OPSEC 1854

MILITARY GROUND VEHICLE FUEL LUBRICITY TESTER
(IMPROVING THE SENSITIVITY OF THE HFRR)

INTERIM REPORT
TFLRF No. 489

By
Greg A Hansen

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

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

Contract No. W56HZV-15-C-0030 (WD15)

UNCLASSIFIED: Distribution Statement A. Approved for public release

October 2018

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Approved by:

Gary Bessee

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Research Facility (SwRI®)

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 15-10-2018	**2. REPORT TYPE** Interim Report	**3. DATES COVERED** *(From - To)* March 2017 – October 2018

4. TITLE AND SUBTITLE
Military Ground Vehicle Fuel Lubricity Tester
(Improving the Sensitivity Of The HFRR)

5a. CONTRACT NUMBER
W56HZV-15-C-0030

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Greg A. Hansen

5d. PROJECT NUMBER
SwRI 08.22812

5e. TASK NUMBER
WD 15

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI®)
Southwest Research Institute®
P.O. Drawer 28510
San Antonio, TX 78228-0510

8. PERFORMING ORGANIZATION REPORT NUMBER
TFLRF No. 489

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army RDECOM
U.S. Army TARDEC
Force Projection Technologies
Warren, MI 48397-5000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
UNCLASSIFIED: Dist A
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A new test method was developed called the HFRR-LC. This builds upon previous research done at SwRI. This new test method improves the correlation between laboratory wear and fuel system test response and improves the detectability limit of CI/LI at nominal treat rates under reciprocating conditions.

15. SUBJECT TERMS
F-24, FT-SPK, Jet A-1, CHCJ-5, DF-2, F-76, JP-5, Fuel Lubricity, Fuel Pump, Wear, Friction, Film Thickness

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	Unclassified	36	

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

EXECUTIVE SUMMARY

In diesel engines, the fuel pumps and fuel injectors are subjected to tremendous pressures, upward of 200 MPa in modern systems. In order to generate and maintain this level of pressure, the internal pump and injector components are made to an exacting standard. The drawback is the moving components are largely lubricated with only the diesel fuel. If the diesel fuel has insufficient lubricating quality, catastrophic wear and subsequent failures can occur. Some lubricity problems have been spawned by higher quality fuels and their associated refining processes.

The Army requires use of an approved lubricity additive in the fuel it acquires for use in diesel engines. If treated with an approved additive, at a maximum rate between 20 and 30 mg/kg, even poor lubricity fuels will be able to operate for the life of the engine. Unfortunately, the HFRR wear result does not discriminate between these neat and additized jet fuels at approved treat rates.

The purpose of this program was to develop a new analytical test method that ensures adequate fuel lubricity additive performance for military diesel engines. The work performed in this program builds upon previous internal research done at SwRI.

A new method was developed that utilizes both a new set of test specimens and a new set of testing parameters. This new method is able to better distinguish lubricity performance between different fuel types and is able to detect very low levels of lubricity additive.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period April 2017 through December 2018 under Contract No. W56HZV-15-C-0030. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the TARDEC contracting officer's technical representative and the project technical monitor.

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

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ACRONYMS AND ABBREVIATIONS

MPa	Mega Pascals
mg/kg	Milligrams/kilogram
µm	micrometer
°C	Degrees Celsius
N	Newton
CI/LI	Corrosion Inhibitor/Lubricity Improver
ATJ	Alcohol to Jet
SPK	Synthetic Paraffinic Kerosene
FT	Fischer Tropsch
ASTM	American Society for Testing and Materials
EN	Européen de Normalisation (European Standard)
WSD	Wear Scar Diameter
NATO	North American Treaty Organization
HFRR	High Frequency Reciprocating Rig
HFRR-LC	High Frequency Reciprocating Rig – Line Contact
TARDEC	Tank Automotive Research, Development, and Engineering Center
TLFRF	TARDEC Fuels and Lubricants Research Facility
SwRI	Southwest Research Institute
BOCLE	Ball on Cylinder Lubricity Evaluator
SL-BOCLE	Scuffing Load BOCLE
BOT	Beginning of Test
EOT	End of Test
COF	Coefficient of Friction
HRC	Rockwell Hardness ‘C’ Scale
HV	Vickers Hardness

1.0 BACKGROUND & INTRODUCTION

In diesel engines, the fuel pumps and fuel injectors are subjected to tremendous pressures, upward of 200 MPa in modern systems. In order to generate and maintain this level of pressure, the internal pump and injector components are made to an exacting standard. The drawback is the moving components are largely lubricated with only the diesel fuel. If the diesel fuel has insufficient lubricating quality, catastrophic wear and subsequent failures can occur. Some lubricity problems have been spawned by higher quality fuels and their associated refining processes.

The measure of a fuel's ability to prevent wear is called lubricity. The lubricity standard for diesel fuel is set in ASTM D975. Currently, a result of 520 µm wear scar diameter (WSD) on the High Frequency Reciprocating Rig (HFRR), by ASTM D6079, is the maximum allowable value for diesel fuel lubricity in the United States. A result of 460 µm is the maximum allowable limit under the European Standard for Diesel, EN 590.

In accordance with the NATO Single Fuel Forward doctrine, the US Army currently utilizes aviation turbine fuel in all of its compression ignition ground vehicles and equipment during operations. Aviation turbine fuel is similar to Grade 1D diesel fuel, although it can have a lower viscosity due to its low temperature requirements. The current aviation turbine fuel specifications, MIL-DTL-83133 and ASTM D1655, allow specific synthetic fuel components to be used, which can exacerbate the historically poor lubricity issue. The currently approved synthetic fuel components are typically devoid of the aromatic, polar, and heteroatom molecules which can promote good lubricity. While not intended for standalone use, they are routinely tested neat to assess their performance characteristics. With these synthetic fuel components, the HFRR result can be as high as 900 µm WSD [1], which, if run in an engine un-additized, will cause both quick and catastrophic pump failures.

The Army requires use of an approved lubricity additive in the fuel it acquires for use in diesel engines. If treated with an approved additive, at a maximum rate between 20 and 30 mg/kg, even poor lubricity fuels will be able to operate for the life of the engine. Unfortunately, the HFRR wear result does not discriminate between these neat and additized Jet fuels at approved treat rates [2,3,4].

To illustrate, TARDEC Fuels and Lubricants Research Facility (TFLRF) completed a fuel evaluation program for the Army where a variety of fuels were run on diesel engine fuel pump systems (IR437). In this program, pump tests ran up to 1,000 hours. Using a synthetic fuel component, untreated, with a HFRR result of 840 µm WSD, the pump seized after only 30 minutes of operation. That same fuel, treated at 23 mg/kg with DCI-4A (an approved commercial additive), only exhibited a HFRR value change to 800 µm WSD. These values fall within the repeatability limits of the test: 80 µm at 60 °C. With the treated synthetic fuel component, the pump ran the entire 1,000 hours with only moderate wear levels at the end of the test. While these fuels and fuel components represent the high end of wear, they are not unusual. The fact they respond to additives makes them an ideal medium for evaluating potential alternative test practices.

In 1990, Lacey and Mason published a compilation database of over 175 fuel pump tests [5]. Their database attempted to correlate fuel pump tests with results of various laboratory scale fuel property tests. The correlation values versus lubricity test type are seen in Figure 1. In terms of accurately predicting the behavior of additized fuels, the HFRR at 60 °C gives the worst metric. Further, all sliding point contact tests yield less than 30% correlation with additized fuels.

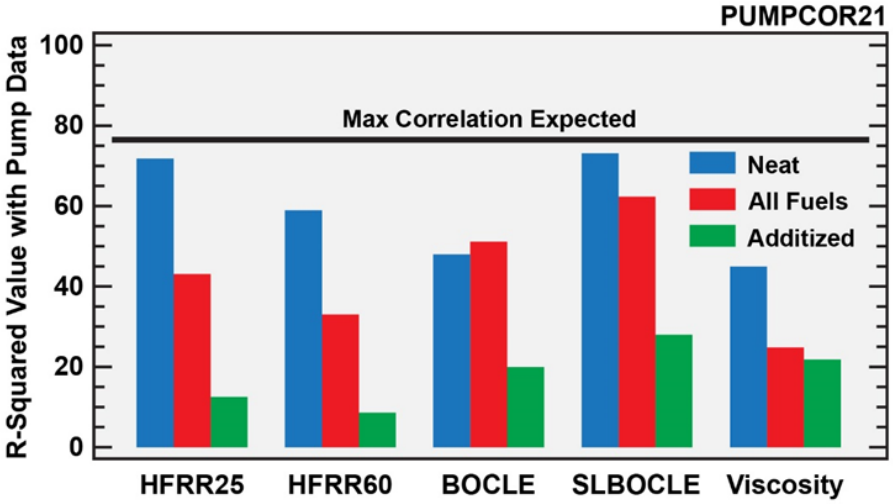

Figure 1. Lacey and Mason Correlation

On a deeper dive into some potential reasons why the above referenced pump tests did not correlate with lubricity results, it was important to understand how both systems operated from a tribological perspective. It is critical to understand the specific energy input into contacting surfaces (pressure, temperature, speed) if real contacts (fuel pumps) are to be replicated in a laboratory environment (lubricity tests).

The HFRR utilizes a 6mm ball (HRC60) and a 10mm disk (HV30) which calculates to a Hertzian contact pressure of approximately 825 MPa at the start of the test. If the HFRR wear scar has a mean diameter of 520, the end of test contact pressure is around 80 MPa. If the Stanadyne rotary injection pump (used in IR437) is torn down, a few critical wear components can be identified. Figure 2 shows an exploded view with some actual examples of the critical pump components.

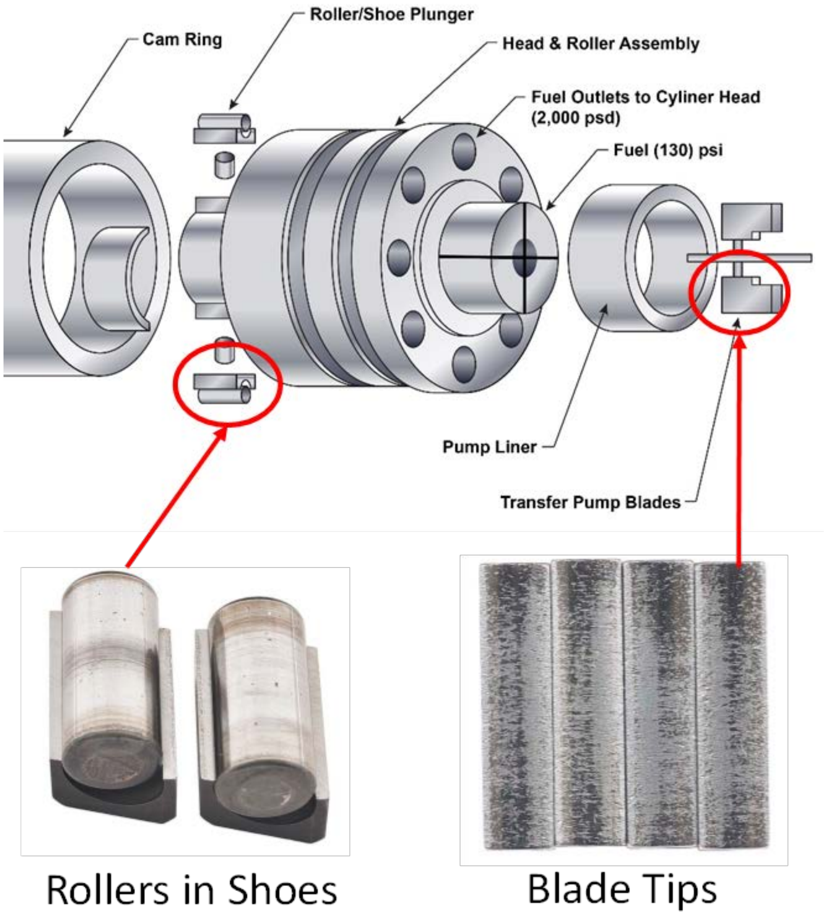

Figure 2. Exploded view of Stanadyne pump, with 2 critical components identified

The Stanadyne injection pump line pressure can vary from 30 to 280 bar depending on engine conditions. These line pressures can be traced back using part geometry and fluid paths to give an operating range of 0.6 to 10 MPa of contact pressure between the roller and the shoe. Similarly, the pump housing pressure and pump speed can be used to calculate a maximum initial contact pressure of 300 to 600 MPa on the blade tips. Observation of EOT blade tip wear areas give between 30 and 70 MPa. While the blade pressures are in a similar range to the HFRR, the roller-shoe contact pressures are not.

2.0 TEST OBJECTIVE

The purpose of this program was to develop a new analytical test method that ensures adequate fuel lubricity additive performance for military diesel engines. The work performed in this program builds upon previous internal research done at SwRI [6]. It was expected that this program would improve the correlation between HFRR test results and hardware durability by altering the HFRR and test geometry from a point contact (ball on flat) to a line contact (pin on flat), henceforth called High Frequency Reciprocating Rig – Line Contact (HFRR-LC). It was believed that by reducing the Hertzian contact pressure and increasing the active test surface area will make the HFRR-LC more sensitive, and better able to distinguish between fuel chemistries and lubricity additive concentrations. A range of HFRR-LC test conditions were also explored.

3.0 FUEL INFORMATION

There were three main fuels used in this program: F-24, Fischer Tropsche-Synthetic Paraffinic Kerosene (FT-SPK), and an Alcohol to Jet (ATJ) blend. The F-24 is the current Army sourced and approved fuel which is also being used on other current pump testing programs at SwRI. The FT-SPK was used previously on pump tests as reported in IR437. The ATJ blend was also used previously on pump tests as reported in IR468 [7]. The standard HFRR (ASTM D6079) and Ball on Cylinder Lubricity Evaluator (BOCLE) (ASTM D5001) results for these fuels are seen in Figure 3 and align with prior reported data.

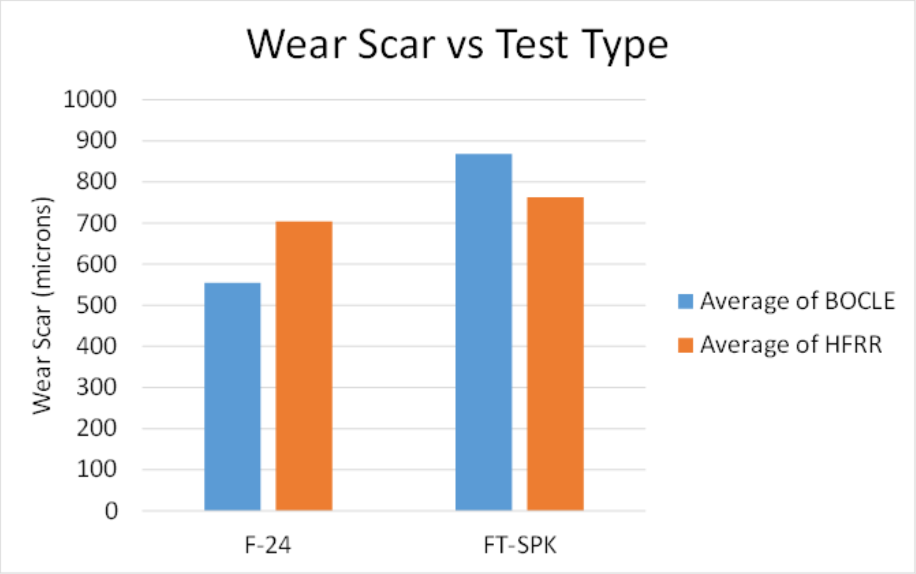

Figure 3. Standard HFRR and BOCLE results for neat test fuels

The F-24 was chosen as a ‘good’ performing baseline fuel due to its current approved status. The FT-SPK was chosen as a ‘poor’ performing baseline fuel due to its oxidative wear behavior and known lubricity issues when un-additized. The ATJ blend fuel was chosen to perform the bulk of the development work due to having a large quantity on hand at SwRI, and it being an ‘intermediate’ performing fuel when additized as concluded in IR468. The standard HFRR results for various treat rates of this ATJ blend fuel can be seen in Figure 4. The standard HFRR method is incapable of detecting Corrosion Inhibitor/Lubricity Improver (CI/LI) at or below 50ppm, which is approximately twice the maximum treat rate as allowed in MIL-PRF 83133.

The CI/LI used in this program was INNOSPEC DCI-4A.

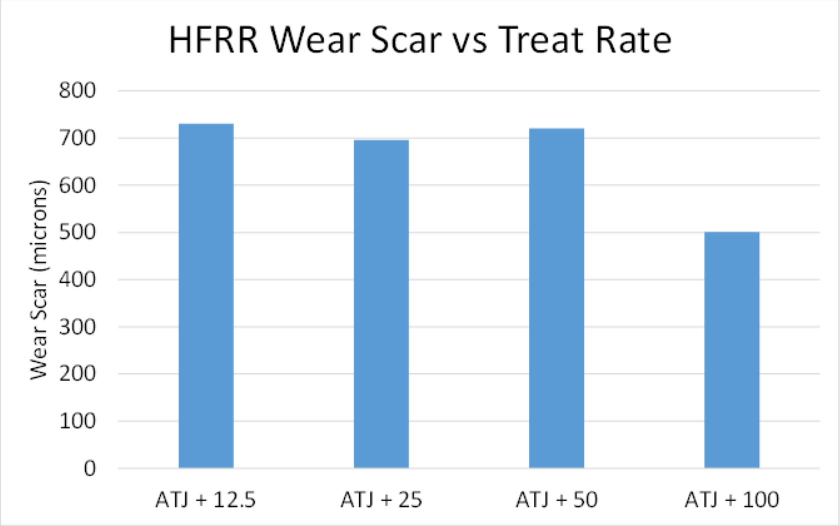

Figure 4. Standard HFRR result for ATJ blend at various treat rates

4.0 TEST RIG DESCRIPTION

In order to meet the needs of the program, a TE-81 Single Station Fuel Lubricity Test Rig was purchased from Phoenix Tribology (UK) as seen in Figure 5. The TE-81 specifications are shown in Table 1. The machine utilized a dead-weight loading system and reciprocated the upper specimen via a gear box attached to an electric motor. The lower specimen sat in a small bath that could be heated. Friction was measured via a force transducer attached to the heating plate for the bath. After installation, the rig was renamed the High Frequency Reciprocating Rig (HFRR-LC).

Figure 5. TE-81, image courtesy of Phoenix Tribology Ltd

Table 1. TE-81 Specifications

Contact Geometry:	Ball on Plate (Point Contact)
	Cylinder on Plate (Line Contact)
Ball Specimen:	6 mm diameter
	10mm diameter
Cylinder Specimen:	6mm diameter x 10mm
Load:	2 N to 20N
Stroke:	1 mm to 5 mm
Frequency:	5 Hz to 50 Hz
Maximum Stroke @ 50 Hz Frequency:	1 mm
Maximum Frequency @ 5 mm Stroke:	20 Hz
Temperature:	ambient to 100 °C
Controlled Parameters	Frequency
	Temperature
	Test Duration
	Load
Analog Outputs	Friction Force
	RMS Friction
	Friction Noise
	Contact Potential

Figure 6 and Figure 7 show the HFRR-LC as it was initially installed at SwRI. The environmental chamber allows humidity control to meet the tight control window in ISO 12156-1 (HFRR), as it is known that humidity can have a strong influence on lubricity test results.

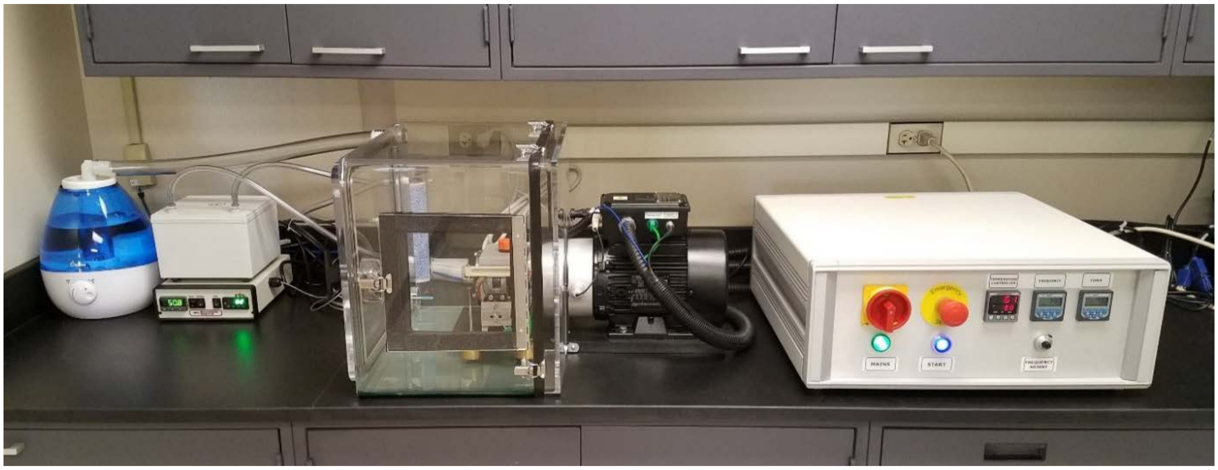

Figure 6. HFRR-LC after initial installation

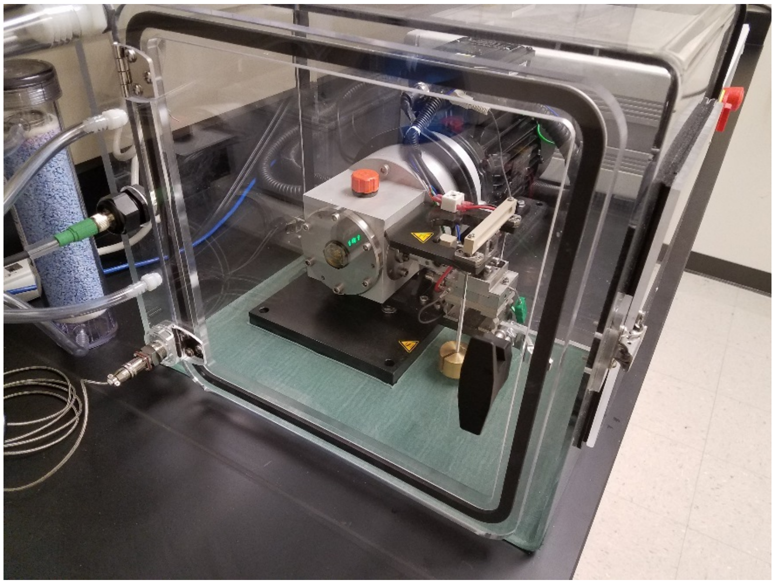

Figure 7. Test section inside environmental chamber, after initial installation

After some initial tests, it was determined that the larger bath size of the HFRR-LC promoted evaporation of the fuel sample. In order to combat this, and more accurately represent real fuel systems, a low flow programmable pump was added to the system as seen in Figure 8.

Figure 8. Pump added for test fluid flow rate control

A drain was also installed in the lower specimen bath approximately 2mm above the height of the lower specimen as shown in Figure 9. This allowed all excess fuel to naturally exit the system at the same rate at which it entered, while maintaining a constant liquid level over the specimen.

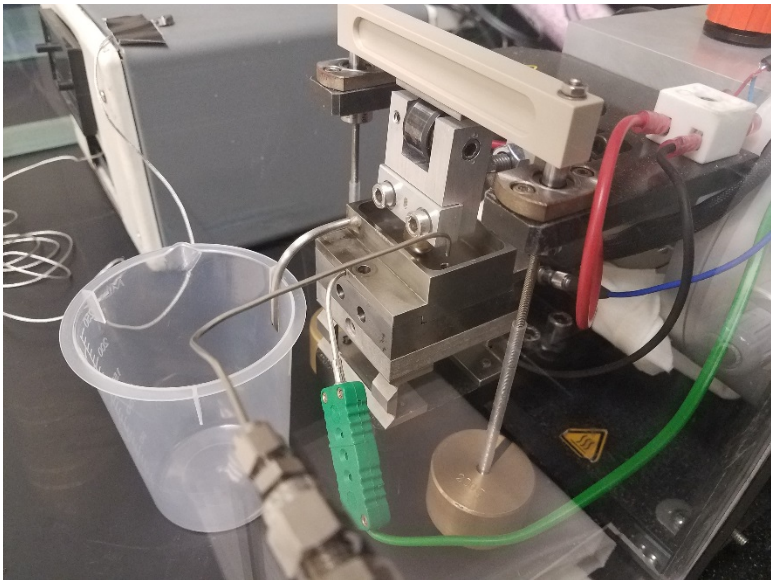

Figure 9. Modified setup showing fuel supply tube and fluid exit from lower specimen bath

The specimens used in this program were both the standard parts (HFRR 6mm ball and 10mm disk) and custom parts. The custom parts consisted of a 6x10mm pin supplied by JTEKT North America (p/n ZRO.6x10) and a disk made to the same specifications as in ASTM D6079, but with a 15mm outer diameter.

5.0 RESULTS

Initial HFRR-LC testing was done on custom pins manufactured by SwRI. Due to the lack of dimensional control, there was a fairly high test rejection rate due to irregular wear scars. It took some time before suitable specimens were sourced (JTEKT N.A.), and so the first 3 series of baseline testing on F-24 and FT-SPK was done on the SwRI pins. The goal of the baseline testing was to find approximate run conditions in which the wear scar for FT-SPK was significantly larger than that of the F-24.

The first series of tests using the pin (LC) setup on the HFRR-LC were a relatively high load baseline as compared to later testing. After varying stroke length from 1-5mm, and frequency from 10-50Hz, all at constant total sliding distance, it was found that the wear scar was only mildly influenced by load as seen in Figure 10. All other variables are included in this data set as none had a more significant impact on results than did the load, and so the figure represents data from 16 total tests.

It is currently understood that similar contact pressures dampened the magnitude of the result. The contact pressure was calculated by estimating the area of the EOT wear scar and dividing into the total applied load (calibrated value of the reciprocating head mass plus the external load mass with the reciprocating arm pivot joint in the locked position). Contact pressures for these tests ranged from 4-8MPa.

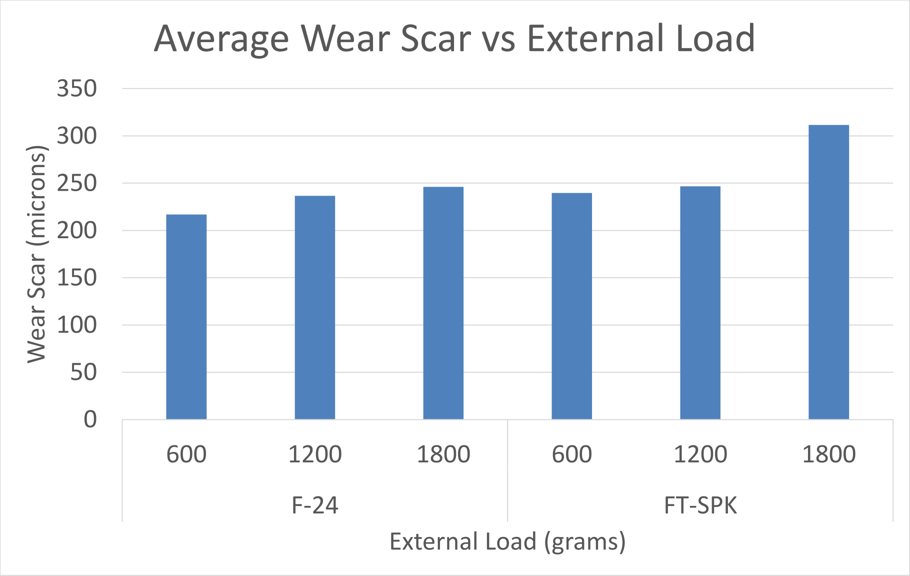

Figure 10. High load baseline tests, multiple variables averaged

A similar analysis was performed where reciprocating frequency was the variable of interest, and the variables of stroke length and load were not considered. While total sliding distance was held constant as was average sliding velocity, there was no observed global trend with respect to frequency as seen in Figure 11.

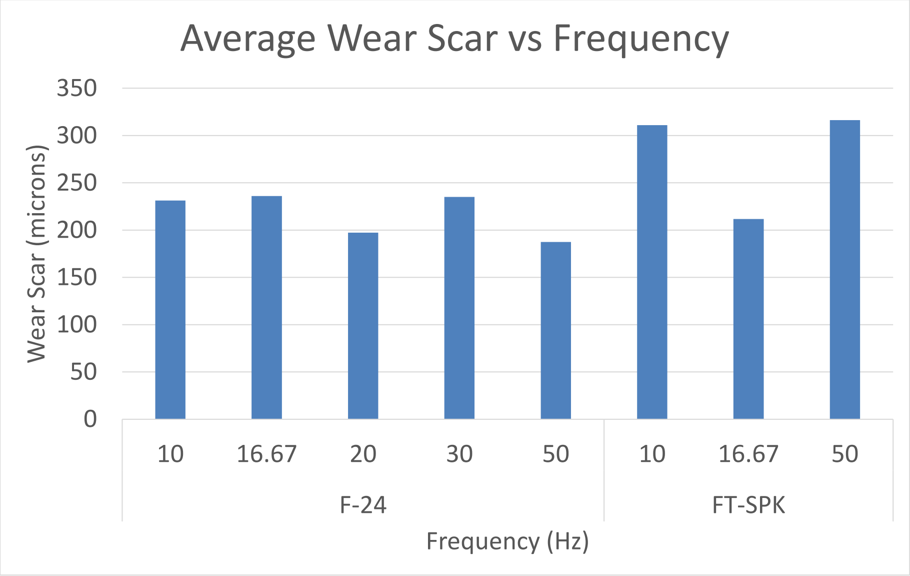

Figure 11. Frequency baseline tests, multiple variables averaged

A final analysis was performed where sliding distance was the variable of interest, and all other test variables were averaged. In Figure 12, it can be seen that increased sliding distance dampens differentiation between the fuels. The decrease in FT-SPK wear scar with sliding distance is likely due to both the increased test result variability of low lubricity fuels, and an unequal number of tests between the two sliding conditions.

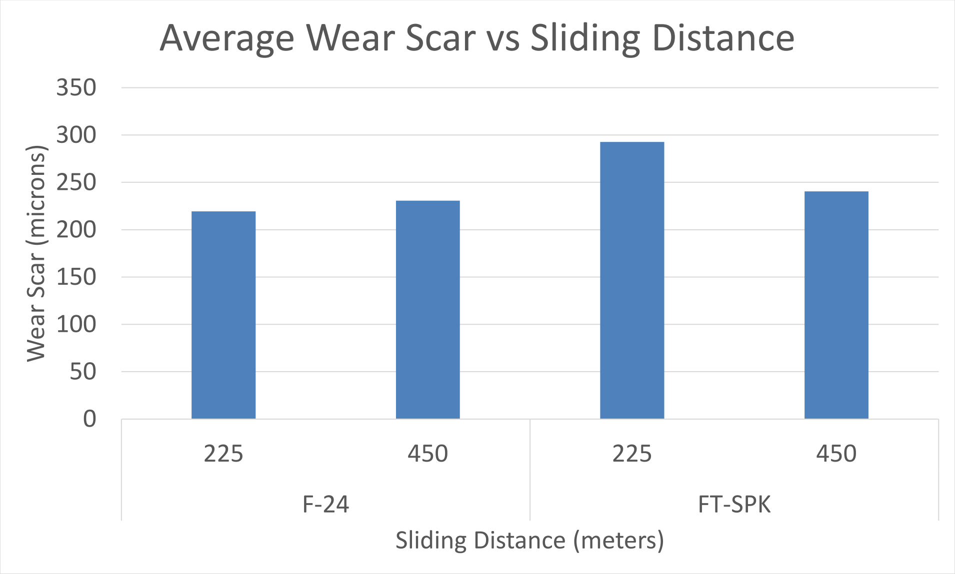

Figure 12. Sliding distance baseline tests, multiple variables - averaged

In all of these baseline tests, it was apparent that there was strong differentiation lacking between any test variable and the test fuels.

Some additional changes were made at this point to the HFRR-LC. In its initial setup, the fluid bath containing the lower specimen and the test fuel was filled statically at the beginning of the test. For severe tests (high speed, high load) on the FT-SPK fuel it was observed that the fuel evaporated to the point of running the contact dry, and so about half way through the test a few additional mL would be added to make up for this evaporative loss. To automate this process a pump was added to the HFRR-LC system and the bath was modified with an overflow drain. All future testing would be run at 2mL/min flow rate in addition to the initial static fill.

It was also observed that at high speeds and light loads, the external load (brass weights) could not be less than 250 grams or the reciprocating head could cause excessive vibration and occasionally bounce vertically from stroke to stroke. A new reciprocating head was manufactured out of aluminum (according to a drawing supplied by Phoenix Tribology Ltd). This reduced the reciprocating head mass by 64 grams and allowed the minimum external load to be lowered to 100 grams.

Finally, the high precision pins arrived from JTEKT N.A., and these three changes allowed the program to continue with much better results.

A new set of tests was run with constant stroke (5mm), frequency (10Hz), and sliding distance (225m). From 100 to 300 grams both the F-24 and FT-SPK were run and the results are presented in Figure 13. Light load comparison of baseline fuels' wear response.

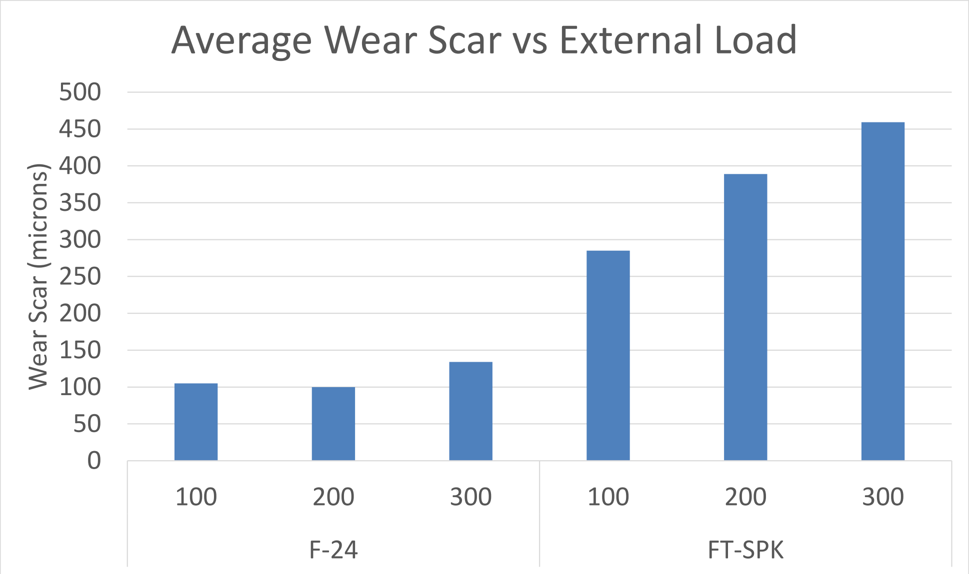

Figure 13. Light load comparison of baseline fuels' wear response

At 300 grams of load, there is now a 70% reduction in wear scar from the FT-SPK to the F-24. This is much more than the differences in HFRR, BOCLE, and SL-BOCLE as reported in Table 5 of IR437 (if F-24 and fully additized Jet A-1 can be assumed similar).

In addition, the EOT contact pressures now span a range from 0.8 to 6.5 MPa.

The HFRR-LC also has the ability to capture real time friction, noise, and film thickness data. It was the film thickness data that led to the selection of the final criteria. As seen in Figure 14, the FT-SPK experienced a dramatic collapse in film thickness at a load of 300 grams.

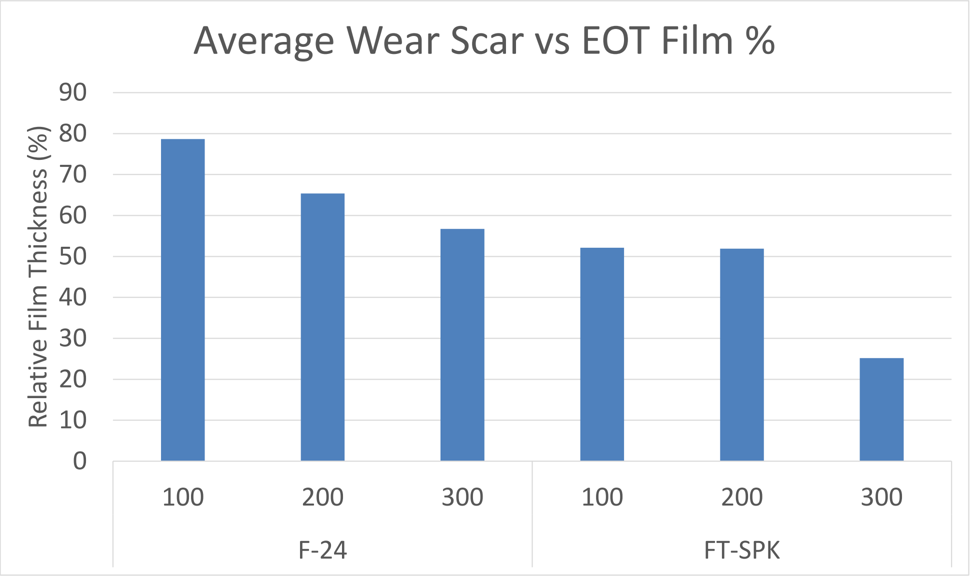

Figure 14. Light load comparison of baseline fuels' film thickness

Figure 15 and Figure 16 show what this difference in film thickness looked like over the course of 1 test each for F-24 and FT-SPK. The F-24 quickly builds a relative film thickness of 55% while the FT-SPK struggles to get to 20%. This shows that the thin film allows more physical contact, and thus wear, between the upper and lower specimens.

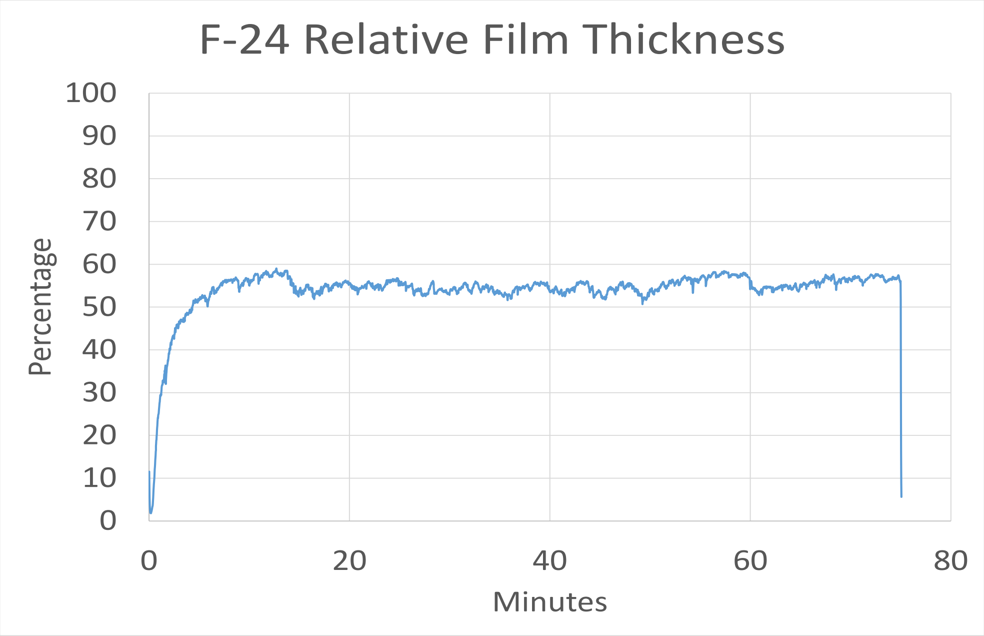

Figure 15. F-24 film thickness at 300 grams

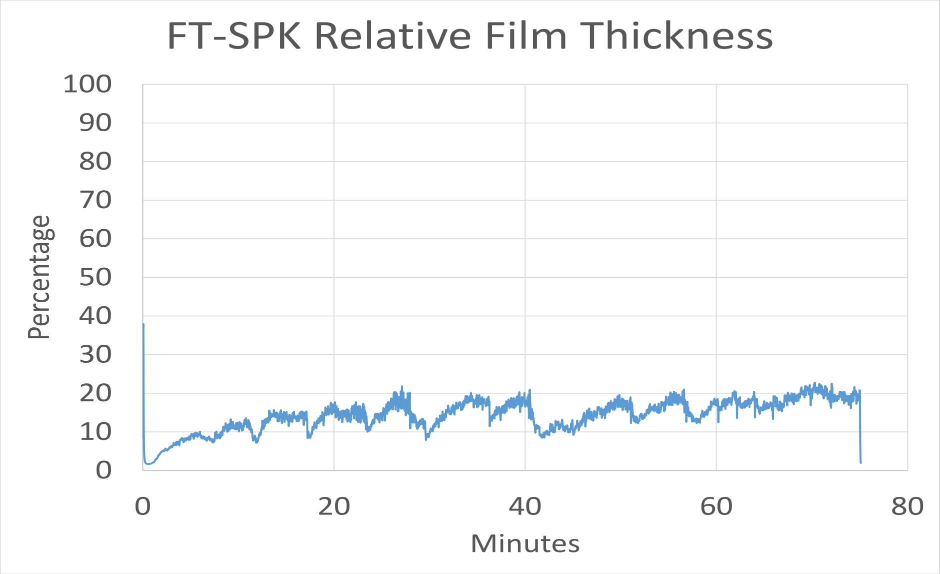

Figure 16. FT-SPK film thickness at 300 grams

For these two fuels (F-24 and FT-SPK) at the 300 gram load point, it was useful to compare the characteristics of the entire wear scars of both the pins and plates. Figure 17, Figure 18, and Figure 19 show the wear scar for FT-SPK, exhibiting both abrasive and oxidative wear. Figure 20, Figure 21, and Figure 22 show the wear scar for F-24, exhibiting only abrasive wear.

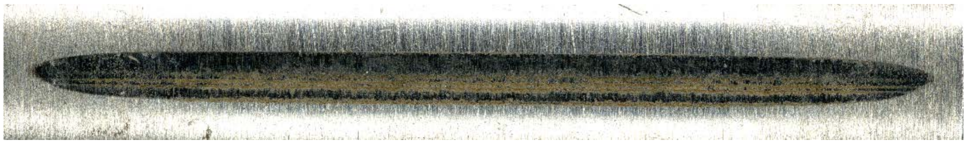

Figure 17. FT-SPK showing an 8.9mm x 513 micron wear scar

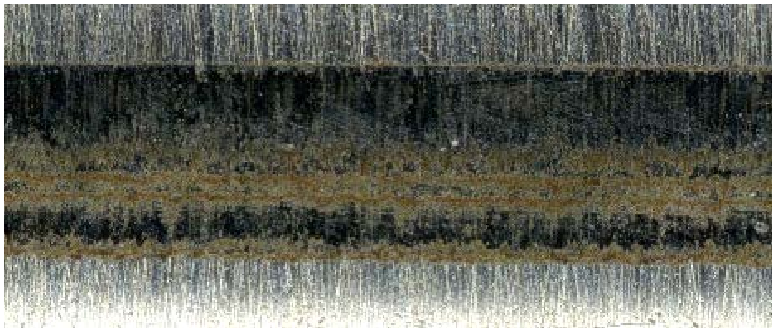

Figure 18. Close in view of the FT-SPK scar at the midpoint

Figure 19. FT-SPK wear marks on the disk

The FT-SPK showed a maximum wear scar width of 513 microns on the pin, which removed more than 7 microns of material depth, given the 6mm diameter. The scar on the disk however was less than 0.2 microns deep at the end of the 5mm stroke.

Figure 20. F-24 showing a 5.8mm x 133 micron wear scar

Figure 21. Close in view of the F-24 scar at the midpoint

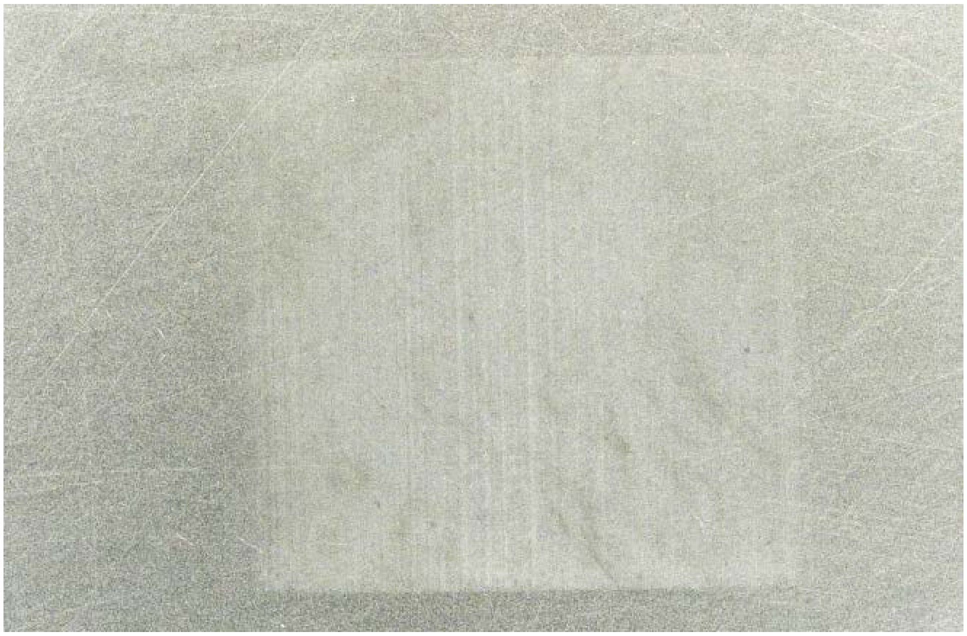

Figure 22. F-24 wear marks on the disk

The F-24 showed a maximum wear scar width of 133 microns on the pin, which removed less than 1 micron of material depth, given the 6mm diameter. The scar on the disk showed no measureable wear, and only a slight change in surface roughness.

Both of these wear scar analyses shows that the wear is significantly biased toward the pin (which is the part proposed to be measured in the HFRR-LC test method) as opposed to the standard HFRR which usually exhibits more wear on the disk than on the ball due excessively high initial contact pressure.

It can also be observed that the scars on the pins do not traverse the entire length, this is due to a slight design curvature in the JTEKT N.A. parts. This leads to an increasing scar length (along the pin length) with increasing scar width (severity of the test result). However, this is still a realistic result that produces an easy to measure wear scar (width at the midpoint of the pin) and a contact area that can be easily estimated to produce reasonably confident EOT contact pressures. For these cases, the FT-SPK gave an EOT contact pressure of 0.91 MPa, and the F-24 gave 5.39 MPa. Since contact pressure scales inversely with wear scar size, it can be inferred that the load carrying capacity of the F-24 fuel is more than 5 times higher than that of the FT-SPK.

The next step was to run these test conditions on an intermediate performing fuel that had been treated at various rates with CI/LI. The nomenclature in Figure 23 is the base fuel name plus the treat (or not) in ppm. At 4ppm a 40% reduction in wear scar was observed. At 8 ppm a 52% reduction in wear scar was observed. When compared to Table 5 of IR437, this is a dramatic improvement over the HFRR and BOCLE ratings, and a moderate improvement over the SL-BOCLE ratings.

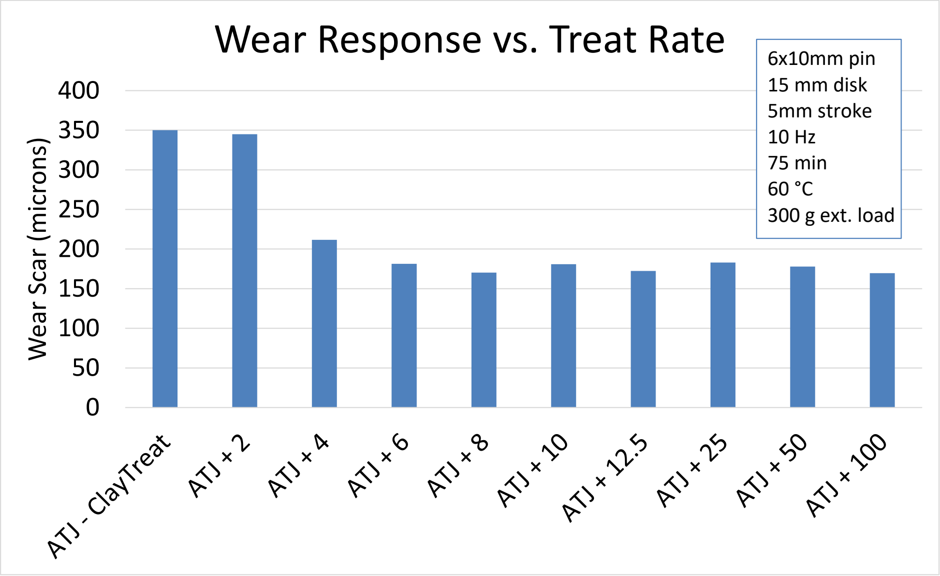

Figure 23. Wear response vs treat rate for proposed test conditions

For visual comparison of the wear scars, Figure 24 and Figure 25 show the difference between the neat fuel and the 8ppm treat rate fuel.

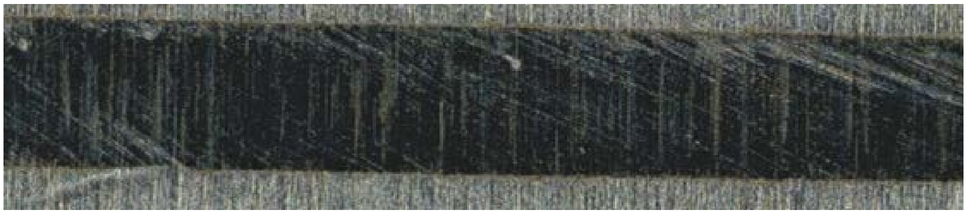

Figure 24.Clay Treated ATJ showing 362 micron wear scar

Figure 25: ATJ w/ 8ppm CI/LI showing 169 micron wear scar

In order to verify the proposed test conditions were correct, some parameter sweeps were performed around the target conditions to judge sensitivity of the wear response. In Figure 26, the wear response is shown for the ATJ fuel at various treat rates and 3 different external loads. The results demonstrate a slight widening of the plotted wear curve from 4 to 8 ppm. This technique may be useful in determining the load carry capacity of different types of additives. For the same data set, end of test coefficients of friction (EOT COF) were compared in Figure 27, and it was found that while increasing load gave the expect result of decreasing COF, it was also found that for a given load, treat rate had no significant impact.

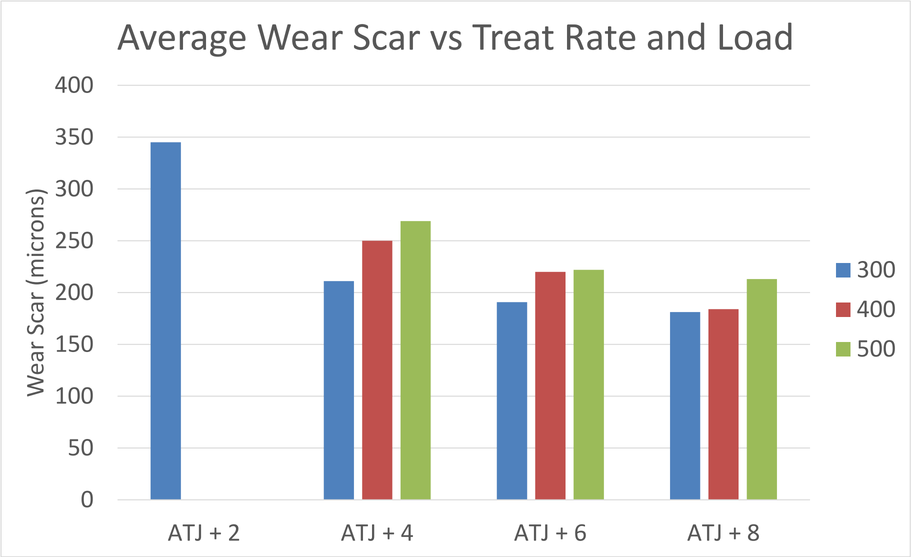

Figure 26: Wear Scar vs Load Sweep

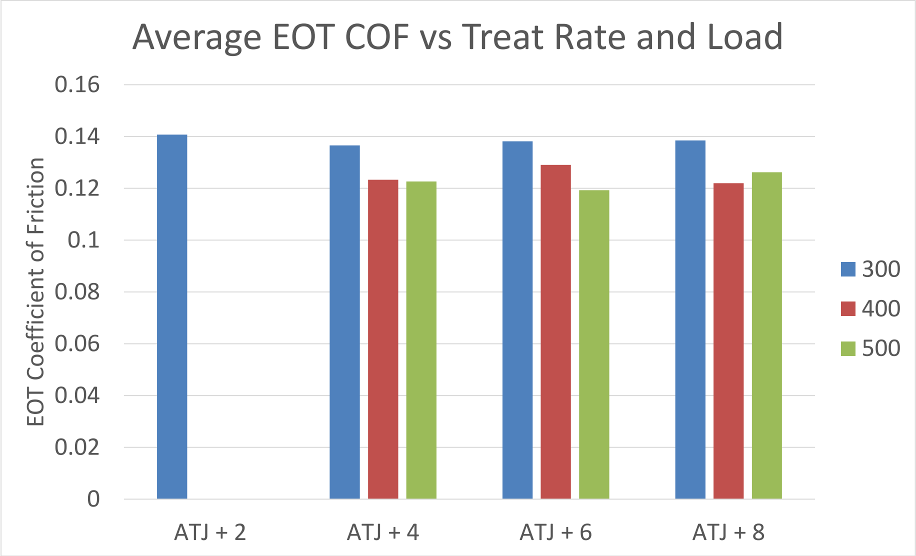

Figure 27: Friction vs Load Sweep

The second parameter sweep performed was with temperature. Figure 28 shows the results for the same additive treat rates, and the nominal test conditions, but at 3 different temperatures. The results demonstrate that there is no apparent wear impact of a decrease in fuel viscosity (driven by increasing temperature) for this test method. This means that the wear result for this base fuel is driven by the chemical surface film created by the CI/LI and its corresponding treat rate. This is not to say that the viscosity of the fuel did not change with temperature, which it did, and is shown evidence of in Figure 29. It just means that the slight decrease in physical film thickness did not have an impact on the performance of the chemical film in regards to wear protection. It is also interesting to note that for a given temperature, treat rate did not impact the EOT film thickness measurement.

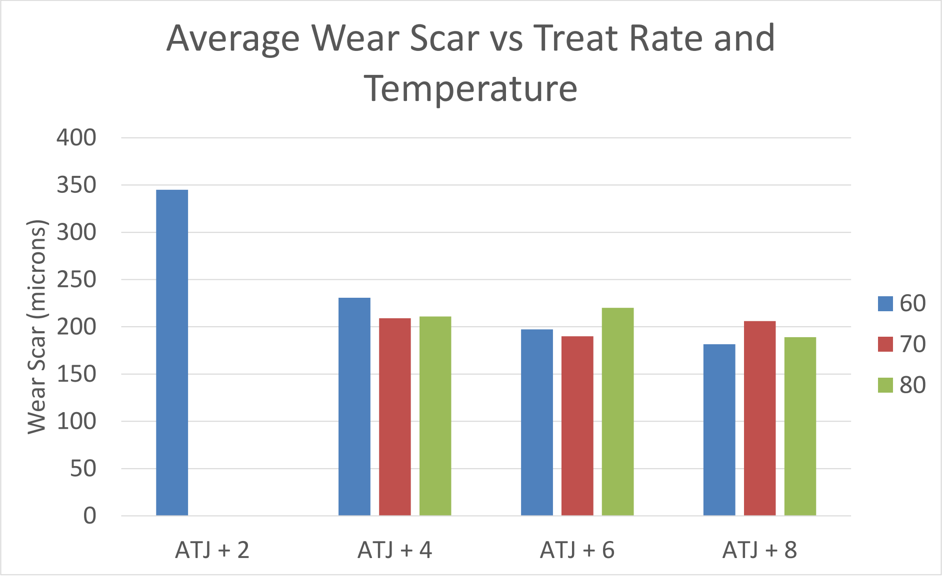

Figure 28: Wear Scar vs Temperature Sweep

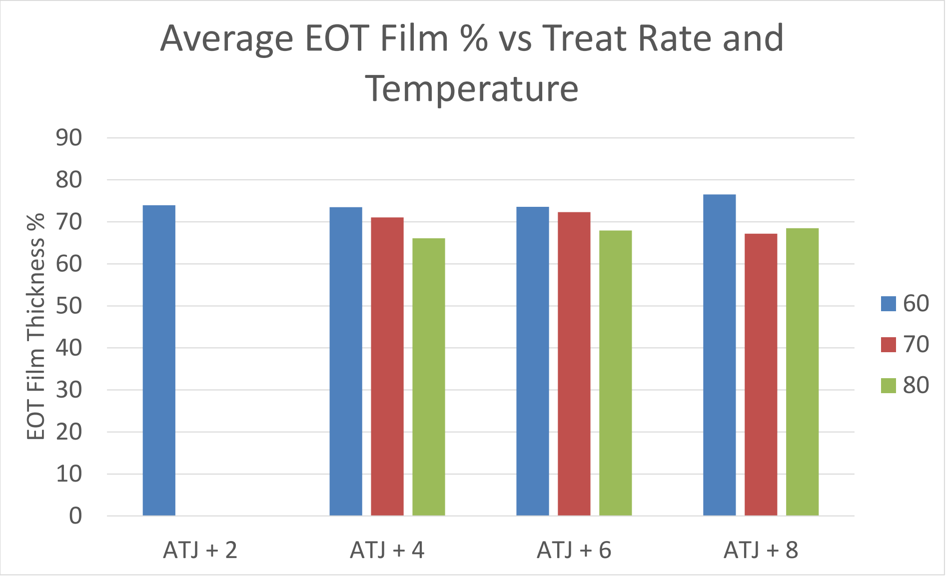

Figure 29: Film Thickness vs Temperature Sweep

6.0 TEST METHOD

6.1 RIG PREPARATION

Both the bath (lower specimen carrier) and the reciprocating head (upper specimen carrier) was cleaned prior to every test in a 50/50 mixture of propanol and iso-octane. To avoid frequent removal of the reciprocating head, it was cleaned in place. After cleaning the reciprocating head, and to promote drying of the crevices, it was rinsed with heptane.

If the current test to be run utilized a different fuel than the previous test, approximately 250 mL of a 50/50 mixture of propanol and iso-octane was run through the pump and supply lines. Then 250 mL of the current test fuel was run through the pump and supply lines. This ensured that there was no carryover in either additive or base fuel from the previous run.

6.2 SPECIMEN PREPARATION

Prior to testing, both the upper and lower specimens were cleaned in a 50/50 mixture of isopropyl alcohol and iso-octane for 2 minutes. The specimens were dried in air. All cleaned specimens should be handled with gloved hands to prevent contamination prior to testing.

6.3 TEST PARAMETERS

These are the final proposed HFRR-LC test parameters for evaluating the lubricity of military ground fuels and their additives.

Stroke: 5mm ±0.01mm
Frequency: 10Hz ±0.05Hz
Test Duration: 75min ±2sec
Temperature: 60 °C ±0.2 °C
Load: 300 grams external weights ±1g
Flow rate: 2mL/min ±0.1mL/min

6.4 EVALUATION

The pin scar was evaluated on a calibrated optical microscope and the scar width was measured at the approximate midpoint as indicated by visual inspection. For test specimens aligned properly, the scar width should be constant for several millimeters around the midpoint of the scar.

If the scar on the pin is observed to have a left-to-right or right-to-left taper, the test head was improperly aligned and the test should be re-run. Similar observations of correct or incorrect test operation can also be observed in the wear pattern on the disk.

7.0 REPEATABILITY ANALYSIS

For the fuels tested, a repeatability analysis was performed (Figure 30). Each fuel type (or additive treat rate) was tested between 5 and 9 times. It was found that all fuels had less than 30 microns of standard deviation in the wear scar measurement, and most fuels had less than 10% coefficient of variation. For most of the fuels tested, the variation in wear scar result increased with increasing wear scar size.

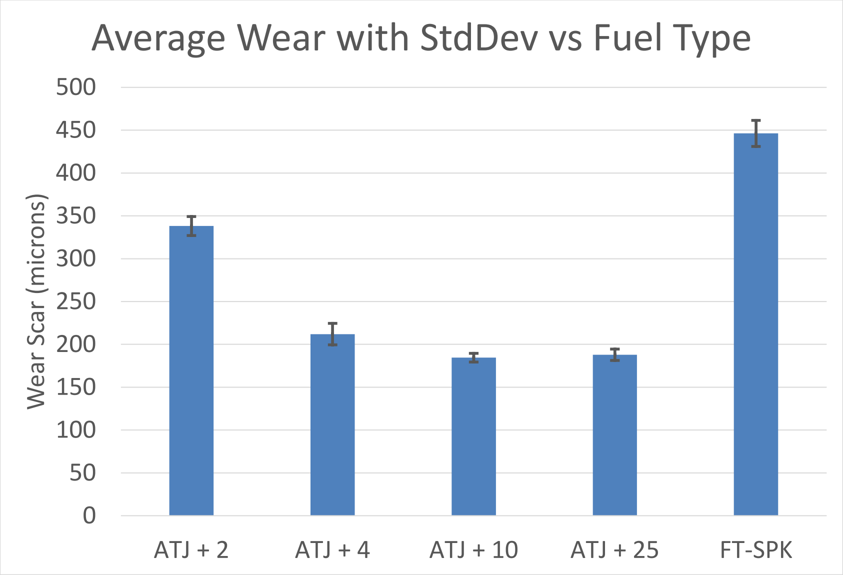

Figure 30: Repeatability analysis of test fuels

7.1 OTHER MILITARY FUELS

At the end of this testing program several additional military fuels were evaluated using both the recommended HFRR-LC procedure (Figure 31), and a load sweep (Figure 32). This was done to verify procedure compatibility with available diesel engine fuels (fuel on hand at SwRI). The HFRR-LC procedure was run 5 times for each fuel. The fuels used were:

- CHCJ-5, fully treated as used in testing by TFLRF [8]
- F-76, downgraded from JP-5, supplied by US Navy, sample # 7152C727
- Jet-A, untreated as used in IR437
- ULSD, untreated as used in IR437

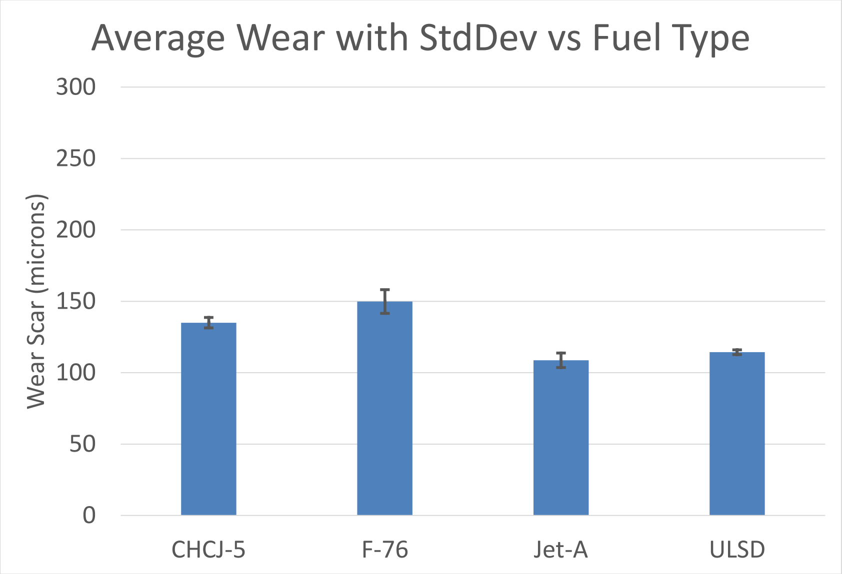

Figure 31: Wear results for other diesel engine fuels

All 4 fuels show baseline lubricity results that are both comparable to F-24 and better than ATJ at maximum treat rate (as presented earlier in this report).

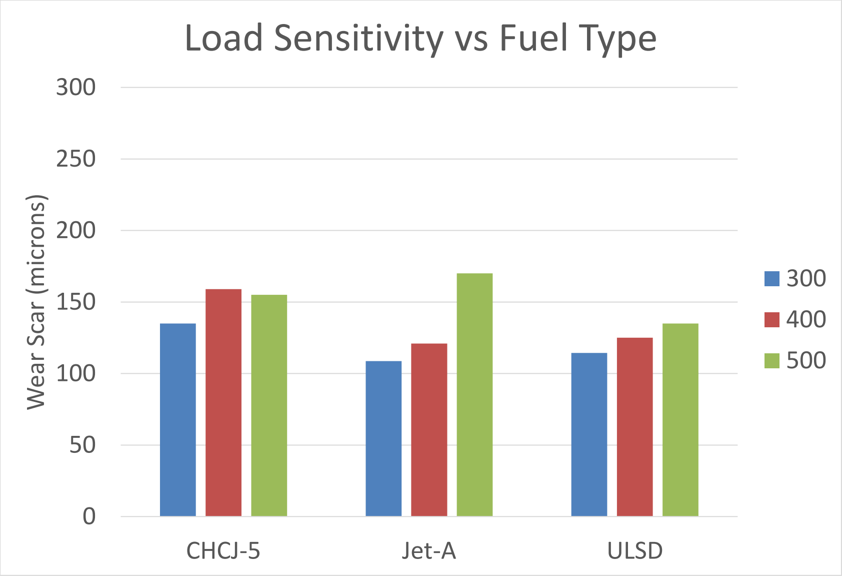

Figure 32: Load sensitivity of other diesel engine fuels

The load sensitivity shows that the CHCJ-5 and ULSD have more linear wear response than the Jet-A. While the untreated Jet-A exhibited the lowest wear scar at 300 grams, it also had the largest wear scar at 500 grams.

8.0 CONCLUSIONS

A new test method has been developed that is able to better differentiate low levels of lubricity additive in military ground fuels than any of the currently published methods.

In determining the operating parameters for this test, it was discovered that:

- Fuel viscosity does not play a significant role in the wear results.
- Reciprocating frequency does not play a significant role in the wear results.
- Too high of a load can reduce differentiation between known good and poor performing fuels.
- Too long of a test (total sliding distance) can reduce differentiation between known good and poor performing fuels.
- A long stroke length biases wear towards the pin (object of evaluation).
- Both mild (abrasive) and severe (oxidative) wear regimes can be observed using the same test conditions, but different test fuels.

For a more comprehensive comparison with fuel pump operation, it may be useful to run a series of HFRR-LC tests with varying initial loads to span the entire range of expected contact pressures.

9.0 REFERENCES

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