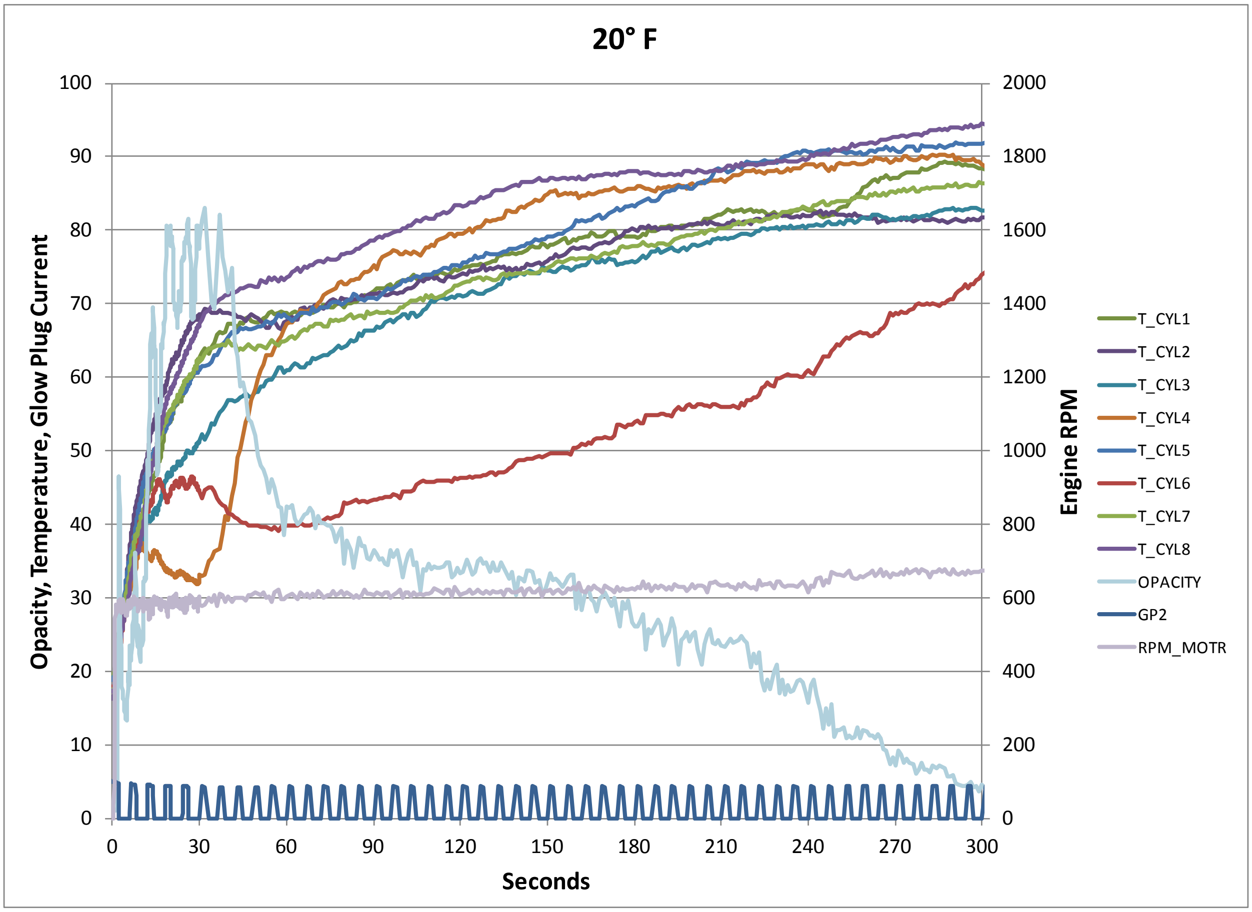


Figure C-17. Low Cetane Cold Start at 20 °F

At 0 degrees Fahrenheit, the engine was again unable to start without the use of glow plugs. As seen in Figure C-18, the engine started immediately with no hesitation, firing on all cylinders. After 20 seconds, cylinder 6 stopped firing followed by cylinder 1 at about 60 seconds. The data is continued in Figure C-19.

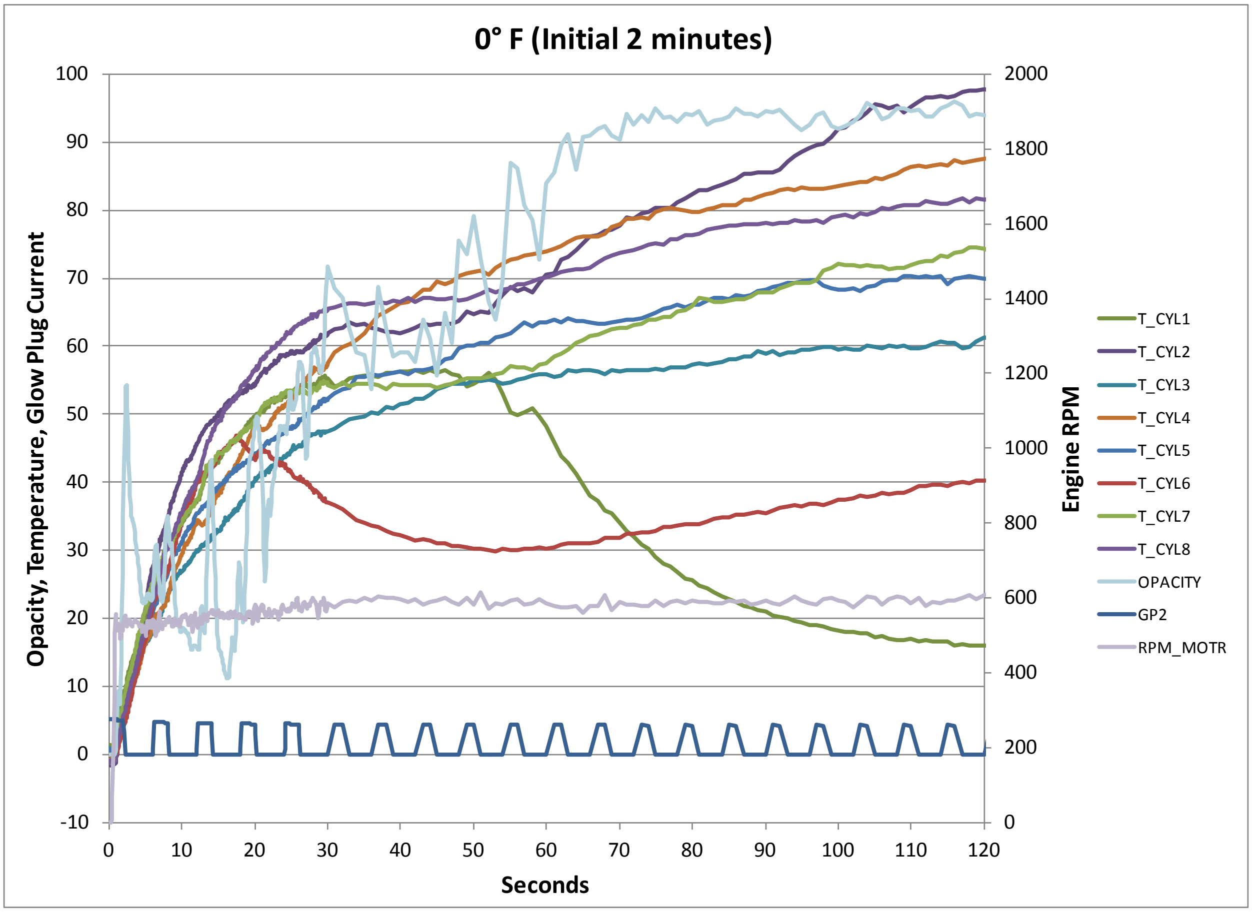


Figure C-18. Low Cetane Cold Start at 0 °F (Initial 2 Minutes)

Cylinder 6 continued to gain heat from the surrounding cylinders and started firing intermittently at about 120 seconds. Around 300 seconds consistent combustion was achieved on cylinder 6. Cylinder 1 did not fully relight until 480 seconds after ignition began.

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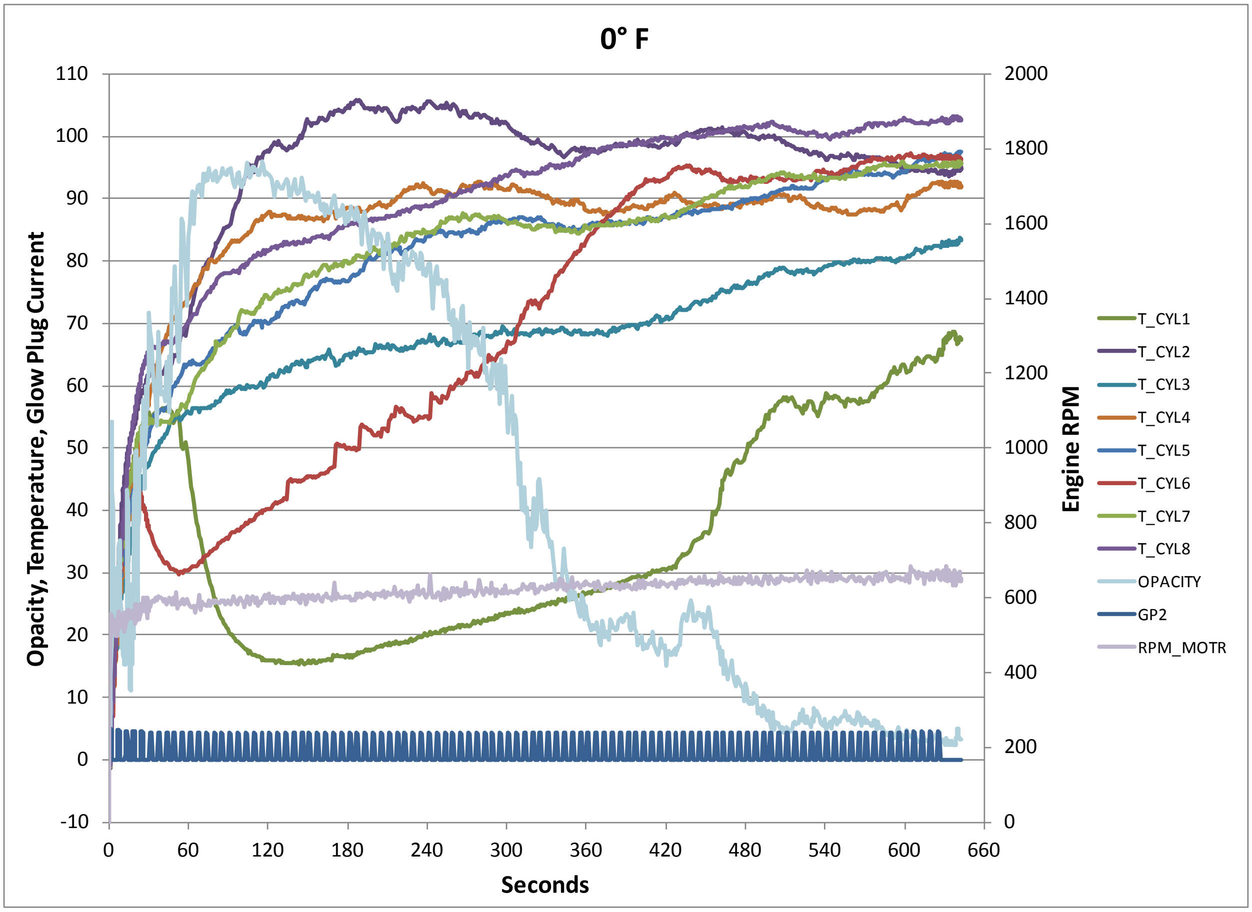

Figure C-19. Low Cetane Cold Start at 0 °F

At -20 degrees Fahrenheit, the engine was again unable to start without the use of glow plugs. As seen in Figure C-20, the engine started immediately with no hesitation, firing on all cylinders. The opacity decreased for the first 30 seconds until cylinders 4 and 6 stopped firing. The data is continued in Figure C-21.

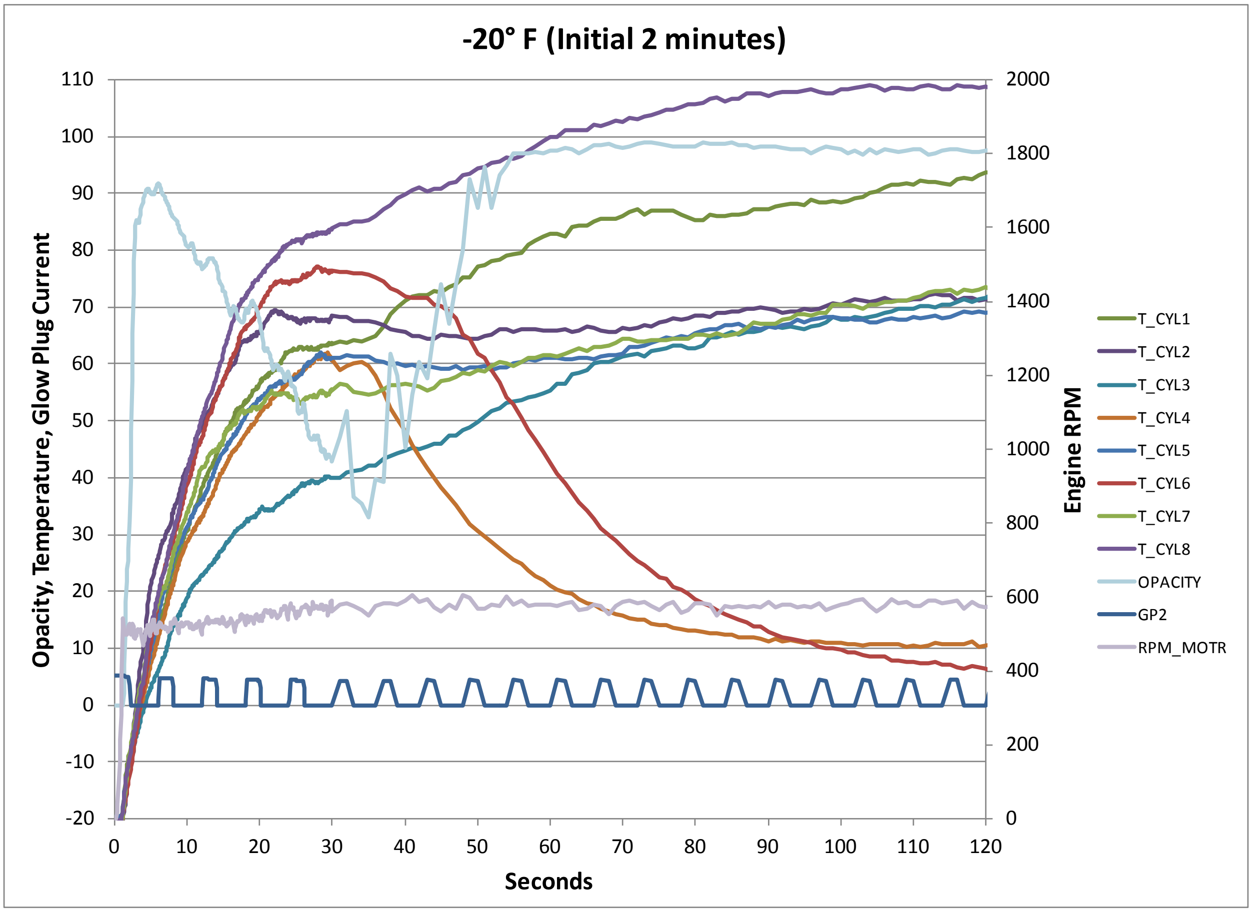

Figure C-20. Low Cetane Cold Start at -20 °F (Initial 2 Minutes)

For almost a full 9 minutes the engine slowly warmed up on 6 of the 8 cylinders. Between 500 and 600 seconds, cylinders 4 and 6 attempted to relight, and fired occasionally for another 500 seconds. After 630 seconds of operation, the glow plugs are automatically disabled to prolong their life. Cylinder 4 fully relit after almost 17 minutes, and cylinder 6 relit successfully a full 20 minutes after ignition.

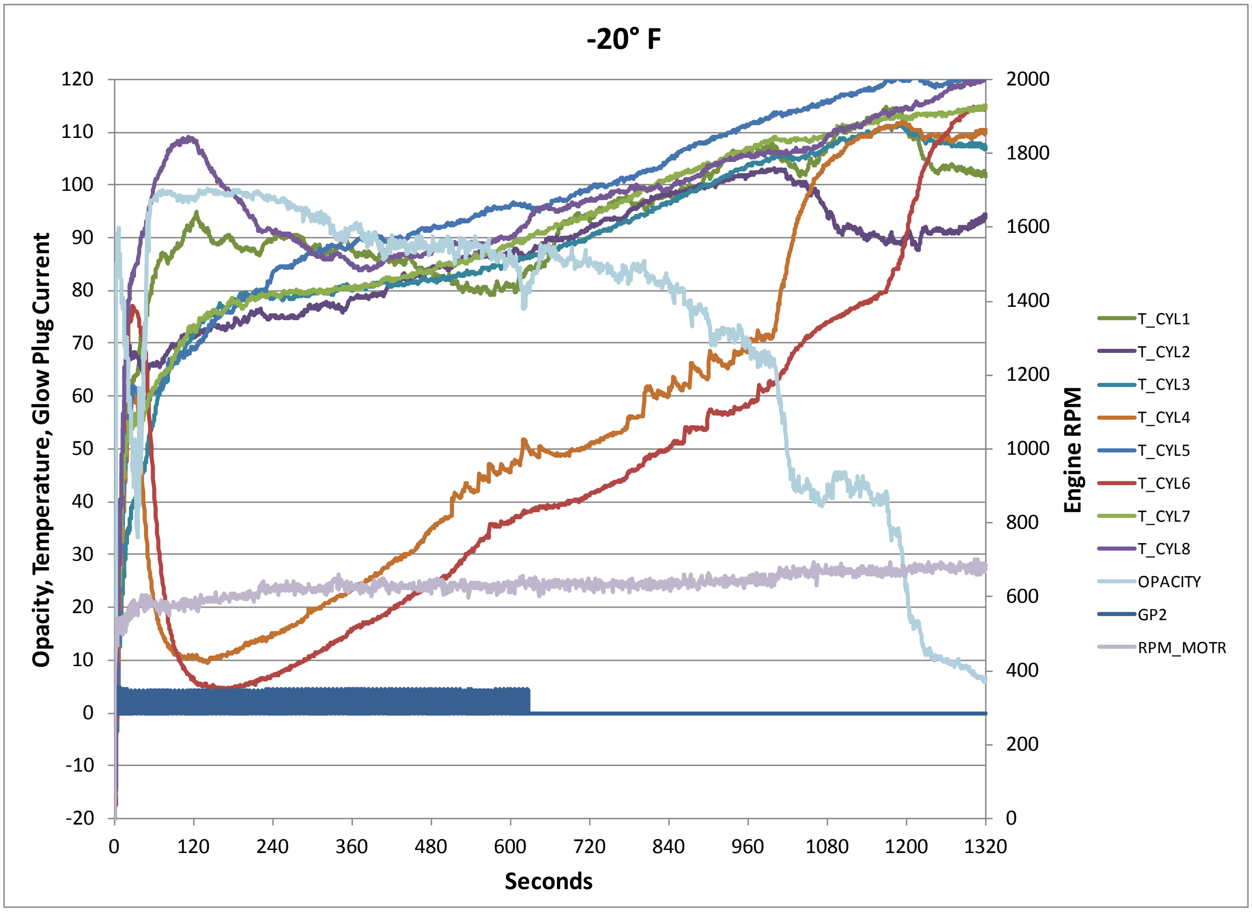

Figure C-21. Low Cetane Cold Start at -20 °F

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C.12.0 SUMMARY

For the Ford 6.7L engine operating on the three fuels tested, TFLRF was unable to observe any behavior that would be considered detrimental. At light load conditions, the heat release rate was well controlled even if the timing of the heat release events was shifted due to cetane.

Traditionally high cetane fuels operating on engines with static timing promotes NO_X formation. However, at high load conditions where excessive NO_X formation typically occurs, the timing changes in the main heat release event were not large enough to drastically impact the engine out emissions.

Although there was a correlation of decreasing peak power with decreasing fuel density, the magnitude of the loss was low. A 1.4% loss of density resulted in a 1.3% decrease in power.

The common rail architecture of the Ford 6.7L also allows the engine to be insensitive to other fuel properties such as bulk modulus which can change the static timing in a pump-line-nozzle style engine.

The GEP 6.5L engine operating in the cold box was able to distinguish large differences in the fuel. Even at a relatively warm 40 degrees Fahrenheit, the low cetane fuel was unable to start in the engine without the aid of glow plugs.

While the high cetane fuel did not experience any cylinders ceasing combustion after ignition until the temperature dropped to -20 Fahrenheit, the low cetane fuel had two cylinders deactivate after ignition at only +20 Fahrenheit with the glow plugs continuing to activate. And at the -20 Fahrenheit condition, the low cetane fuel caused cylinders 4 and 6 to cease firing for 17 and 20 minutes, respectively. This is a much worse result than with the high cetane fuel.

Appendix D

O-Ring Material Compatibility

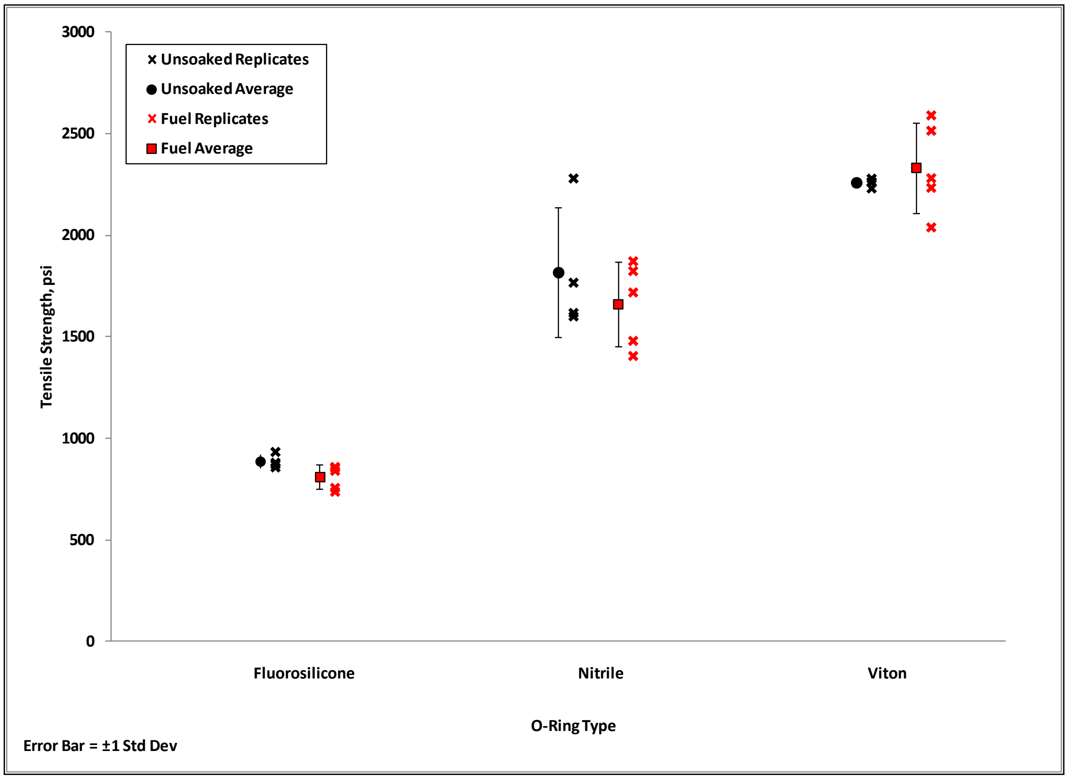

Figure D-1. O-Ring Tensile Strength with ATJ Blend

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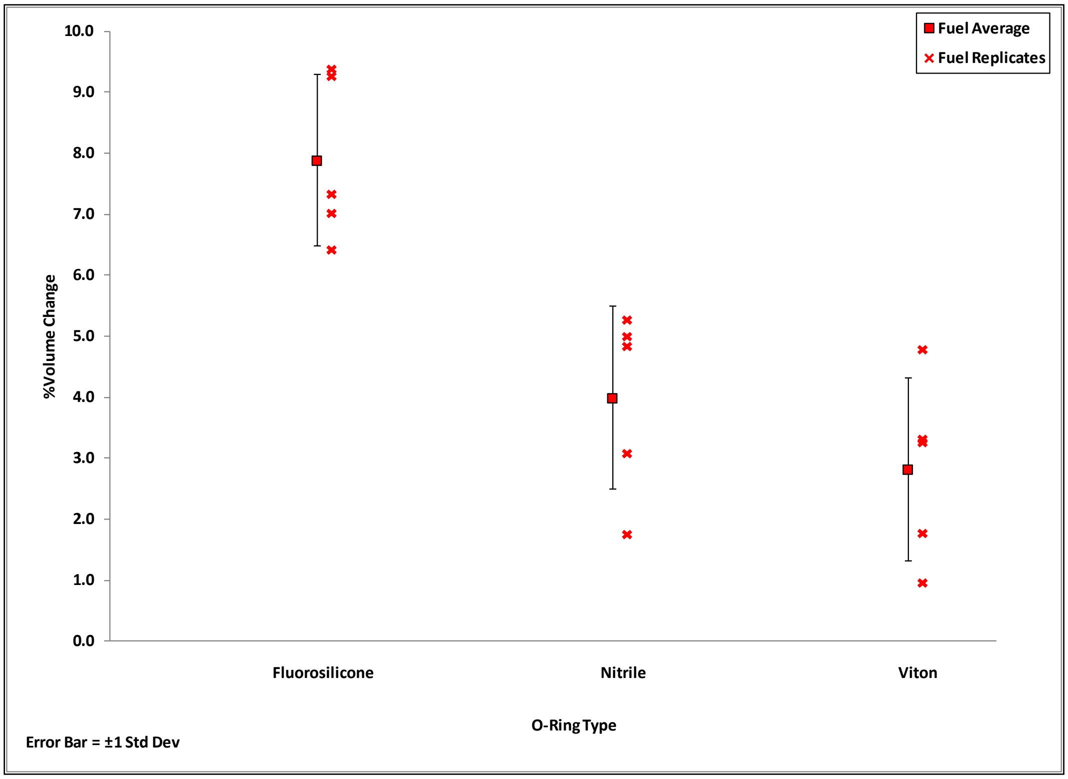

Figure D-2. O-Ring Volume Swell with ATJ Blend