AD A

Investigation of Portable Oil Analysis Requirements for Army Application

INTERIM REPORT
TFLRF No. 344

by

H. W. Marbach, Jr.
E. A. Frame
U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
San Antonio, TX

Under Contract to

U.S. Army TARDEC
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13. ABSTRACT (Maximum 200 words)

The objectives of this project were to define critical used oil properties and to investigate and analyze oil analysis methods that could be used at the unit level to provide a go/no-go result regarding oil condition and the equipment readiness. Implementation of unit-level analysis could provide a reduction of samples sent to AOAP labs for full analysis thereby reducing costs.

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EXECUTIVE SUMMARY

Problems and Objectives: AOAP leaders have been directed to reduce costs. Unit commanders need to know the readiness state of equipment and/or lubricants more quickly than the current AOAP system allows. The objective is to investigate solutions for reducing the number of samples sent to AOAP for oil analysis and provide field personnel with devices that will help determine whether a sample needs to be submitted to AOAP.

Importance of Project: Oil testing in the field will be faster and more efficient for a more mobile battlefield. The goal is to reduce the number of used oil samples sent to AOAP for analysis by approximately 80%. It will also reduce the volume of used oil that AOAP must dispose.

Technical Approach: The approach was to develop the critical oil analysis requirements for CI engines, turbine engines (M1), transmissions, hydraulic systems, and generators. The approach was also to develop a test plan for evaluating portable oil analysis devices with AOAP tests and standard ASTM methods in the laboratory and field.

Accomplishments: A list was compiled of the major manufacturers of engines, transmissions, hydraulic systems, generators, and manual transmissions/final drives representative of Army ground equipment. These manufacturers were contacted for their oil change criteria and for oil degradation and equipment condition. A list was compiled of the key parameters of used oil properties required for oil monitoring, component monitoring, or both. The rationale for identifying critical lubricant properties was included. The TARDEC market survey of portable oil analysis techniques was reviewed, and a suite of methods was recommended for evaluation. Also, a comprehensive test plan was developed for evaluating portable oil analysis devices with standard ASTM methods and AOAP results.

Military Impact: The establishment of the unit portable oil analyzers would increase vehicle and equipment readiness and enhance the following areas:

> Tactical - oil testing will be faster and more efficient for a more mobile battlefield.
>
> Logistics - Determine the useful life of lubricants and fluids and ease the logistics burden.
>
> Environmental - Reduce the impact of used drained oil disposal, and used oil sample disposal.
>
> Maintenance - Extend the useful life of oils and help to eliminate the erroneous use of oils and fluids and reduce maintenance cost.
>
> Savings - Would provide a large reduction of samples sent to AOAP labs for full analysis and a reduction in sampling efforts.

FOREWORD/ACKNOWLEDGMENTS

This work was performed by the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, during the period September 1998 through August 1999 under Contract No. DAAK70-92-C-0059. The work was funded and administered by the U.S. Army Tank-Automotive RD&E Center, Petroleum and Water Business Area, Warren, Michigan. Mr. Luis Villahermosa (AMSTA TR-D/210) served as the TARDEC contracting officer's representative and project technical monitor.

The authors acknowledge the assistance provided by the staff of their organization and that of TARDEC, with special recognition to the following: Luis Villahermosa and Steve Moyer for their technical guidance and Wendy Mills of TFLRF for her help in the preparation and editing of this report.

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ACRONYMS AND ABBREVIATIONS

AOAP	Army Oil Analysis Program
ASTM	American Society for Testing and Materials
CI	Compression Ignition
CUCV	Commercial Utility Cargo Vehicle
FMTV	Family of Medium Tactical Vehicles
HMMWV	High Mobility Multi Wheeled Vehicle
ICP	Inductively Coupled Plasma Spectroscopy
hp	Horsepower
JOAP	Joint Oil Analysis Program
POL	Petroleum, Oil and Lubricants
SAE	Society of Automotive Engineers
SwRI	Southwest Research Institute
TAN	Total Acid Number
TARDEC	TACOM Research, Development and Engineering Center
TBN	Total Base Number
TFLRF	TARDEC Fuels and Lubricants Research Facility
TGA	Thermogravimetric Analysis
VI	Viscosity Index

I. BACKGROUND

The Army Oil Analysis Program (AOAP) helps reduce catastrophic failures of ground and aviation equipment and optimize oil change frequency. This is accomplished when operating units transport a used oil sample for analyses to one of 21 field or four depot AOAP laboratories located across the United States, Europe and Korea. AOAP also has two mobile labs for training and wartime roles. Even though AOAP offers great benefits by defining the condition of the components, it can take three to ten days for the test results to reach system users. In the field, users want a quick answer, usually within a few minutes or hours, to the following questions:

(1) What is the condition of the mechanical component (i.e., engine, transmission, hydraulic system or final drive)?
(2) What is the condition of lubricant in the mechanical component?
(3) How can premature oil changes be reduced or eliminated?
(4) How can equipment failures and removals be reduced or eliminated?

AOAP has aided in answering questions one and four. However, questions two and three are more difficult to answer. No acceptable method of rapidly establishing the lubricant condition for in-service, stored, captured or host nation lubricants has been found. Unit commanders need to know their oil and equipment's state of readiness sooner than the current AOAP system allows. A listing of AOAP laboratory test procedures is presented in Appendix A.

A test kit that rapidly establishes in-service or used lubricant condition is a familiar concept to the Army. The U. S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) at Southwest Research Institute (SwRI) in San Antonio, Tx has investigated this concept. (1,2)* Along with the Army's investigation of this test-kit concept, AOAP leaders have been directed to reduce costs. Reducing the number of samples sent to AOAP labs for full analysis is one way to accom-

* Numbers in parentheses indicate references listed at the end of the report.

plish both of these objectives. Recent technological developments (3) may enable unit-level oil analysis that provides a go/no-go result regarding the readiness of the equipment and/or oil condition. No-go results may require sending a sample to an AOAP lab for further analysis. The stated objective of TARDEC's POL Quality Analyzer Program is to reduce the number of AOAP lab samples by 75-80%. (4) This would result in substantial cost savings. The total operation and support cost of AOAP labs would be greatly reduced, along with the cost and inconvenience of sample handling, shipping, and disposal. Test results will also be provided in a more timely fashion, in line with commanders' needs.

II. OBJECTIVE

The objectives of this project were to define critical used lubricating oil properties and to investigate oil-analysis methods for use at the unit level to provide a go/no-go result regarding oil condition and equipment readiness. A unit-level analysis could reduce costs by decreasing the number of samples sent to AOAP labs for full analysis.

III. APPROACH

This work was initiated by compiling a list of the major component manufacturers of engines, transmissions, hydraulic systems, generators, and manual transmissions/final drives representative of Army ground equipment. Next, these manufacturers were contacted for their oil change criteria for oil degradation and equipment condition. Using this information, along with TFLRF personnel experience, a list of key parameters of used oil properties was compiled. The properties required for oil monitoring, component monitoring, or both, were identified. The rationale for identifying critical lubricant properties was included. The critical oil analysis requirements for compression ignition (CI) engines, turbine engines (M1), powershift transmissions, and hydraulic systems were developed. TARDEC prepared a market survey of available oil analysis technologies, which included instrument precision.(3) TFLRF reviewed the market survey and matched promising techniques with the critical lube properties. A test plan was also developed for evaluating portable oil analysis devices with standard ASTM methods and AOAP results.

IV. RESULTS

A. Component Manufacturers

The initial effort was to identify those oil properties deemed essential and/or highly recommended for determining oil condition, component condition, or both. Therefore, it was important to acquire component manufacturers' recommendations concerning oil analysis to support and justify the selection of critical properties. A list was compiled of engine, transmission, and hydraulic systems for Army combat, tactical, and support equipment, including generators, construction, and material handling equipment. This list included the major and representative components used by the Army in non-aeronautical equipment. These components are in the AOAP program and are listed in Tables 1-5 below:

Table 1. Representative Combat Engines

Manufacturer	Engine Model
Continental/Hercules	AVDS – 1790 – 2
Cummins	VTA – 903T
Detroit Diesel	6V53T
Detroit Diesel	8V71T
Lycoming Turbine	AGT – 1500*

Table 2. Representative Tactical Wheeled Engines and Other Support Equipment

Manufacturer	Engine Model
Caterpillar	3116
Continental/Hercules	LDS-427-2
Continental/Hercules	LDT-465-1
Cummins	NHC-250
Cummins	NTC-400
Cummins	6CTA 8.3
Detroit Diesel	8V92TA
General Motors	6.2L
General Motors	6.5L

Table 3. Representative Generator Set Engines

Manufacturer	Engine Model
Allis-Chalmers	AC-3500
Caterpillar	D198ERX51
Caterpillar	D298ERX37
Detroit Diesel	DD-353

Table 4. Representative Transmissions	
Manufacturer	**Model**
Allison	TX-100-1 (T)*
Allison	XTG-411-2A (C)
Allison	XT-1410-9 (C)
Allison	CD-850-6A (C)
Allison	X1100-3B (C)
Allison	HT-740-D (T)
Allison	CLBT-750 (T)
Allison	MT-654 (T)
Allison	MD-D7 (T)
Caterpillar	D-7155 (T)
General Motors	THM-400 (T)
General Electric	HMPT-500 (C)
*C=Combat	*T=Tactical

Table 5. Representative Drive Axles & Manual Transmissions	
Manufacturer	**Model**
Eaton (single,2-speed,Tandem)	Various

In Table 1, five engines representative of those used in combat equipment were selected from four manufacturers. The Continental AVDS – 1790 is used in 11 line items, such as the M60 and M48 tanks, M728 combat engine vehicle, M48A5AVLB armored vehicle launcher, and the M88 recovery vehicle (using the 850 HP engine). The Cummins VTA-903T is used in seven line items, such as the M2 and M3 infantry and cavalry-fighting vehicle, the M9 armored combat earthmover, the M993 MLRS carrier, 140T cranes, and the LVTR-7 landing crafts. The Detroit Diesel 6V53T is used in 39 line items, in such equipment as the M113 armored personnel carrier, M1015 signal intelligence/early warning car, M106 self-propelled cargo carrier, M548 self-propelled cargo carrier, M52 transporter loader, 1500M generator sets, and RT-10 rough terrain forklift. The Detroit Diesel 8V71T engine is used in 16 line items, in equipment such as the M107 self-propelled gun, M109 self-propelled howitzer, M578 recovery vehicle, M992 field artillery ammo support vehicle, Bridge-MA mobile assault bridge, and 750PDQ air compressors. The Lycoming AGT-1500 turbine engine is used in only 1 line item, the M1 Abrams tank.

For the representative tactical-wheeled and other support-equipment engines (Table 2), nine different engines from six manufacturers were selected. The Caterpillar 3116 is used in 13 line items, predominantly in 2 ½- and 5-ton (FMTV) trucks. The Continental LDS-427 is used in eight line items, predominantly in 2 ½- and 5-ton trucks. The Continental LDT-465 is used in 34 line items: 2 ½-ton trucks and 5-ton trucks. Many of the Continental LDT-465s are being upgraded to the A3 configuration powered by the Caterpillar 3116 engine. The Cummins NHC-250 is used in 41 line items: mostly 5-ton trucks. The Cummins NHC-250 is also being upgraded by the newer Cummins 6CTA 8.3 engine. The Cummins NTC-400 is used in eight line items, such as the M19 concrete truck, and the M920 HET trucks. The Cummins 6CTA 8.3 is used in the MHE-RT loaders and is replacing many of the older Cummins NHC-250 engines. The Detroit Diesel 8V92TA is used in six line items, such as the M977 10-ton cargo truck, the M978 10-ton tanker, and the M984 10-ton wrecker. The General Motors 6.2L and 6.5L engines are used in 32 line items: predominantly the HMMWV and CUCV vehicles. Similar engines are also used in 20T and 22 ½T trucks, rough terrain loaders, and generator sets.

For the representative generator sets (Table 3), four engines were selected from three manufacturers. These four engines cover the majority of the generator sets. In addition, these engines are also used in road graders, loader scoops, rollers and trucks.

Twelve representative transmissions were selected from four manufacturers from the entire equipment list (Table 4). The Allison TX-100 is used in 28 line items, in equipment such as the M106 mortar carrier, the M113 personnel carrier, the M548 cargo carrier, the M688 and M752 transporter loaders and the M667 missile carrier. The Allison XTG-411 is used in 13 line items, such as the M108, M109 and M110 howitzers, and the M578 recovery vehicle. The Allison XT-1410 is used predominately in the M88 recovery vehicle. The Allison CD-850 is used primarily in the M60 and M48 tanks and the M728 combat engine carrier, while the Allison X1100 is used in the M1 Abrams battle tanks. The Allison HT-740 is used in nine line items, such as the M916 22½-ton tractor truck, the M978 10-ton tanker, and the M985 10-ton cargo trucks. The Allison CLBT-750 is used in three line items: the M911 HET 22½-ton fire trucks. The Allison MT-654 is used in 43 line items: the majority of the 5-ton trucks. The Allison MD-D7 is used in 17 line items: predominantly in the 2 ½- and 5-ton family of medium tactical vehicles (FMTV). The Caterpillar D-7155 is used in 10- and 20-ton tractors, concrete and dump trucks. The General Motors THM-400 and the THM 4L80E are used in 32 line items, predominantly in the HMMWV and CUCV vehicles. The last transmission selected was the General Electric HMPT-500, which is used in eight line items, such as the M2 and M3 fighting vehicles and the M993 rocket launch system carrier.

Eaton represents about 75 line items (Table 5). Only three drive axles are enrolled in the AOAP system, and these are tracked vehicles. All others used hard time (miles and/or hours). All manufacturers in Tables 1-5 were contacted for their oil/fluid change criteria for lubricant/fluid degradation and component condition guidelines. This information (5-15) was received after numerous contacts, with the exception of Continental and Allis-Chalmers. It was learned that Continental was purchased by Wisconsin Engine (Wis-Con), which only manufactures engines with less than 80 hp. Hercules Engines now manufactures many of the larger military engines formerly manufactured by Continental. Hercules reported that they have no records of oil-change criteria. Also, Allis-Chalmers, who manufactured support equipment engines (generator, construction equipment), was sold to H-K-Duetz AG in 1985. Deutz was sold to AGCO, Inc. in 1990 after dispersal of the manufacturing business in 1988.

B. Manufacturers' Oil-Change Criteria/Guidelines

Upon receiving the manufacturers' oil-change criteria/guidelines (5-15), tables were compiled for oil-change properties and their ranges for engines, transmissions, hydraulic systems, drive axles, and manual transmissions (Tables 6-9). This compilation was accomplished with information from DA PAM-738-750, Desert Storm Combat, the Wheeled and Generator Oil Change List, JOAP/AOAP, and the Internet.

Table 6. Engine Oil Drain Criteria Spread	
Property	**Guideline Limits Range**
Viscosity @ 40°C (100°F)	+40% increase; -15% decrease
Viscosity @ 100°C (210°F)	±1 visc. Grade; 3 or 4 cSt of new oil
Fuel Dilution	2.5% max.; 4%max.; 5% max.
Water Content	0.2% → 0.5% max.
Glycol Content	0 → 1000 ppm
TAN	2.5 increase
TBN ASTM D664 ASTM D2896	1.0 min 2.0 → 2.5 min.; ½ of new oil
Soot Content	0.8 → 1.5% max.
Pentane Insolubles	1.0 → 3.0% max.
Toluene Insolubles	2.0% max
Elements	
Silicon, Over Baseline*	1.5 ppm (+10 ppm/10 hrs) to 101 ppm
Sodium, Over Baseline	20 to 50
Boron, Over Baseline	20 to 25 ppm
Potassium, Over Baseline	0 to 20 ppm
Titanium, Over Baseline	5 ppm (+1 ppm/10 hours)
Iron, over Baseline	21 ppm (+4 ppm/10 hours) to 500 ppm
Copper, Over Baseline	6 ppm (+2 ppm/10 hours) to 400 ppm
Zinc, Over Baseline	20 ppm (+4 ppm/10 hours)
Lead, Over Baseline	6 ppm (+1 ppm/10 hours) to 152 ppm
Aluminum, Over Baseline	6 ppm (+2 ppm/10 hours) to 99 ppm
Chromium, Over Baseline	4 ppm (+2 ppm/10 hours) to 45 ppm
Molybdenum, Over Baseline	8 ppm (+2 ppm/10 hours) to 40 ppm
Silver, Over Baseline	0 to13 ppm
Tin, Over Baseline	15 to 90 ppm
*Baseline=Quantity in new oil	

Table 7. Transmissions Oil Drain Criteria Spread	
Property	**Guideline Limits Range**
Viscosity @ 100°C (210°F)	±25%
Water Content	0.2% max
Glycol Content	0
TAN	+3
Carbonyl IR Absorbance/Cell Path Length	+0.3A/0.1 mm
Solids	2% max
Elements	
Silicon, Over Baseline*	28 to 192 ppm
Sodium, Over Baseline	25 ppm
Boron, Over Baseline	0 to 20 ppm
Iron, over Baseline	164 to 677 ppm
Copper, Over Baseline	305 to 904 ppm
Lead, Over Baseline	6 ppm (+1 ppm/10 hours) to 152 ppm
Aluminum, Over Baseline	21 to 301 ppm
Chromium, Over Baseline	31 to 452 ppm
Silver, Over Baseline	5 to 76 ppm
Tin, Over Baseline	11 to 52 ppm
Molybdenum, Over Baseline	0 to 15
*Baseline=Quantity in new oil	

Table 8. Hydraulic Systems Oil Drain Criteria Spread	
Property	**Guideline Limits Range**
Viscosity	+10%
Water Content	0.5% → 0.3% max
Glycol Content	0 → 1000 ppm
TAN	1.0 to 1.5 change
Neutralization Number	0.3 max
Flash Point	247°C (475°F) min.
Particle Count/ml.	Size Max 15 to 25μ 22,800 25 to 50μ 4,050 51 to 100μ 720 100 + μ 128

Table 9. Drive Axles and Manual Transmissions Oil Drain Criteria Spread	
Drive Axles & Manual Transmissions	**Hard Times**
Single, Tandem, 2-Speed	6 to 24 months 500 to 2000 hours 60,000 to 120,000 miles

Depending on the materials used in their engines, certain manufacturers may not require all of the element guidelines. They are shown here to give an overall scope of the wide range of elements used. Interestingly, three major engine manufacturers have slightly different points of view regarding the importance of certain parameters in their engine recommendations. Caterpillar recommends wear metal analysis for detecting oil contamination. Cummins suggests the following primary oil characteristics as warning signals: viscosity; flash point; and the elements silicon, boron, sodium and potassium. Detroit Diesel recommends using primarily viscosity and TBN to establish the condition of the engine oil.

If a transmission manufacturer had no guidelines and could not recommend any, AOAP criteria were used. One manufacturer said the transmission design team had been disbanded, and none of the guideline data could be located. Most manufacturers do not use elements as guidelines. However, AOAP uses elements as guidelines through trend analysis by correlating long-term experience to field results.

Most hydraulic system manufacturers require viscosity, water content, and particle count. The neutralization number and flash point are recommended for fire-resistant hydraulic fluid.

All drive axles and manual transmissions use hard times to change the lubricant, except in the M109 self-propelled Howitzer 155mm and the M548 tracked cargo carrier 6 ton. As illustrated by data contained in these tables, there is a large spread of oil drain criteria. This may present a problem if using only one portable analyzer. It will probably require two to four or more portable analyzers to perform acceptably. Also, a vehicle log and some type of data storage will be needed to record baseline data for comparison and trending analysis. The Army's use of a wide range of lubricants in its equipment (Table 10) may complicate this issue.

Table 10. Army Ground Engine Lubricants and Hydraulic Fluids

Product	Specification	SAE Grade	Symbol
Hydraulic Fluid, Ordinance, Missile	MIL-H-5606	-	OHA
Hydraulic Fluid, Petroleum	MIL-H-6083	-	OHT
Hydraulic Fluid, Fire Resistant	MIL-H-19457	-	-
Hydraulic Fluid, Rust Inhibited, Fire Resistant, Type 1	MIL-H-46170	-	FRH
Hydraulic Fluid, Petroleum, Inhibited	MIL-L-17672	-	2075TH
	MIL-L-17672	-	2110TH
	MIL-L-17672	-	2135TH
Lubricating Oil, Internal Combustion Engine	MIL-PRF-2104	10	OE/HDO-10
	MIL-PRF-2104	30	OE/HDO-30
	MIL-PRF-2104	40	OE/HDO-40
	MIL-PRF-2104	15W/40	OE/HDO-15/40
Lubricating Oil, Internal Combustion Engine, Preservative	MIL-PRF-21260	10	PE-10-1
	MIL-PRF-21260	30	PE-30-1
Lubricating Oil, Internal Combustion Engine, Arctic	MIL-PRF-46167	OW20	OEA
Lubricating Oil, Turbine	MIL-L-23699		

C. Typical Oil Property Evaluation Tests

Vehicle users industry wide typically use certain properties to evaluate the condition of the oil and equipment. A brief discussion of those properties will follow:

1. **Viscosity** measures the oil's resistance to flow. The proper viscosity is extremely important for optimum performance, to maximize engine, transmission, and hydraulic system life, and to indicate many abnormalities. Viscosity is measured at 40° and 100°C

using ASTM D445, and this produces a viscosity index (VI) per ASTM D2270. Increases in viscosity are usually due to high-temperature oxidation, soot accumulation, water and/or coolant contamination, and addition of a heavier oil. A decrease in viscosity usually signals fuel dilution. In multigrades it may be due to a shearing of the VI improver or the addition of a lighter oil or fluid. The 40°C viscosity provides a better indication of fuel dilution or water contamination.

2. **Water Content** measures the amount of water found in the component oil. Water is usually measured by the Karl Fisher Water Content Method, ASTM D4928. Water gets into the crankcase through blow-by from short trips, gasket leaks, water pump seals, and through condensation that can occur during cooldown. Moisture can 1) enhance oxidation by increasing polarity, 2) produce a decline in lubricity, 3) seriously affect oil filter ability, and 4) cause corrosion. Moisture analysis should be conducted in conjunction with glycol analysis, because moisture can be vaporized at engine operating temperatures, leaving glycol behind.

3. **Coolant/Glycol** measures the coolant/glycol in the oil. The coolant/glycol determination is conducted using ASTM D2982 or D4291. Glycol breaks down at higher engine temperatures, and when the water evaporates the glycol forms sludge and oil ball abrasion. It can reduce filterability, and large quantities can corrode bearings and block oil galleries.

4. **Fuel Dilution** measures the amount of fuel in the oil. Fuel dilution is typically measured by ASTM D445, ASTM D93, or ASTM D3524. Fuel dilution is caused by incomplete combustion from extended periods of idling or from using a heavy fuel. It may also be caused by overfueling from a malfunctioning or improperly sized fuel injector or from worn liners or piston rings.

5. **Total Acid Number (TAN)** measures the total amount of acidic products in the oil. It determines the extent to which an oil has been oxidized. Oxidation can lead to bearing corrosion and severe oil thickening. TAN is usually determined by ASTM D664 or D994.

6. **Total Base Number (TBN)** measures the alkalinity of the oil. As oil ages, the alkaline additives neutralize the combustion acids, and alkalinity decreases. Operating a component with low TBN oil can cause wear and deposit formation. The alkalinity can only be replenished by adding or changing oil. This is usually determined by ASTM D4937. ASTM D2896 and ASTM D664 are older, obsolete methods.

7. **Insolubles:** Pentene insolubles measure the oil-insoluble materials and some oil-soluble resinous matter that originate from oil and/or additive degradation. Toluene insolubles measure the following: insoluble materials from external contamination; fuel carbon and highly carbonized materials from degradation of fuel; oil and additives; or engine wear and corrosion materials. Insolubles are determined by ASTM D893.

8. **Soot** measures the amount of fuel soot present in used diesel engine oils. It is usually caused by retarded injection timing and is an indication of non-optimum air-to-fuel ratios. Excessive soot causes abnormal valve and injection-train wear along with increased viscosity. It can also increase exhaust emissions, and in extreme cases, clog filters. This test is now usually conducted using the Detroit Diesel enhanced TGA soot method. An infrared absorption technique is also used.

9. **Elemental Analysis** determines the additive elements, wear elements, wear metals, and contaminants in oil. The concentration of wear metals can indicate abnormal wear if there is baseline data. It can also indicate that an incorrect oil is being used. It can detect coolant leakage and can be used to monitor equipment condition. The method usually used to detect elements is ASTM D5185 (ICP Method).

10. **Particle Counter** measures the particle size and count for a given volume. Particle counting is recommended when using wear metal analysis because it detects wear and deterioration of synthetic friction materials on discs in transmission and wet brakes. It also shows the larger worn particles. The particle counter test has been proposed for ASTM standardization.

It should be mentioned that an ASTM method is the primary "gold standard" for determining an oil property. Other non-ASTM methods of oil analysis, such as those used by AOAP (Appendix A) and many portable oil test units, are useful and acceptable. Most nonstandard oil analysis techniques have been correlated with standard ASTM oil analysis procedures.

V. DISCUSSION AND JUSTIFICATION OF OIL ANALYSIS REQUIREMENTS

A. Diesel Engines

Viscosity change is a measure of diesel engine oil degradation. The proper viscosity is extremely important for optimum performance and maximum engine life. An increase in viscosity is due partly to the evaporation of lighter base oil fractions, as well as the loss of volatile oil degradation products. Increases are also due to high-temperature oxidation, water, coolant contamination, and soot accumulation. Excessive oil viscosity can hinder oil flow to critical engine components, such as bearings and turbochargers. This problem is magnified at start-up under low ambient temperature conditions. Continued use of a degraded, thickened engine oil can cause increased deposits in the ring belt area, leading to ring sticking, high oil consumption, and engine power loss. A decrease in oil viscosity usually indicates fuel dilution, or in multigrades it may be due to a shearing of the V.I. improver. Changes in viscosity can also be caused by the addition of a wrong lubricant. Using an oil with a viscosity that is too low can result in high oil consumption and piston-liner distress, ultimately leading to engine power loss. For these reasons, TFLRF considers oil viscosity to be one of the most important properties to be determined, relating to both oil degradation and engine condition.

Diesel engine oils are formulated with a variety of additives that enhance lubricity, retard oxidation and corrosion, and reduce the tendency for sludge and deposit formation. The level of the additives can be determined by monitoring the TBN. Additive and wear metal levels may also be measured by spectrographic metal analysis. Extended operation using engine oil with inadequate TBN will result in increased engine deposits and possible bearing corrosion. For these reasons, TFLRF considers TBN to be a critical parameter for determining oil degradation level.

Among the most serious engine oil contaminants are coolant, dirt, and soot. Coolant system leaks are probably the most serious, and one of the most common, except for engines that are air cooled. The water enhances oxidation, reduces lubricity, and can seriously effect oil filterability. The glycol breaks down at high temperatures and forms sludge, deposits, and hard abrasive oil balls. In most cases, monitoring water content is not adequately reliable because high temperatures can vaporize water quickly and keep detected levels as low as 0.05%. Coolant level contamination can be detected by measuring glycol or the content of boron or sodium. Glycol will also attack engine bearing materials. Dirt is probably the most common engine oil contaminant, usually operator-induced in dusty environments. High levels of dirt can lead to excessive levels of abrasive engine wear and ultimately power loss. The best way to detect dirt contamination is to monitor the silicon level by spectrograph and total insoluble solids.

Analyzing different types and levels of wear metals can determine which engine components are wearing and if the degree of wear is becoming critical. Wear metal content should be compared to the new oil to obtain the net wear metals and to monitor for rapid increases.

B. Turbine Engines

Gas turbine engine lubricants (unlike diesel engines) are not exposed to combustion by-products. Gas turbines tend to have hot spots and operate at higher temperatures. Therefore, synthetic lubricants are used that have been formulated with oxidation and corrosion inhibitors. Viscosity change can indicate contamination, severe degradation, or use of the wrong makeup oil in gas turbines.

The higher oil temperatures in a gas turbine eliminate most problems from water contamination; however, during periods when the engine is not operated, continuous water contamination can cause hydrolysis, which degrades the synthetic lubricant over time. This degradation can usually be detected by a change in TAN and viscosity.

Wear metal analysis is recommended to determine which engine components are wearing and to what degree this wear becomes critical. If an intercooler system is used, a fuel/oil dilution is possible. Highly degraded turbine engine oils can damage gears, pumps, and bearings due to circulating carbonaceous debris and can even produce partial or total filter plugging, which causes costly damage and engine shutdowns.

C. Power Shift Transmissions

Viscosity is the critical property to evaluate in combat and tactical transmissions. The viscosity increase in a power shift transmission is usually gradual; these components do not tolerate as much viscosity increase as a diesel engine due to the port/orifice sizing, which controls various transmission operational functions. At low-temperature conditions, used oil with increased viscosity can lead to oil starvation and system failure. TAN change resulting from oil oxidation can also be used to indicate viscosity increase.

The most common contaminants are water, dirt, wear particles from wet clutches, wet brakes, and transmission coolant. Water and dirt are usually operator-induced. Some transmissions are cooled with a coolant and require the detection of glycol, boron, or sodium levels in the oil. Dirt and wear particles can best be detected by measuring the levels of silicon and copper/bronze using a spectrograph or particle counter, and by total insoluble solids. Excessive contaminants can cause wet-clutch and/or wet-brake slippage, which affects steering, wear, wet brake/clutch chatter, filter plugging and overall operational performance.

D. Hydraulic Systems

In most cases, the viscosity should increase slowly unless there is a significant increase in temperature. Contamination with other oils/fluids can increase or decrease viscosity quickly.

To further define the cause of a change in viscosity, it is helpful to look at the change in TAN. As hydraulic fluids break down they form acidic by-products.

Contamination is one of the greatest threats to hydraulic systems. The most common contaminants are water, dirt, wrong fluid type, wear metals, and seal deterioration. Water is one of the greatest threats. Water is a poor lubricant and it promotes metal corrosion. The wrong oil can usually be identified by a change in viscosity. Metal wear contamination can be detected with the spectrograph. Particle size and count can detect dirt, metal and seal contamination. Small particles are most damaging to the close-tolerance function valves, while larger particles can restrict flow through port/orifices. Each hydraulic system has its own "steady state" particle level at which the system will normally operate. In this condition, the level of newly generated particles is offset by particles removed by filtration or that settle into low spots.

The measure of particle count is the most subjective of all the hydraulic oil tests. Hydraulic systems usually wear out gradually; therefore, major failures can usually be detected before catastrophic failure.

From the preceding information, Table 11 was developed to show the properties required for oil monitoring and component monitoring. The following definitions were used:

- Oil Degradation = Changes in physical/chemical composition of the oil.
- Oil Contamination = Materials that enter the lubricant.
- Equipment Condition = Property is strongly related to equipment/component condition.

Table 11. Property Identification					
Property	**Equipment/ Component specific**	**Oil Degradation**	**Oil Contamination**	**Equipment Condition**	**Indicates**
Viscosity	N	Y	Y	Fuel Dilution	water/coolant, dirt contamination, wrong lubricant/fuel, oxidation, and v.i. improver degradation
Fuel Dilution (Flash Point)	Y (Engine)	N	Y	Y	fuel
Water content	N	(Condensation)	Y	(Leaks)	water
Glycol Content	Y (Engine)	N	Y	(Leaks)	glycol, may also appear in power shift transmission w/ cooler
Soot Content	Y (Engine)	N	Y	(Possible)	soot
Insolubles: Pentane & Toluene	Y (Engine)	Y	Y(Includes Dirt)	(Possible)	dirt contamination, wear elements
TAN	Y (Engine/Trans)	Y	Y	N	additive depletion and oxidation
TBN	Y (Engine)	Y	(slight)	N	additive depletion and wrong lubricant
Elements	N	Y	Y	Y	coolant, dirt contamination, wrong lubricant, wear elements, and additive depletion
WPA	Y (Hydraulics)	N	Y	Y	dirt contamination and wear elements
Infra-Red (Variety of Properties)	N	Y	Y	(Coolant) Fuel Dilation	water, coolant, fuel, wear elements oxidation, additive depletion, v.i. improver depletion

VI. CRITICAL OIL PROPERTIES AND OIL CONTAMINANTS

Critical lubricant analyses properties were identified based on equipment/component manufacturer oil analysis requirements. The critical oil properties and contaminants were categorized into three levels based on cost and risk (Table 12). The cost factor was primarily the estimated cost of the required analysis instrumentation. The risk factor was defined as a subjective estimate of the risk of not detecting a problem.

Table 12. Test Evaluation Properties

Properties that must be determined		
Level 1: Minimum Cost, Highest Risk	**Level 2:Intermediate Cost, and Risk**	**Level 3: High Cost, Lowest Risk**
Viscosity Water/Glycol TAN Wear metals indirect method*	Viscosity Water/Glycol TAN Wear metals indirect method* Soot Content Insolubles TBN WPA (wear particle analyzer)	Viscosity TAN TBN WPA FT-IR for soot, water, glycol, oxidation, fuel dilution Spectrographic elements direct method
* To be developed		

Level 1 defines the minimum used oil properties that must be determined to provide reasonable protection of equipment. This least costly set of properties would involve the highest level of risk that a problem would be missed. For level 1, an inexpensive indirect measurement of wear metals is recommended; however, a method needs to be developed.

Level 2 analysis includes all Level 1 determinations plus soot content, insolubles, total base number (TBN) and wear particle analysis (WPA). Level 2 cost and risk were estimated to be intermediate.

Level 3 analysis includes all Level 1 and 2 determinations, and Fourier-Transform Infrared (FT-IR) and spectrographic techniques. Level 3 has the highest estimated cost and lowest estimated risk.

VII. OIL ANALYSIS INSTRUMENTS

TARDEC conducted an excellent market survey of available oil analysis instruments.(3) TFLRF collected information on some of the instruments in the TARDEC market survey; however, the TARDEC survey was more extensive and will be used as a basis for recommending appropriate instruments for Level 1, Level 2 and Level 3 properties as shown in Table 12.

A. Level 1

Level 1 determinations were estimated to be the most critical for defining oil condition at a low cost. Direct property or contaminant measurement, portability and cost were three of the key parameters considered in selecting appropriate instruments to determine the following Level 1 parameters:

1. **Viscosity** - At least 11 potential stand-alone, direct methods were identified, along with four on-board type methods. TFLRF recommends that the Eitzen Visguage and Gerin V-3 be evaluated. Both are relatively simple and very inexpensive (<$500). The Kittiwake Oil Test Center (OTC) should also be evaluated. While it is relatively expensive ($10,000), this instrument is multifunctional. The Cambridge Viscolab 3000 is well-proven, but relatively expensive. The CSI 520V Oil View Digital Viscometer, an accessory to the Oil View Analyzer 5100, is estimated to cost more than $10,000.

2. **Water/Glycol** - At least three direct water-determination instruments are available. TFLRF recommends evaluating the DEXsil Hydroscout ($525) and the UCC H_2Oil portable device (unknown cost). The multifunctional Kittiwake OTC is another recommended possibility. From the descriptions of the instruments, TFLRF could not determine if glycol contamination would also be detected. An indirect method such as a dielectric constant (the Lubrisensor) may also be useful in detecting water and/or glycol.

3. **Total Acid Number** (TAN) - The multifunctional Kittiwake OTC ($10,000), the Gerin TAN/TBN test kit (<$5/test) and the DEXsil TAN/TBN Titralube should be evaluated.

4. **Wear Metals** - TFLRF recommends that more than just ferrous debris be measured. Many wear areas produce nonferrous wear elements. No inexpensive direct or well-proven indirect method has been identified. The predict DLI navigator (impedance) measures a change in high-frequency permittivity and costs about $3,500. Absolute wear-metal concentrations are not obtained; thus, trends compared to a reference standard are used. The instrument may also indicate water contamination.

In summary, TFLRF recommends that initially the following suite of instruments be evaluated for determining Level 1 Critical determinations:

Instrumentation	Approximate Cost ($)
Eitzen Visguage	225
DEXsil Hydroscout	525
Gerin TAN/TBN or DEXsil	5/sample
Predict PLF Navigator	3,500
Lubrisensor	600
Total Estimated Cost	**$4,855**

Critical Level 1 Oil determinations might be determined for as little as $4,855 in instrument cost. The Kittiwake OTC should also be evaluated as it provides multifunctional information, which may be worth the added cost.

B. Level 2

Level 2 parameters include all Level 1 determinations plus soot content, insolubles, total base number (TBN), and wear particle analysis (Table 12).

1. **Soot content of used oil** - TFLRF recommends evaluating the Wilks InfraCal Instrument ($4,925). This is a direct measurement technique that appears to have proven results. Indirect methods such as dielectric constant may provide useful indications of soot content, but would require additional correlation and development.

2. **Insolubles** - There does not appear to be a quick, simple, direct instrument for determining insolubles. TFLRF recommends investigating one of the dielectric constant instruments for possible correlation.

3. **Total Base Number (TBN)** - The Gerin and DEXsil test kits should be evaluated. Both are simple and direct; however, glassware and chemical disposal are drawbacks. The Kittiwake instrument should also be evaluated.

4. **Wear Particle Analysis** - There are at least eight instruments available to determine wear particle analysis (particle counting). The price ranges from $10,000-15,000. TFLRF recommends including one of the particle counters in the Level 2 suite of instruments. Additional review of the methods available and possible manufacturer demonstrations are recommended before selecting the two particle counters to evaluate.

In summary, TFLRF recommends that initially the following instruments be added to the Level 1 suite of instruments for determining Level 2 critical perameters:

Instrumentation	Approximate Cost ($)
Level 1 Instruments	4,855
Kittiwake OTC	10,000
Level 2 Instruments	
Wilks InfraCal Soot meter	4,925
Unspecified WPA	14,000
Total estimated Level 2 Cost	**35,000**

For Level 2 instrument costs, TFLRF recommends including the multifunctional Kittiwake OTC, which brings total estimated cost for Level 2 instruments to approximately $35,000.

C. Level 3

Level 3 properties would provide the most detailed oil analysis; however, instrument cost soars. The addition of FT-IR and direct element analysis allows elimination of some of the instruments from the previous suites for Level 1 and Level 2.

For Level 3, the following instrument suite is recommended for evaluation:

Instrumentation	Approximate Cost ($)
Eitzen Visguage	225
TAN/TBN DEXsil or Gerin	5/sample
Top Source FT-IR + Atomic emission spectrometer for elements	70,000
Level 3 Approximate Total Cost	**$71,000**

The total estimated cost of each set of oil analysis instruments influences how and where the oil analyses will be deployed. Additional investigation is recommended to determine if an approach that utilizes Level 3 at some central field location, which could be deployed closer to the actual equipment user and maintenance personnel, is cost-effective compared to the Level 1 set of instruments of lower cost.

VIII. RECOMMENDATIONS

Test Plan for Evaluating Oil Analysis Devices

A comprehensive test plan was developed. This test plan would compare AOAP results with ASTM results and portable oil-analysis-device results from engine, transmission and hydraulic systems oils. The oil analysis devices with the best results will be validated in a field demonstration. These test results will be compared to ASTM test results. The devices with the best results in the selected parameters will be recommended for use at the unit level. The test plan is outlined below:

1. Collect used engine, transmission and hydraulic oil samples from AOAP laboratories.
   a. Pass and fail from various causes.
   b. Obtain AOAP test results on these oils.
   c. Obtain new/baseline oil test results (plus any trend data).
   d. Analyze the used AOAP oils with portable test devices and ASTM tests where enough oil is available.
   e. Obtain new oil and conduct ASTM tests.*
   f. Compare all the test data.

2. Locate/develop engine, transmission, and hydraulic oils from test stands.
   a. Obtain both pass and fail results by ASTM tests.
   b. Conduct test with portable test devices.
   c. Obtain new oil and conduct ASTM tests.*
   d. Compare all the test data.

3. Use the portable test devices and ASTM tests to analyze samples prepared in lab.
   a. Engine, transmission, and hydraulic oils with increasing water content such as 0.02, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 2.0 and 5.0 percent.
   b. Engine, transmission, and hydraulic oils with increasing coolant content, such as glycol, silicon, boron, sodium, and potassium.
   c. Engine, transmission, and hydraulic oil with increasing fuel dilution such as 0.1, 0.25, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0 and 7.0 percent.
   d. Standard viscosity oil ranges: 50%+ to 25%-; 15W40, 30, 10W, 0W-20 arctic; sheared multi-viscosity oils.
   e. Engine oil with increasing soot (0.5, 1.0, 2.0, 3.0, 5.0, 7.5, 10 percent).
   f. Interaction of contaminants: water + glycol; water + fuel; fuel + glycol; water + soot; fuel + soot; fuel dilution + water + glycol + soot, etc.
   g. Analyze with appropriate portable devices and ASTM tests.
   h. Compare all test data.

* All new and used oil samples should have the following tests conducted: viscosity @40°C and 100°C, V.I., TAN, TBN, water content, fuel dilution, glycol content, insolubles, soot content, wear metal, particles.

4. Field Demonstration/Validation

   a. Take portable test devices to field location.

      •Sample approximately 200 components.

      •Take enough oil samples from above components for ASTM tests.

      •Obtain new oil samples where possible for baseline.

   b. Compare portable test devices with ASTM results.

   c. Prepare recommendations based on test-kit ability to correlate with standard ASTM methods.

IX. REFERENCES

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2. H.W. Marbach, Jr., "Lubricant Quality Analysis System Development," Interim Report BFLRF No. 293, ADA293038, January 1994.

3. Corinna Tunac and John Zimmerman, "Market Investigation for Oil Analysis Instruments," Technical Report TARDEC, March 1999.

4. "Petroleum and Water Supply Overview," briefing by Steve Moyer, Petroleum and Water Business Area. TARDEC, February 23, 1999.

5. Cummins Service Bulletin No. 3810340-02, May 1996

6. Detroit Diesel Technician's Guide

7. Caterpillar, Oil and Your Engine

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9. Caterpillar, D330 Oil Drain; intervals - E-Mail Project Engineer

10. Textron Lycoming - Fax from Staff Engineer

11. Allison Transmission - E-Mail from Military Transmissions Engineer

12. Joint Oil analysis Program Manual

13. GM Guidelines on Manufacturer's Used Lubrication Oil Chemical analysis - 6.2L Engines and THM-400 Transmission

14. Detroit Diesel Engineering Bulletin No. 49

15. Eaton General Drive Axle and Transmission Service Bulletin

APPENDIX A
AOAP LABORATORY TEST PROCEDURES

AOAP revised the analysis procedure by replacing the 15-year-old crackle test (water/fuel presence); viscosity (presence of fuel and antifreeze); and Millipore blotter test (antifreeze and soot) with the FT-IR spectrometry oil analyzers. AOAP reports that the FT-IR quantitatively determines the presence of water, soot fuel, coolant, oxidation, nitration, sulfate products and oil additive depletion.

JOAP Tests

Laboratory Testing Requirement (Army)

Engines (non-aeronautical)
1. Spectrometric
2. Viscosity
3. Blotter
4. Crackle (water
5. K.F. (water)

Transmissions
1. spectrometric
2. Viscosity
3. Water

Hydraulic systems
1. Spectrometric
2. Viscosity
3. Water
4. Particulate Count
5. Color Metric Patch

Transfer Case, Steering, & Differential
1. Change when maintenance requires or hard times (mileage/T11) and apparently manual transmissions.

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AOAP Laboratory Tests

Crackle:

Determines the presence of free water when one or two drops of oil are placed onto a laboratory hot plate heated to 150 to 175 degrees

Celsius.
Results: A positive test for coolant or water is indicted by splattering and an audible cracking of the oil. A positive indication of fuel contamination is an audible sizzling sound of the oil. .

Fourier Transform Infrared Spectrometry (FTIR)

The FTIR Spectrometry Oil Analyzer replaces 15 year old Army physical property analytical laboratory instruments and tests such as, Crackle Test (water/fuel presence); Viscosity (nametre viscometer for presence of fuel and antifreeze); and Millipore blotter test (antifreeze and soot).

Determines quantitatively the presence of water, soot, fuel, coolant, oxidation, nitration, and sulfate products formed during normal system operations, also, the oil additives depletion levels in synthetic and mineral lubricants servicing aeronautical and nonaeronautical components.

The trend analysis information provided by FTIR spectroscopy:

Oxidation - Organic compounds subjected to high temperatures

Nitration - Nitro compounds due to incorrect combustion or carburetor/ injection pumps

Soot - too rich fuel/air mixtures forming buildup which changes viscosity, and prematurely clogs component system filters

Sulfate/sulfonate levels - internal engine by-products of diesel fuel blow-by
from bad piston rings, faulty injector pump/seals, etc.

Water and acidity contamination - typically found in the presence of glycol contamination due to faulty head gaskets, water pump/seals, etc.

Fuel contamination - blow-by of the gases from piston rings or leaky fuel
pump which dilute the servicing oil system

Glycol (or other coolant) contamination - faulty water pump or leaky head gasket seals

Base oil detergents additives - prevents welding of moving metal

surfaces
which results in coking effect resulting from depletion of oil inhibitors.
Most common additive is zinc dialkyl phosphate (ZPD)

Viscometer

Tests viscosity of used lubricating oils and identifies fuel and coolant dilution problems.

Lubrication fluids are affected by high temperatures and aeration during service which promote oxidation. This oxidation, if allowed to continue indefinitely, leads to increased viscosity, varnish, and sludge.

Blotter Spot Test

Determines insoluble contaminates and dispersive ability.

Procedure: After vigorous shaking, one drop of used oil is placed in the center of an oil filter circle and allowed to disperse for 15 minutes.

Results: The spot is evaluated for total contaminants and lubricant dispersive effectiveness.

Spectrometric Oil Analysis

Determines the type and amount of wearmetals in lubricating fluid samples. Abnormal concentrations may indicate damage wear of the equipment.

Results: Once abnormal wear is verified, the equipment may be repaired avoiding a major failure of a fluid wetted component, increased maintenance man-hours and high dollar equipment costs.

Ferrographic Analysis

Determines the size, shape, and type of wear-metal particles being generated by a piece of equipment and the mode of wear (e.g., spalling, rubbing, and cutting) which produces the particles.

Procedure: Particles are deposited on a substrate by a magnetic gradient and analyzed with a biochromatic microscope.

Roles in the Army Oil Analysis Program

Introduction to AOAP I Laboratory Locations I AOAP Laboratory Tests I Roles in AOAP
AOAP Publications & Links I Ongoing AOAP Projects I Ground Equipment Enrolled in AOAP

Information Current as of 15 June 1998 I Email: aoap@logsa.army.mil

TABLE 2-4. NONAERONAUTICAL EQUIPMENT LUBRICANT SAMPLE ANALYSIS REQUIREMENT GUIDE

The sequence of the following tests is provided as a guide, not as mandatory requirements for all services.

I. ENGINES

A. Spectrometric
  1. Pass - Go to I.B.
  2. Fail - See wear-metal guidelines for specific equipment
    a. Critical - Resample to verify
      (1) Wear Metals - abnormal or high range
      (2) Oil contamination by dirt or dust - Si increase
    b. Noncritical - Resample to verify, then change oil
      (1) Oil contamination by dirt or dust - Si increase
      (2) Additive depletion - Zn, Mg, or Cu decrease
      (3) Coolant problem - B or Na increase by 20 PPM or more

B. Viscosity
  1. Pass - Go to I.C.
  2. Fail - See viscosity guidelines
    a. Low - Fuel dilution or wrong oil. Verify by flashpoint test and change oil.
    b. High - Soot, sludge, water or wrong oil. Verify by insoluble or water test and change oil.

C. Blotter
  1. Pass - Go to I.D. or I.E.
  2. Fail - See blotter test instructions in Vol II, para 4-4.b.
    a. Contaminated oil - Soot or water is present. Verify by insoluble or water (crackle or KF) test and change oil.
    b. Additive depletion - Spot has poor dispersancy. Verify by spectrometric analysis (large decrease in Zn, Mg, or Cu) and change oil.

D. Crackle Test for Water
  1. Pass - Go to I.E. if quantitative degree of water content required (optional).
  2. Fail - See crackle test instructions in Vol II, para 4-4.d.(1).
    a. Free water - Change oil.
    b. Coolant leak - Verify by spectrometric (B or Na increase by 20 PPM or more) and change oil.
    c. Dissolved water - Verify by KF test and consult guidelines.

E. Karl Fischer Test for Water
  1. Pass
  2. Fail - See guidelines, Vol II, para 4-4.d. (2).

TABLE 2-4. NONAERONAUTICAL EQUIPMENT LUBRICANT SAMPLE ANALYSIS REQUIREMENT GUIDE (Cont)

II. TRANSMISSIONS

A. Spectrometric
1. Pass - Go to II.B.
2. Fail - See wear-metal guidelines for specific equipment
a. Critical - Resample to verify.
(1) Wear metals - abnormal to high range
(2) Oil contamination by dirt or dust - Si increase
b. Noncritical - Resample to verify, then change oil.
(1) Oil contamination by dirt or dust - Si increase
(2) Additive depletion - Zn, Mg, or Cu decrease
(3) Water or moisture condensation - Na increase

B. Viscosity
1. Pass - Go to II.C.
2. Fail - See viscosity guidelines
a. Low - Wrong oil, change oil.
b. High - Sludge, water or wrong oil. Verify by insolubles test and change oil

C. Water Test - Crackle or Karl Fischer
1. Pass
2. Fail - See guidelines, Vol II, para 4-4.d.

III. HYDRAULIC SYSTEMS

The following tests are approved methods of testing hydraulic fluid condition and may be directed by services as required. These tests may be performed singly or in combination as required. (Army laboratories shall use spectrometric, viscosity, and water testing as a minimum.)

A. Spectrometric

B. Viscosity

C. Water testing, Crackle or Karl Fischer Method

D. Electronic Particulate Count

E. Colorimetric Patch Testing