

## Development and Laboratory Evaluation of On-Board Oil Condition Monitoring Sensors for HMMWV Diesel Engines

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**Abstract:** This paper describes a project to investigate the feasibility of developing a prototype sensor system for on-board monitoring of diesel engine oils. The successful application of the sensor system to US Army vehicles would increase the confidence determination of the condition of in-service oils while reducing the number and cost of oil samples submitted to the Army Oil Analysis Program (AOAP) laboratories for extensive testing. The research described herein determined that the used oils obtained from High Mobility, Multipurpose Wheeled Vehicle (HMMWV) diesel engines had low levels of antiwear/antioxidant additives (RULER™ instrument analyses) resulting in increased levels of oxidation and contributing to accelerated wear rates. A sensor system combining a viscosity sensor with a voltammetric oil condition sensor detected all of the abnormal oil samples (high levels of water, soot, wear metals and oxidation) included in this investigation, and thus, has potential for development into an on-board oil condition monitoring sensor for HMMWV and other vehicle diesel engines. Additional sensors for monitoring soot and other suspended debris (wear, dirt, etc.) would further increase the monitoring capabilities of the on-board oil condition sensor system. Although the sensor technologies described herein were designed specifically for monitoring the condition of diesel engine lubricants, they also have potential for monitoring other vehicle fluid systems such as automatic transmission fluids and axle gear oils.

**Keywords:** antioxidant analyses, dielectric sensors, diesel engine oils, FTIR, HMMWV, oil condition monitoring, on-board sensors, RULER™, viscosity, voltammetric sensors

**Introduction:** Currently, the US Army changes oil based on condition, not mileage. In active Army units, oil samples from engines are typically obtained every 60 days/25 hours from operating and stored combat equipment and every 90 days/100 hours from tactical wheeled equipment. The samples are sent to regional AOAP laboratories that use rotating disk electrode atomic emission spectrometers and Fourier Transform Infrared

(FTIR) spectrometers to evaluate the condition of each submitted oil sample. Based on the AOAP laboratory analyses, recommendations such as continue routine sampling (normal), resample immediately (abnormal), perform oil change (abnormal), etc. are made. Since an estimated 95% of the approximately 1.3 million used oil samples analyzed per year are determined to be normal by AOAP laboratory analysis, prescreening the sampled oils with on-site or on-board analyses would significantly reduce the number of submitted samples and thus reduce the annual operating costs of the AOAP. Providing a predetermined condition/problem for each submitted sample would aid the AOAP laboratory in selecting the most pertinent analyses to be performed while increasing the accuracy and precision of the condition determinations of the in-service oils.

Therefore, research was performed to identify sensors suitable for development into an on-board condition monitoring sensor system for in-service diesel engine oils. An on-board sensor system is preferred to an on-site screening device since the on-board system could provide continuous oil condition outputs without sampling, labor and human error.

The research was performed in two main phases. The first phase involved a literature search to identify sensors capable of on-board oil condition monitoring diesel engines. As the sensors were identified, they were tested and optimized in the laboratory with new diesel engine oils containing contaminants expected to be present in used diesel engine oils. The second phase of the research was the laboratory evaluation of the optimized sensors with used oil samples obtained from the diesel engines of military vehicles. The used oils were identified as abnormal and normal samples by AOAP laboratories and were supplied with vehicle information and analytical results.

**Literature Search Introduction:** For a sensor to be suitable for monitoring the condition of an in-service diesel engine oil, it must monitor either additive depletion, accumulation of degradation products and/or build-up of contaminants. Additionally, on-board use requires that the sensor must be easy and inexpensive to operate; be inexpensive to construct or purchase; be rugged, reliable and rapid; be able to differentiate contaminants and be suitable for miniaturization. Numerous sensors with potential to monitor additive depletion or degradation product/contamination accumulations were identified during the literature search [1]. The majority of the identified sensors were not commercially available for on-board use or for laboratory testing during this project. The following sensors were studied during this project.

*Voltammetric Sensors.* The voltammetric sensor [1,2] monitors oxidation by applying a low frequency, small voltage waveform to two Ni posts (2 mm dia. and gap) or an array of Ni lines (115 micron width and spacing) on a polyimide film inserted into an oil sample. The output (current converted to voltage prior to output) of the voltammetric sensor is indirectly proportional to the condition of the analyzed oil, i.e., output increases as condition decreases. In initial tests [1], both voltammetric sensors indirectly detected water levels above 0.2% (by weight) after 48 hours (additive degradation), while the array sensor directly detected water levels above 0.5% (by weight), in fresh diesel engine oil.

*Dielectric Sensor.* Commercial sensors have a single, cylindrical electrode (15 mm dia.) that is inserted into the oil sample to measure the dielectric constant [3]. Used oil and contaminants such as water, coolant, soot and acids from oxidation have higher dielectric constants than new oil. As the contaminants increase in the used oil, the dielectric constant increases. As a rule of thumb for dielectric measurements, an increase of 0.02 in the dielectric constant is negligible while a 0.08 change is considered very large [3]. In initial tests [1], the dielectric sensor was able to detect water concentrations above 0.8% (by weight) in fresh diesel engine oil in agreement with the literature.

*Viscosity Sensor.* Since viscosity increases with severe oxidation, decreases with fuel dilution and changes if incorrect grade oil is used to top-off the in-service oil, viscosity sensors were evaluated. Viscosity sensors (rotating spindle [4] and sound waves [1]) were into the oil sample to measure the absolute viscosity. In initial tests [1], the viscosity sensors were able to detect diesel and Jet A fuel concentrations above 2.5% (by weight).

*Vapor Sensor.* A commercial vapor sensor based on a heated tin dioxide ( $\text{SnO}_2$ ) that is sensitive to organic (fuel) vapors above the oil was also tested [4]. When the fuel vapor contacts the  $\text{SnO}_2$  element, the resulting current is proportional to the concentration of fuel in the vapor phase. Sensors based on polymer changes due to exposure to organic vapors were also identified [1] but not considered for this work due to temperature and sensor life concerns. In initial tests [1], the  $\text{SnO}_2$  vapor sensor was able to detect diesel and Jet A fuel concentrations above 5% (by weight) in a fresh diesel engine oil.

*Particle and Wear Debris Sensors.* Ferrous, nonferrous and nonmetallic debris sensors (magnetic, inductive, conductive screen, etc.) were considered for this work [5]. Sensing pressure drops across filters to monitor particle loading was also considered for this work [1]. Initial tests of on-board debris sensors were not performed during the research described here-in.

**Used Oil Sample Evaluations of Sensors: *Used Oil Characterization.*** To evaluate the capabilities of the identified sensors to monitor the condition of in-service diesel engines oils, used oil samples removed from HMMWV and other tactical vehicles were obtained from AOAP labs at Ft. Hood and Ft. Campbell. Of the 22 samples received from the AOAP labs, 11 samples were considered abnormal and 11 samples were considered normal. The paperwork detailing the vehicle and oil types, physical/chemical analyses and FTIR analysis were included with each used oil sample to allow the condition and contamination level of each oil sample to be recorded. The sample number (assigned by AOAP), equipment type, spectrometric iron concentration, and FTIR ratings for soot and water are listed in Table I for the normal (NM) used diesel engine oil samples. The same information plus AOAP lab comments are listed in Table II for the abnormal (AB) used oil samples. The information listed in Tables I and II indicates that the used oil samples represent a wide range of oil conditions and contamination levels and that the samples were obtained from the diesel engines of several types of vehicles.

TABLE I  
NORMAL USED DIESEL ENGINE OIL SAMPLES FROM AOAP \*

Sample No.	Equipment Type	Fe (ppm)	FTIR Rating	
			Soot	H <sub>2</sub> O
NM284	Truck, 5 Ton	66	0	15
NM632	HMMWV, Truck, Utility	241	21	13
NM634	HMMWV, Truck, Utility	133	0	12
NM635	HMMWV, Truck, Utility	168	18	14
NM636	HMMWV, Truck, Utility	161	11	18
NM638	HMMWV, Truck, Utility	172	4	14
NM639	HMMWV, Ambulance	136	3	20
NM644	Truck, 5 Ton Cargo	114	5	11
NM646	Truck, 5 Ton Wrecker	28	0	10
NM705	HMMWV, Truck, Utility	180	10	15
NM5343	HMMWV, Utility Truck	465	17	13

\*Sampled September 2000      \*\* (Karl Fisher analysis, % water by weight)

The data in Table II indicates that all of the abnormal samples from HMMWV diesel engines (except AB869, 12% water) contain much higher levels of iron wear debris than the abnormal samples from diesel engines of the other vehicles. Of the normal samples, only sample NM5343 (HMMWV) in Table I contains a high level of iron.

The data in Table II also indicates that used oil sample (AB1113) was abnormal due to fuel contamination and that two used oil samples (AB1474 and AB1989) were abnormal due to high levels of non-iron (Cr and Pb) metal concentrations. The lab comments in Table II indicate that FTIR analysis detected excessive water in three abnormal samples (AB869, AB1064 and AB2297) and detected excessive soot in three other abnormal samples (AB706, AB5354 and AB5388).

TABLE II  
ABNORMAL USED DIESEL ENGINE OIL SAMPLES FROM AOAP \*

Sample No.	Equipment Type	Fe (ppm)	FTIR Rating		Comments
			Soot	H <sub>2</sub> O	
AB706	Carrier, Personnel	164	51	12	Soot, Hot
AB869	HMMWV, Truck, Utility	40	8	677 (12%)**	Resample
AB871	HMMWV, Truck, Utility	480	27	16	Unknown
AB1041	HMMWV, Truck, Utility	589	35	14	Fe, Pb
AB1064	Truck 2 ½ Ton Cargo	107	5	85 (0.12%)	Unknown
AB1113	Tractor, Full track	67	14	24	Fuel
AB1474	HMMWV, Truck, Utility	280	21	18	Cr, Pb
AB1989	HMMWV, Truck, Utility	445	10	13	Pb
AB2297	HMMWV, Truck, Utility	998	17	225 (1.6%)	Fe
AB5354	Tractor, 5Ton	61	75	19	Soot
AB5388	HMMWV, Truck, Utility	472	51	15	Soot, Oxid.

\*Sampled September 2000      \*\* (Karl Fisher analysis, % water)      Oxid.: Severe Oxidation

Abnormal FTIR Ratings in Table II: Soot >50 and Water >65

Therefore, the results in Tables I and II indicate that the abnormal used diesel engine oil samples received for this project had experienced one or more of the following problems: water/coolant contamination (3 samples), fuel contamination (1 sample), soot accumulation (3 samples), severe oxidation (1 sample), high iron concentration (4 samples) and high non-ferrous metal content (4 samples).

*RULER™ Analyses of Used Oil Samples.* The RULER™ [2,6] is a hand-held instrument that performs voltammetric analyses to determine the antioxidant concentration, total base number and total acid number of alcohol diluted oil samples. The RULER™ was used in this project to provide additional information on the used oil samples in Tables I and II to better understand the results of the identified sensors. The % remaining zinc dialkyl dithiophosphate additive (ZDDP - oxidation/wear inhibitor) of each used oil sample was measured with the RULER™. The RULER™ analyses were made using normal sample NM636 (Table II) as the 100% standard because new oil samples were not available and NM636 had the highest ZDDP level and lowest soot/iron levels (lowest usage) of the tested oils. In Figure 1, the ZDDP concentration (RULER™) was plotted versus the iron concentration for each used diesel engine oil to study the relationship between antioxidant depletion/oil degradation and wear (iron) rate.

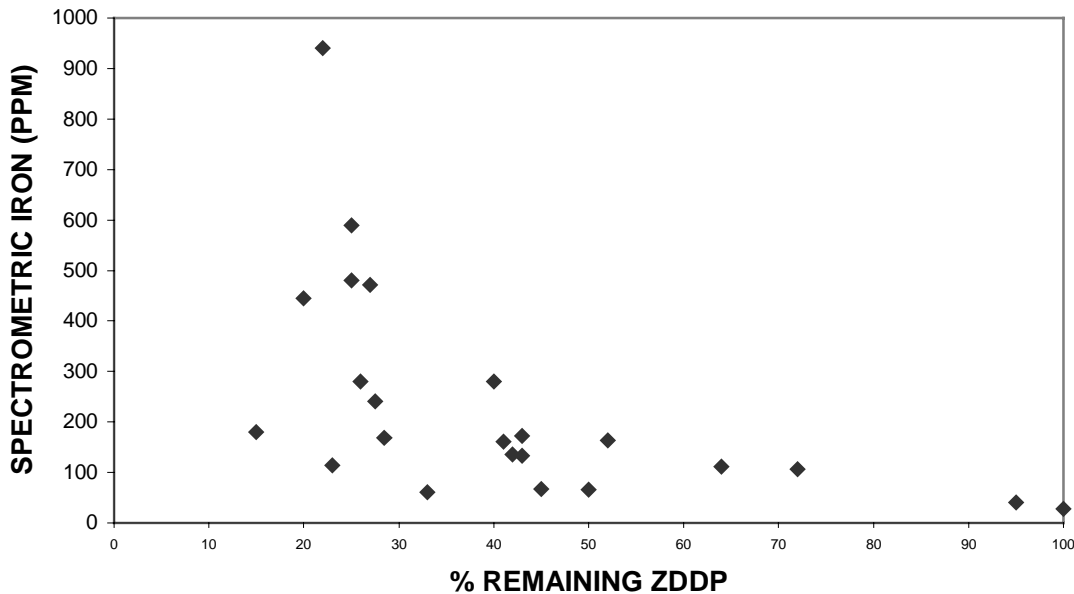


Figure 1. Plot of Spectrometric Iron (AOAP) Versus % Remaining ZDDP Additive (RULER™) for Used Diesel Engine Oils. NM636 Used as 100% ZDDP Standard.

The plot in Figure 1 indicates there is a strong relationship between ZDDP depletion and iron concentration for used diesel engine oils regardless of equipment type, i.e., iron concentration increases with ZDDP depletion. Knowledge of the hours since oil change for the sampled engines would also allow any relationships between ZDDP depletion rate and wear rate to be defined (ZDDP depletion rate may also be more important in determining wear rate as is the case for spectrometric metal analyses).

In agreement with other research [7], the results in Figure 1 and Tables I and II indicate that the used oil samples containing high iron concentrations obtained from the HMMWV diesel engines were likely due to accelerated wear rates resulting from depleted ZDDP concentrations.

*Viscosity Measurements of Used Oil Samples.* The viscosities of the used oil samples in Tables I and II did not show a trend with oil condition [1]. Overall, sample AB5388 had the highest viscosity (abnormal due to oxidation and soot) while sample AB1113 had the lowest viscosity (abnormal due to fuel contamination). The viscosities of the used oil samples indicate that an on-board viscosity sensor would be successful in identifying in-service oils undergoing fuel dilution (decreased viscosity) or severe oxidation (increased oxidation). Also the on-board viscosity sensor would be capable of detecting oil top-offs with oils of incorrect viscosities. Representative new oils for the sampled vehicles were not available for comparison to the used oil samples to improve the capability of the viscosity sensor to detect small changes/trends produced by abnormal conditions.

*Vapor Sensor Readings of Used Oil Samples.* During laboratory tests [1], the SnO<sub>2</sub> vapor sensor was sensitive to additions of diesel and jet fuels to new diesel engine oil for fuel levels well below 5%. Since 5% fuel dilution is the condemning limit set by AOAP, the vapor sensor appeared well suited for detecting fuel dilution in used oil samples. However, the SnO<sub>2</sub> vapor sensor was not sensitive to fuel dilution in actual used oil samples. Abnormal sample AB1113, identified by AOAP as containing excessive levels of fuel, had one of the lower vapor sensor readings. The abnormal used oil samples had the lowest vapor sensor readings (volatiles, low ends of basestock removed by use).

The results indicate that the SnO<sub>2</sub> vapor sensor is not capable of detecting fuel dilution in actual used oil samples as opposed to the laboratory results. In addition to the poor performance with the used oil samples, the vapor sensor appeared to have poor repeatability during laboratory tests [1] and would require the most engine modifications for on-board operation. Therefore, since the viscosity measurements detected the used oil samples with fuel dilution, the SnO<sub>2</sub> vapor sensor was eliminated from further consideration as a potential on-board sensor.

*Dielectric Sensor Readings of Used Oil Samples.* The dielectric sensor is reported [1,3] to be sensitive to oxidation, soot, water and coolant accumulation in used oil samples. The room temperature (70°F) dielectric sensor readings for the used diesel engine oil samples are illustrated as bar graphs in Figure 2. Since the new oils were not available to calibrate the dielectric sensor, the dielectric reading (2.31) of normal sample NM646 (highest percent remaining ZDDP in Figure 1) was selected as representative of a new oil dielectric reading. A dielectric reading above 2.39 (2.31 + 0.08, since 0.08 change considered significant [3]) is considered abnormal in Figure 2.

Using the 2.39 reading as abnormal in Figure 2, the dielectric sensor successfully detected the three samples with excessive water and two of the three samples with high soot levels (Table II). Overall the dielectric sensor readings are slightly higher for the abnormal samples than for the normal samples regardless of vehicle type. The results in Figure 2

indicate that the dielectric sensor has limited potential for on-board monitoring of in-service oils used in HMMWV and other type vehicles. Calibration with new oils representative of the diesel engine oils used at Fort Hood and Fort Campbell would most likely improve the accuracy of the dielectric sensor results.

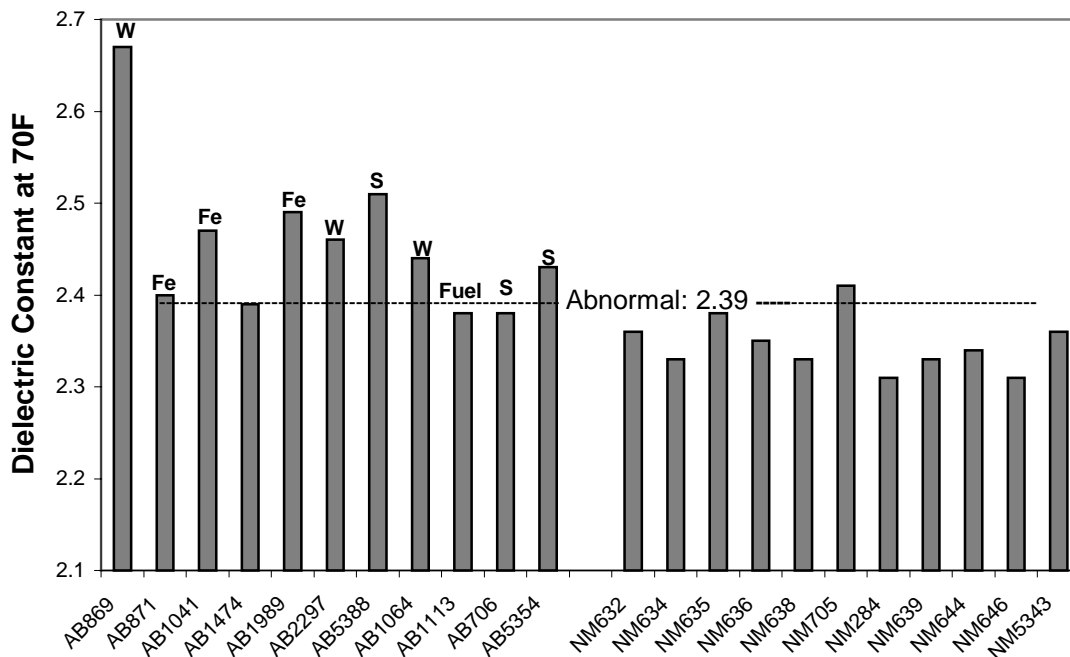


Figure 2. Plot of Dielectric Constants for Used Diesel Engine Oils Measured at 70°F.  
On Graph, Fe: High Iron > 450 ppm, W: High Water and S: High Soot by FTIR.

**Voltammetric Measurements of Used Oil Samples.** The last type of sensors to be evaluated for development into on-board sensors are referred to as voltammetric sensors. The voltammetric sensors use two Ni posts (3mm diameter/gap) or an array of Ni lines (line width/spacing - 115 microns) on a polyimide film [1,2]. The room temperature (70°F) results for the voltammetric array and post sensors are shown in Figures 3 and 4, respectively, for the abnormal and normal used diesel engine oil samples. For Figures 3 and 4, an abnormal reading is 20% above the reading for normal sample NM646 (highest percent remaining ZDDP in Figure 1)

The results in Figure 3 indicate that the voltammetric array sensor is very sensitive to water/coolant contamination (AB869, AB2297, and AB1064). The AB1113 sample containing fuel produced the next highest voltammetric readings with the array sensor. The array sensor produces similar readings for the majority of the abnormal and normal used oil samples in Figure 3, i.e., low potential for condition monitoring. In contrast to the array sensor, the voltammetric post sensor measurements at room temperature in Figure 4 are much higher for the abnormal samples than the normal samples regardless of the vehicle type sampled. Although the samples with water/coolant contamination still produce the highest readings in Figure 4, the percent increases due to water/coolant are much smaller for the voltammetric post sensor than the voltammetric array sensor.

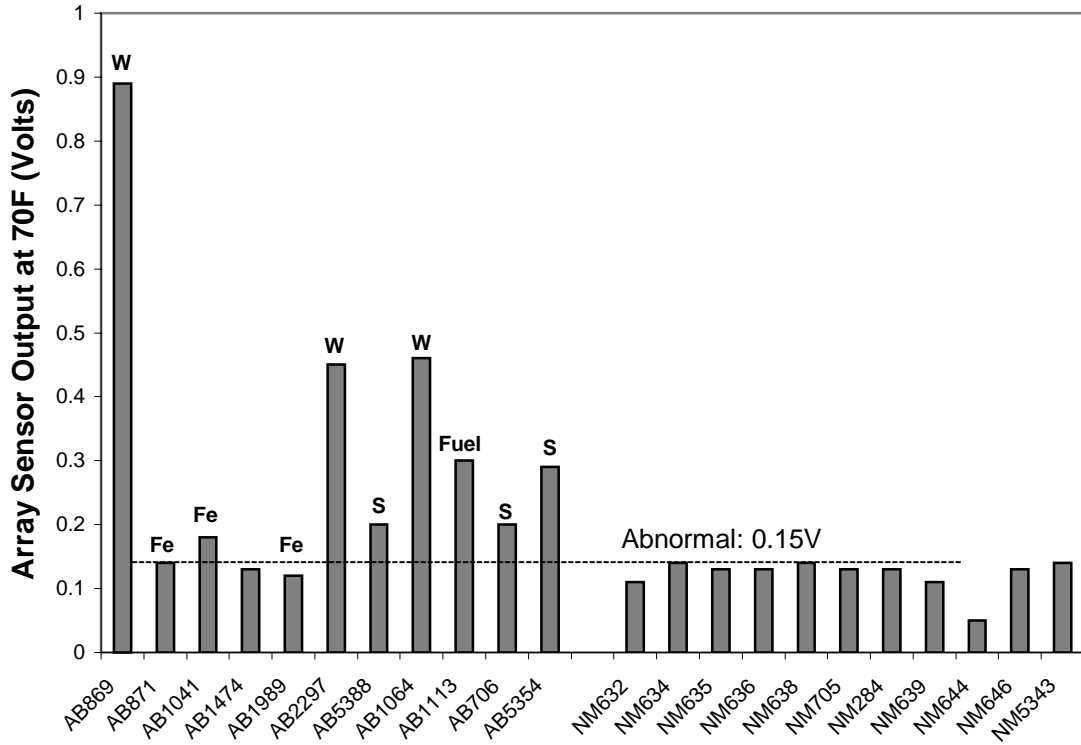


Figure 3. Plot of Voltammetric Array Sensor Outputs at 70°F for Used Diesel Engine Oils. On Graph, Fe: High Iron, W: High Water and S: High Soot by FTIR. Voltammetric Abnormal Reading: 0.15V = 120% of NM646 Reading.

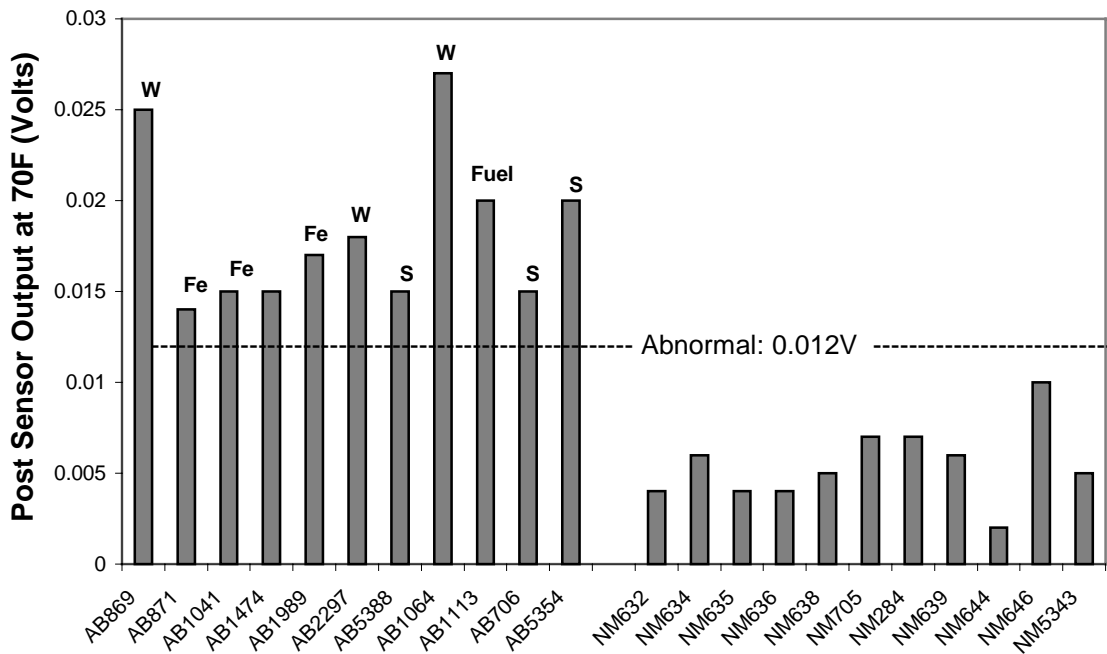


Figure 4. Plot of Voltammetric Post Sensor Outputs at 70°F for Used Diesel Engine Oils. On Graph, Fe: High Iron, W: High Water and S: High Soot by FTIR. Voltammetric Abnormal Reading: 0.012V = 120% of NM646 Reading.

The voltammetric measurements of the used oil samples were also performed at 170°F (70°C) to simulate engine operating temperatures. However, heating the used diesel engine oil samples degraded the used oil samples, i.e., the room temperature voltammetric and dielectric readings increased dramatically after heating for 1 hour at 170°F (70°C). It is believed that water accumulation during 1 year storage (confirmed by Karl Fisher water analyses) degraded the additives in the used oil samples as was seen previously during water contamination tests [1]. The presence of water also explains the inability of the dielectric and voltammetric array sensors to distinguish between normal and abnormal used oil samples since the sensors are very sensitive to water (Figures 2 and 3).

Even without the high temperature results, the results in Figures 3 and 4 indicate that the voltammetric Ni array on polyimide film sensor is very sensitive to water/coolant and fuel contaminations and the voltammetric Ni post sensor is very sensitive to additive degradation/oil oxidation as well as fluid contamination. The voltammetric Ni post sensor is the only sensor tested to date that correctly categorized all of the used oil samples as abnormal or normal regardless of vehicle type. Therefore, a sensor system combining an on-board viscosity sensor (identify fuel contamination) with an on-board voltammetric sensor(s) has the best potential to date for on-board oil condition monitoring of in-service oils used in the diesel engines of HMMWV and other vehicles.

*Soot and Particle Analyses of Used Oil Samples.* Although commercial sensors capable of detecting soot, particles (dust, organic, debris, etc.) and iron/metallic debris were identified during the literature search [1,5], the sensors were not deemed suitable (cost, size, availability) for this project. The plots in Figures 1, 3 and 4 indicate that the high iron levels in the used oil samples are related to the depletion of the ZDDP antiwear additive, degradation of the used oil and/or coolant leakage. Consequently, timelier monitoring of the in-service oils has the potential of preventing the acceleration of the wear processes responsible for the iron containing debris. None of the samples obtained for this project were identified by AOAP as abnormal due to nonmetallic particle contamination so the potential benefit of a particle detection sensor could not be evaluated.

**Summary:** The RULER™ analyses indicated that the abnormal HMMWV diesel engine used oil samples had low levels of ZDDP additives resulting in increased levels of oxidation and contributing to accelerated wear rates. Consequently, the used oil samples received to date from the HMMWV diesel engines were identified as abnormal mainly due to oxidation and to a lesser extent due to soot, water/coolant contamination and metallic wear debris. The water levels of two abnormal samples were well above the condemning level of 0.2% indicating an on-board sensor would have detected the water prior to the periodic AOAP sampling, further minimizing the resulting component wear. The used oil samples received to date from the non-HMMWV were identified as abnormal due to soot, water/coolant contamination and fuel build-up. All of the abnormal oil samples evaluated during this project were detected by the Ni post sensor at room temperature. The addition of a viscosity measurement would help detect fuel dilution (viscosity decrease), oxidation (viscosity increase) and top-offs with incorrect

grades of oils. The addition of the voltammetric Ni array on polyimide film sensor would help identify oils with water/coolant leaks. If the durability of the voltammetric array sensor is determined to be poor by future testing, then the dielectric sensor would be useful in identifying oils with water/coolant contamination and possibly soot contamination.

The fact that the voltammetric sensors were able to detect abnormal used oil samples without fresh oil samples for comparison and without oil usage data, oil top-off rates or previous used oil samples for trending purposes further indicates that an on-board voltammetric sensor combined with a viscosity sensor has great potential for oil condition monitoring of in-service diesel engine oils. Based on this initial research, a HMMWV diesel engine test stand will be used in a follow-on effort to further evaluate the capability of the on-board voltammetric and dielectric sensors to monitor the condition and contamination of in-service diesel engine oils. On-board viscosity, soot and debris sensors recently commercialized or developed will also be tested on the diesel engine test stand.

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## References

1. Kauffman, R. E. and Wolf, J. D., "Development of Onboard Sensors for Monitoring Diesel Engine Oil Condition," TACOM-TARDEC Final Report, Warren, MI, Steve C. Moyer as Technical Monitor, March 2001.
2. Kauffman, R.E., "On-board and Off-Line Measurements of Thermal and Oxidative Degradations of Aircraft Turbine Engine Oils - Part I: Laboratory Evaluations," *Lub. Eng.*, V.51 (11), pp 914 - 921, 1995.
3. User Manual for Extended Beta Test Version of OilView 5500 "Dielectric and Temperature Monitor," May 2000, Computational Systems, Inc., Knoxville, TN.
4. Kauffman, R.E., et al., "Flow-Through and Handheld Devices to Provide Advanced Lubricant Segregation Capability for Prototype Oil Collection Facilities," *Lub. Eng.*, V.51(6), pp. 497 - 501, 1995.
5. Saba, C. S. and Toth, D. K., "In-Line Wear Debris Monitoring," JOAP International Condition Monitoring Conference Proceedings, pp. 153 - 169, November 1994.
6. Kauffman, R.E., "Remaining Useful Life Measurements of Railroad Diesel Engine Oils, Automotive Engine Oils, Hydraulic Fluids, and Greases," *Lub. Eng.* V51 (3), pp 223 - 230, 1995.

7. Kirkpatrick, J.F., "Diagnostic Tools for for Reciprocating Engine Cogeneration Systems, Phase I," Gas Research Institute Report No. GRI9010022, 1990.