③

AD

DEFINITION OF HIGH-TEMPERATURE USE LIMITS FOR MIL-L-2104 ENGINE OILS

INTERIM REPORT
BFLRF No. 295

By

E.A. Frame
Belvoir Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
San Antonio, Texas

Under Contract to

U.S. Army TARDEC
Mobility Technology Center–Belvoir
Fort Belvoir, Virginia

Contract No. DAAK70-92-C-0059

November 1993

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Trade names cited in this report do not constitute an official endorsement or approval of the use of such commercial hardware or software.

DTIC Availability Notice

Qualified requestors may obtain copies of this report from the Defense Technical Information Center, Cameron Station, Alexandria, Virginia 22314.

Disposition Instructions

Destroy this report when no longer needed. Do not return it to the originator.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Submitted 1993 Nov Issued 1994 Jul	Interim Apr 85 to Nov 93

4. TITLE AND SUBTITLE

Definition of High-Temperature Use Limits for MIL-L-2104 Engine Oils (U)

5. FUNDING NUMBERS

DAAK70-85-C-0007; WD 9, 11
DAAK70-87-C-0043; WD 5, 20
DAAK70-92-C-0059; WD 13

6. AUTHOR(S)

Frame, Edwin A.

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

Belvoir Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
P.O. Drawer 28510
San Antonio, Texas 78228-0510

8. PERFORMING ORGANIZATION REPORT NUMBER

BFLRF No. 295

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

U.S. Army TARDEC
Mobility Technology Center-Belvoir
5941 Wilson Road, Suite 230
Ft. Belvoir, Virginia 22060-5843

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The high-temperature use limits for military and commercial diesel engine oils were found to be engine specific. With respect to oil properties such as viscosity grade and volatility, the two-cycle 6V-53T engine with trunk-type pistons was the most sensitive of the three engines that Belvoir Fuels and Lubricants Research Facility (SwRI) investigated. Catastrophic engine distress is probable if certain oils are used at increased operating temperatures in this engine. Operation of the 6.2L engine at increased temperatures caused oil degradation. Oil thickening from oxidation and soot accumulation was observed as was TAN increase. While the oil degraded substantially in the 6.2L engine, overall engine operation continued with no apparent problems. Long-term wear problems would be expected if the engine continued operation using the highly acidic and very viscous degraded oil. However, the VTA-903T engine was not sensitive to the oil used, and oil degradation at increased temperatures was fairly mild. Unfortunately, operation of the VTA-903T engine at increased temperatures was limited by engine hardware problems that were not lubricant related.

14. SUBJECT TERMS

Diesel Engine Oil	TAN	MIL-L-2104
Diesel Engine	6V-53T	
Oil Oxidation	6.2L	
High Temperature	VTA-903T	

15. NUMBER OF PAGES

95

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

EXECUTIVE SUMMARY

Problems: Definition of the upper oil sump temperature (OST) limit can potentially reduce engine damage caused by operation at excessive OST. If the upper OST limit can be increased for continuous operation, vehicles can be designed with less cooling hardware, resulting in a decrease in vehicle weight. Increased power density, enhanced vehicle performance, and reduced fuel consumption are potential benefits from the reduced vehicle weight allowed by higher OSTs.

Objective: The objective of this project was to define the maximum allowable OST for continuous operation of MIL-L-2104 engine oils in U.S. Army engines.

Importance of Project: Currently, engine oils meeting MIL-L-2104 are limited to a maximum OST of 121°C (250°F) for continuous operation. Brief excursions, not to exceed 15 minutes, up to 135°C (275°F) OST are allowed. Engine oils of current technology may be able to function continuously at increased oil sump temperatures. A need exists to define the upper OST use limit of MIL-L-2104 engine oils.

Technical Approach: The approach was to define the OST upper limit for a two-cycle diesel engine believed to be very sensitive to oil temperature (DDC 6V-53T), and for representative four-cycle diesels (GM 6.2L and Cummins VTA-903T). The oil temperature limits were defined by engine dynamometer tests conducted at increased OSTs using oils of the lowest performance level allowed by MIL-L-2104 to ensure against worst case occurrence in the field.

Accomplishments: Performance of MIL-L-2104 engine oils at increased operating temperatures was determined in a two-cycle diesel engine and two different four-cycle diesels.

Military Impact: It was determined that MIL-L-2104 diesel engine oils provide satisfactory performance in four-cycle diesel engines at 121°C (250°F) OST. It appears that the short-term excursion limit of 15 minutes/hour could be increased from 135°C (275°F) to 143°C (290°F).

Most, but not all, of the MIL-L-2104 oils provide satisfactory performance at 121°C (250°F) OST in a two-cycle diesel engine with trunk-style pistons. Operation of this type of engine at OST > 121°C (250°F) is not recommended. Synthetic SAE 30 and petroleum SAE 40 oils provided better high-temperature performance in this type of engine.

FOREWORD/ACKNOWLEDGEMENTS

This work was performed by the U.S. Army Belvoir Fuels and Lubricants Research Facility (BFLRF) located at Southwest Research Institute (SwRI), San Antonio, TX, during the period April 1985 to November 1993 under Contract Nos. DAAK70-85-C-0007, DAAK70-87-C-0043, and DAAK70-92-C-0059 with the Mobility Technology Center-Belvoir. Mr. T.C. Bowen (AMSTA-RBFF) of the U.S. Army TARDEC Mobility Technology Center-Belvoir served as the contracting officer's representative, and Mr. M.E. LePera (AMSTA-RBF) served as the project technical monitor.

The authors would like to acknowledge the invaluable assistance provided by the BFLRF engine and chemical laboratories as well as the BFLRF editorial group, including Mr. J.W. Pryor and Mses. L.A. Pierce and M.M. Clark.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION AND BACKGROUND

Definition of the upper oil sump temperature (OST) limit can potentially reduce engine damage caused by operation at excessive OST. If the upper OST limit can be increased for continuous operation, vehicles can be designed with less cooling hardware, resulting in a decrease in vehicle weight. Increased power density, enhanced vehicle performance, and reduced fuel consumption are potential benefits resulting from the reduced vehicle weight allowed by higher OSTs.

Currently, engine oils meeting MIL-L-2104 are limited to a maximum OST of 121°C (250°F) for continuous operation.(1)* Brief, not to exceed 15 minutes, excursions up to 135°C (275°F) OST, are allowed. Engine oils of current technology may be able to function continuously at increased OSTs. A need exists to define the upper OST use limit of MIL-L-2104 engine oils.

Much of the engine laboratory equipment used in this project provided temperatures in °F. To metricate this report, the Farhenheit temperatures were converted to Celsius using the formula (°F-32) × 5/9 = °C. Unless required for accuracy, the °C was rounded to the nearest whole degree.

II. OBJECTIVE AND APPROACH

The objective of this project was to define the maximum allowable OST for continuous operation of MIL-L-2104 engine oils in U.S. Army engines.

The approach was to define the OST upper limit for a two-cycle diesel engine believed to be very sensitive to oil temperature (DDC 6V-53T) and for representative four-cycle diesels (GM 6.2L and Cummins VTA-903T). The oil temperature limits were defined using oils of the lowest performance level allowed by MIL-L-2104 to ensure against worst case occurrence in the field.

* Underscored numbers in parentheses refer to references at the end of this report.

Preliminary engine screening tests were run using limiting oils to estimate the maximum allowable OST in a two-cycle DDC 6V-53T diesel engine. Both SAE 15W-40 and 30-grade viscosity oils were used. A screening procedure based on multiple 20-hour segments of the 240-hour Tracked-Vehicle Cycle (TVC) was used to determine the effect of raising OST and coolant-out temperature (COT) on engine condition. Used oil viscosity and wear elements, airbox inspections, blowby level, and oil consumption were used to evaluate the effects of operation at elevated OST. From these evaluations, an estimate of maximum allowable OST for continuous two-cycle diesel engine operation was made. High-temperature use limits were investigated in the GM 6.2L diesel engine following the Wheeled Vehicle Cycle (WVC), while the TVC was used for the Cummins VTA-903T engine.

III. MATERIALS

A. Engine Lubricants

Diesel engine lubricants used in this program included MIL-L-2104D and MIL-L-2104E reference oils and selected other oils. Qualification data for MIL-L-2104 oils were reviewed to identify oils with potentially marginal performance at increased temperatures. TABLE 1 presents a summary description of each oil and the engines in which each oil was evaluated. TABLE 2 contains the analyses for each oil evaluated, including: physical properties, elemental analyses, gas chromatographic boiling point distribution, oxidation stability (TFOUT), and high-temperature, high-shear viscosity.

Five of the oils were evaluated in an oxidation-corrosion bench test (FTM 791C Modified Method 5307) (2) at 191°C (375°F) for 48 hours and in an evaporation test (ASTM D 972) at 191°C (375°F) for 22 hours. Oxidation-corrosion test details are presented in TABLE 3, while the summarized results are shown in TABLE 4. Oil F had the least oxidation as indicated by viscosity increase, yet was the most corrosive to the lead coupon. Oil B, the 75 viscosity index (VI) SAE 30 oil, had a high evaporation loss compared to the other SAE 30 oil (Oil A). In addition, Oils E and F were evaluated in the same procedure at 232°C (450°F). The evaluations were stopped at 40 hours because of oil solidification from extreme oxidation.

TABLE 1. Lubricants Description

Oil Code	SAE Viscosity Grade	Description	Engines Tested		
			6V-53T	6.2L	VTA-903T
A	30	Army Reference Oil (MIL-L-2104D)	×	×	×
B	30	MIL-L-2104D Marginal Quality	×	×	
C	30	REO-203	×		
D	40	Army Reference Oil (MIL-L-2104D)	×		×
E	15W-40	Army Reference Oil (MIL-L-2104D)	×	×	×
F	15W-40	MIL-L-2104D	×		×
G	15W-40	MIL-L-2104D	×		
H	15W-40	Commercial API CE			×
I	15W-40	Commercial API CE			×
J	10W-30	Synthetic Commercial	×		

B. Test Fuel

The test fuel was Reference No. 2 diesel fuel supplied by a local refinery in San Antonio, TX. The specification requirements for this fuel, commonly referred to as "Cat fuel," are set forth in Section 5.2, Methods 354 and 355 of Federal Test Method Standard (FTMS) 791C and described in Appendix F of ASTM STP 509A, Parts I and II.(2) This test fuel is a straight-run, mid-range natural sulfur fuel manufactured under closely controlled refinery operation to minimize batch-to-batch compositional and physical property deviations. Properties of the test fuel are given in TABLE 5.

TABLE 2. New Oil Properties

Oil	A	B	C	D	E	F	G	H	I	J
SAE Viscosity Grade	30	30	30	40	15W-40	15W-40	15W-40	15W-40	15W-40	10W-30
K. Vis at 40°C, cSt	98.55	124.17	104.60	139.38	98.25	106.47	103.27	98.61	107.24	56
K. Vis at 100°C, cSt	11.36	11.62	11.71	14.00	13.24	13.62	13.59	13.60	14.03	10
VI	102	76	100	97	133	127	131	137	132	167
TAN	3	2.4	2.9	3	2.5	2.8	3.1	3.2	2.4	3
TBN, D 664	8.4	11.0	5.3	6.9	5.3	7.1	8.8	8.1	6.4	5.7
Sulfated Ash, wt%	0.84	1.51	1.02	0.72	1.02	0.85	0.79	0.91	1.00	1.1
Flash Point, °C	230	ND	230	ND	237	221	218	221	233	224
Elements, wt%										
S, XRF	0.54	0.61	0.43	0.57	0.60	0.47	0.52	0.70	0.59	0.33
N, CLM	0.076	0.044	0.006	0.066	0.053	0.065	0.075	0.124	0.056	0.14
Ca	NIL	0.26	0.24	NIL	0.16	NIL	NIL	0.10	0.17	0.25
Mg	0.15	0.08	NIL	0.13	0.04	0.12	0.12	0.07	0.05	NIL
Zn	0.13	0.13	0.09	0.11	0.14	0.11	0.11	0.14	0.11	0.13
P	0.12	0.12	0.08	0.10	0.11	0.10	0.10	0.11	0.10	0.13
B, ppm	NIL	NIL a	1	6	71	138	158	195	117	NIL
GCBPD, °C at wt% off										
0.5	319	309	333	330	307	326	314	312	322	299
1	337	324	348	350	318	343	333	336	338	332
5	380	362	404	391	354	378	372	368	371	393
10	400	380	426	414	371	395	388	383	387	413
20	429	399	444	445	394	412	405	405	408	425
30	451	413	457	466	412	423	419	427	425	435

a = 0.04 wt%, Na.

TABLE 2. New Oil Properties (Cont'd)

Oil	A	B	C	D	E	F	G	H	I	J
Elements, wt%										
GCBPD, °C at wt% off										
40	471	427	467	485	428	433	433	446	440	444
50	488	441	476	504	444	443	447	465	453	467
60	505	458	487	528	460	463	462	485	469	479
70	526	481	500	564	479	467	482	511	492	491
80	555	516	521	>600	510	487	513	571	552	519
90	>600	598	>600	>600	>600	566	600	>600	>600	557
Residue, wt%	15	10	11	25	15	9	10	18.6	17.2	3.4
TFOUT, minutes	150	112	126	124	140	130	125	201	163	183
HTHS Viscosity, 150°C, cP	3.62	3.37	ND	4.11	3.91	3.89	3.97	3.92	3.84	3.13

TABLE 3. Oxidation-Corrosion Test (Method 5307 Modified)

- Oil, 200 mL
- Glassware, heated in Al block
- Oxygen Flow, 10 L/hr
- Metal Specimens
  - Cast Iron
  - Copper
  - Lead
  - Aluminum
- Temperature: 191°C (375°F) or 232°C (450°F)
- Time: 48 hr (16-, 24-, 40-, and 48-hr oil samples)
- Measure Change in:
  - Viscosity
  - TAN
  - Metal Weight

TABLE 4. High-Temperature Oil Screening

Oil Code	A (Drum 1)	A (Drum 2)	B	E	F
SAE Viscosity Grade	30	30	30	15W-40	15W-40
Oxidation/Corrosion Test					
191°C (375°F), 48 hr					
K. Vis, 100°C, %increase	35.1	45.5	30.8	20.7	2.7
TAN, change	+2.9	+3.5	+2.9	+3.8	+4.2
Coupon wt loss, mg/cm^2					
Cu	4.8	5.4	2.4	1.8	5.7
Pb	35.9	33.5	17.1	2.8	43.8
Evaporation Test, D 972					
22 hr at 191°C (375°F)					
% wt loss	20.0	23.8	38.7	37.8	28.9

TABLE 5. Test Fuel Analysis

Properties	ASTM Method No.	Reference No. 2 DF	
		Test Fuel	Specification[a]
Gravity, API°	D 287	34.5	Record
Viscosity, cSt, at 38°C (100°F)	D 445	3.3	1.6 to 4.5
Flash Point, °C (°F)	D 93	85 (185)	37.8 (100) min
Cloud Point, °C (°F)	D 2500	-2.0 (+28)	Record
Pour Point, °C (°F)	D 97	-12 (+10)	-6.7 (+20) max
Water and Sediment, vol%	D 1796	0.0	0.5 max
Carbon Residue, wt%	D 524	0.10	0.20 max
Sulfur, wt%	D 129	0.41	0.35 min
Acid No., mg KOH/g	D 664	0.0	Record
Aniline Point, °C (°F)	D 611	63 (145)	Record
Copper Corrosion	D 130	1A	No. 2 max
Distillation, °C (°F)	D 86		
Initial Boiling Point		207 (405)	Record
10%		241 (465)	Record
50%		273 (524)	260 (500) min
90%		317 (603)	316 to 338 (600 to 640)
End Point		348 (658)	343 to 366 (650 to 690)
Cetane No.	D 613	52	0 to 45
Net Heat of Combustion, MJ/kg (Btu/lb)	D 240	42.13 (18,130)	Record
Ash, wt%	D 482	0.006	0.01 max

a = ASTM STP 509A, Part I and II, Appendix F.

IV. TWO-CYCLE DIESEL ENGINE LUBRICANT SCREENING

A. Engine

Engine dynamometer evaluations were conducted at increased oil sump and coolant-out temperatures to determine the high-temperature use limits for various oils. The Detroit Diesel Corporation (DDC) 6V-53T two-cycle diesel engine was used because it is representative of an engine family that has proven to be sensitive to oil temperature-dependent properties such as viscosity and volatility. A description of the DDC 6V-53T engine is presented in TABLE 6, and a photograph of the engine dynamometer installation is shown in Fig. 1. The two-cycle diesel engine family is widely used in U.S. Army combat and tactical equipment, as shown in TABLE 7.

TABLE 6. DDC 6V-53T Engine Specifications

Model:	5063-5395
Engine Type:	Two-Cycle, Compression Ignition, Direct Injection, Turbo-Supercharged
Cylinders:	6, V-Configuration
Displacement, liters (in.^{3}):	5.21 (318)
Bore, cm (in.):	9.8 (3.875)
Stroke, cm (in.):	11.4 (4.5)
Compression Ratio:	18.7:1
Fuel Injection:	DD Unit Injectors, N-70
Rated Power, kW (BHP):	224 (300) at 2800 rpm
Rated Torque, Nm (ft-lb):	858 (633) at 2200 rpm

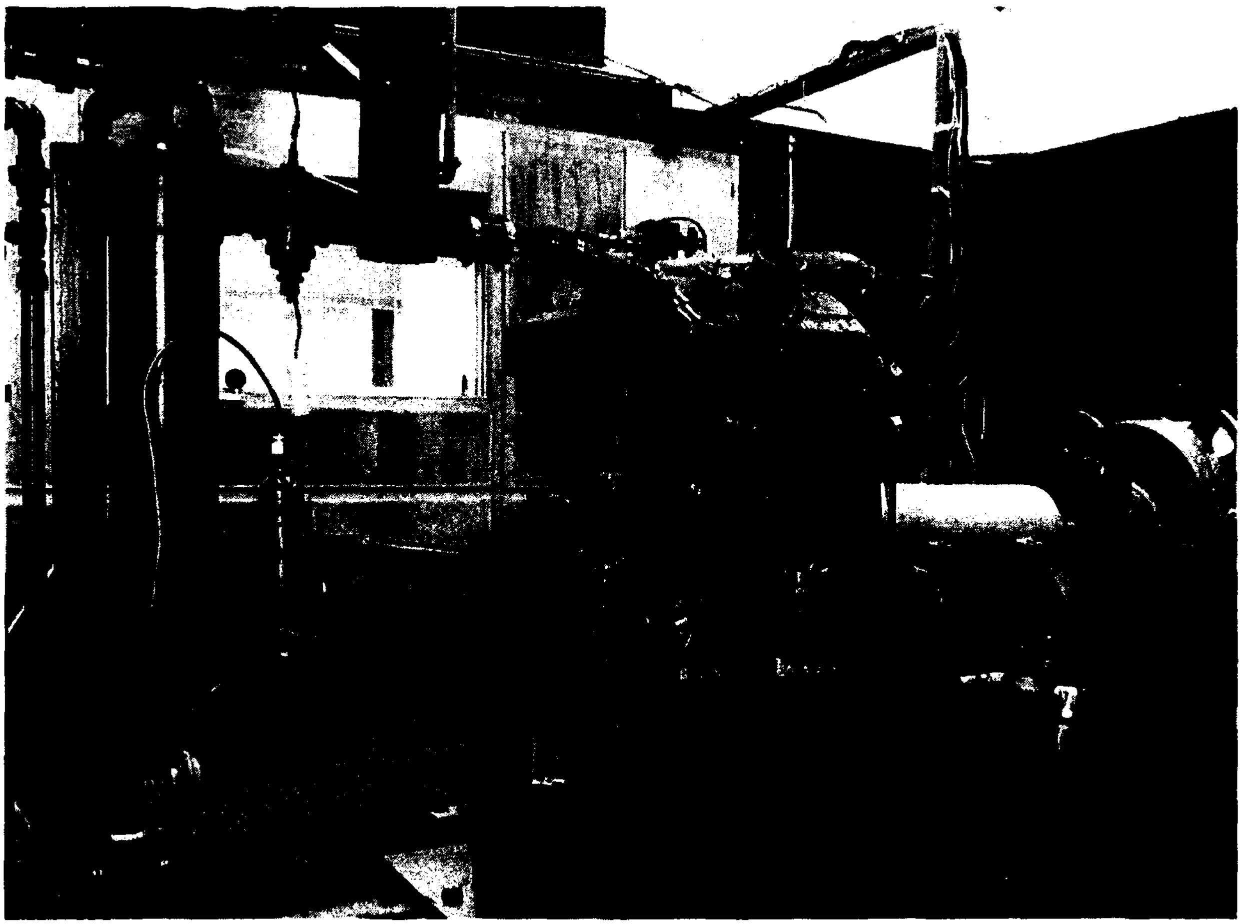

Figure 1. DDC 6V-53T engine installation

TABLE 7. Army Combat/Tactical Vehicles Powered by DDC Two-Cycle Engines

Designation	Description	Engine Model
M106A1, A2	Mortar, Self-Propelled (SP), 107 mm	6V-53
M107	Gun, Self-Propelled, 175 mm	8V-71T
M108	Howitzer, Self-Propelled, 105 mm	8V-71T
M109A1, A2, A3	Howitzer, Medium, 155 mm	8V-71T
M110A1, A2	Howitzer, Self-Propelled, 8 inch	8V-71T
M42A1	Gun, Anti-Aircraft, SP	6V-53
M163A1	Gun, Air Defense, SP	6V-53
M113A1, A2	Carrier, Guided Missile, TOW; Personnel, Full-Tracked (FT)	6V-53
M113A1 (Stretch)	Carrier, Personnel, Stretched, FT, Armored	6V-53T
M113A2E1	Carrier, Personnel, FT, Armored	6V-53T
M125A1, A2	Mortar, Self-Propelled, FT	6V-53
M132A1	Flame Thrower, Self-Propelled	6V-53
M116	Carrier, Cargo, Amphibious	6V-53
M548	Carrier, Cargo, Tracked	6V-53
M548 (Stretch)	Carrier, Cargo, Tracked, Stretched	6V-53T
M551	Armored Reconnaissance/Airborne Assault Vehicle (Sheridan)	6V-53T
M561	Truck, Cargo, 1-1/4 T (Gamma Goat)	3-53
M792	Truck, Ambulance, 1-1/4 T	3-53
M577A1, A2	Carrier, Command Post, Light-Tracked	6V-53
M578	Recovery Vehicle, FT, SP	8V-71T
M992, XM1050	Field Artillery Ammunition Support Vehicle (FAASV), FT, SP	8V-71T
M752, M688E1	Carrier, Loader/Launcher/Transporter (Lance)	6V-53
M667	Carrier, Guided Missile (Lance), Equipment, SP, FT	6V-53
XM727	Carrier, Guided Missile, Equipment, SP, FT	6V-53
M730, A1	Carrier, Guided Missile (Chaparral), SP, FT	6V-53
M730, A2	Carrier, Guided Missile (Chaparral), SP, FT	6V-53T
M741, A1	Chassis, Gun, AA (VULCAN), 20 mm, SP, FT	6V-53
M806E1	Recovery Vehicle, FT, Armored	6V-53
M901, A1	Improved TOW Vehicle Carrier, FT	6V-53
M981	Fire-Support Team Vehicle, FT, SP	6V-53
M1015, A1	Carrier, Electronic Shelter, FT, SP	6V-53
M1059	Carrier, Smoke Generator, FT, SP	6V-53
M113A1, A2	Fitters Vehicle, FT, SP	6V-53
M878, A1	Truck, Tractor, 5 T, Yard Type	6V-53T
M911	Truck, Tractor, Heavy Equipment Transporter	8V-92TA
M746	Truck, Tractor, Heavy Equipment Transporter	12V-71T
M977, 978, 985	Truck, Cargo, Tactical, 8 × 8 HEMTT	8V-92TA
M978	Truck, Tank, FT, 2500 gal.	8V-92TA
M983	Truck, Tractor, Tactical	8V-92TA
M984	Truck, Wrecker, Tactical	8V-92TA

B. Test Cycle

The engine test cycle used in this portion of the program was a modified version of FTM 791C, Method 355.(2) This cycle has been correlated to 6,437 kilometers (4,000 miles) of proving ground operation.(3)

The lubricant screening procedure used in this program had the following modifications from Method 355: oil sump and coolant-out temperatures were variable, and the test duration was 45 hours (9 × 5 hr, Period 1 from TABLE 8). Cylinder kits (piston, rings, liner) were replaced between 45-hour screening tests for each cylinder showing distress. The engine was completely rebuilt as needed.

Engine operating variables are presented in the following format:

oil sump temperature (OST), °C (°F) at 2800 rpm/OST,
°C (°F) at 2200 rpm/coolant-out temperature (COT), °C (°F).

For these measurements, the °F temperatures were converted mathematically to °C.

TABLE 9 shows the key operating test temperatures for the standard FTM Method 355, high-temperature condition A (HT-A) and high-temperature condition B (HT-B). The generalized formula for HT-A conditions in °F is:

$$x / x / x-45,$$

while the formula for HT-B conditions is:

$$x / x-10 / x-60,$$

where x = OST, °F at 2800 rpm. For most of the BFLRF evaluations, conditions were based on HT-B with x = 121° to 135°C (250° to 275°F).

TABLE 8. Army/CRC 240-Hour Tracked-Vehicle Endurance Cycle (FTM Method 355)

Period*	Time, hr	Rack/Setting
1	0.5	Idle
	2.0	Maximum Power
	0.5	Idle
	2.0	Maximum Torque
2	0.5	Idle
	2.0	Maximum Power
	0.5	Idle
	2.0	Maximum Torque
3	0.5	Idle
	2.0	Maximum Power
	0.5	Idle
	2.0	Maximum Torque
4	0.5	Idle
	2.0	Maximum Power
	0.5	Idle
	2.0	Maximum Torque
5	4	5 min idle, followed by shutdown

* These five periods yield 20 hours of running with a 4-hour shutdown; this cycle is repeated 12 times for a total test time of 240 hours.

C. Discussion

Eight different engine oils were evaluated in the 6V-53T engine at various oil sump temperatures. Oils A, B, C, D, E, F, G, and J from TABLE 2 were included. The following SAE viscosity classes were represented: 3 × SAE 30, 1 × SAE 40, 4 × SAE 15W-40, and 1 × SAE 10W-30.

During the conduct of each screening evaluation, used oil samples were taken at 2.5-hr intervals and analyzed for viscosity and engine wear elements. In addition, engine blowby was

TABLE 9. 6V-53T Engine Test Conditions

Oil Sump Temperature, °C (°F)	FTM 791C Method 355 Condition Set	High-Temperature Conditions HT-A	HT-B
Max power, 2800 rpm	113 (235)	121 (250)	121 (250)
Max torque, 2200 rpm	107 (225)	121 (250)	116 (240)
Coolant-out temperature, °C (°F)	77 (170)	96 (205)	88 (190)
Abbreviated Code, °C (°F)			
(OST at 2800/OST at 2200/COT)	113/107/77 (235/225/170)	121/121/96 (250/250/205)	121/116/88 (250/240/190)

closely monitored to indicate engine condition. Airbox inspections were made when liner distress was indicated by wear metals.

Observed engine performance generally could be grouped into one of three sets as shown in TABLE 10. Acceptable performance was characterized by very low liner scuffing, no used oil viscosity increase, and fairly low wear metals (Fe 10 to 30 ppm and Cu 10 ppm). Unacceptable performance Type 1 had liner scuffing in less than 45 hours and resulted in high used oil iron (250+ ppm), while Cu remained around 10 ppm. Fig. 2 illustrates wear metal accumulation for a representative Type 1 unacceptable performance. Type 2 unacceptable performance was characterized by high used oil copper content fairly early in the test, and was followed by high iron content later in the test. This behavior was eventually determined to be caused by connecting rod pin bushing failure followed by liner scuffing. Fig. 3 shows a representative used oil plot of wear metals versus time for a Type 2 unacceptable behavior.

Summarized results for the 45-hour 6V-53T engine lubricant screening determinations are presented in TABLE 11. Plots of used oil iron and copper wear metals versus time are presented in Appendix A. The performance of each lubricant is discussed individually, and performance comparisons are made within viscosity grades and between viscosity grades.

TABLE 10. Observed 6V-53T Engine Performance
45-Hour Tests

Acceptable

- Very low liner scuffing
- No oil viscosity increase
- Used oil: Fe 10 to 30 ppm, Cu 10 ppm

Unacceptable Type 1

- Liner scuffing < 45 hours
- Used oil: Fe 250+ ppm, Cu 10 ppm

Unacceptable Type 2

- Connecting rod pin bushing failure + scuffing
- Used oil: High Cu, followed by high Fe

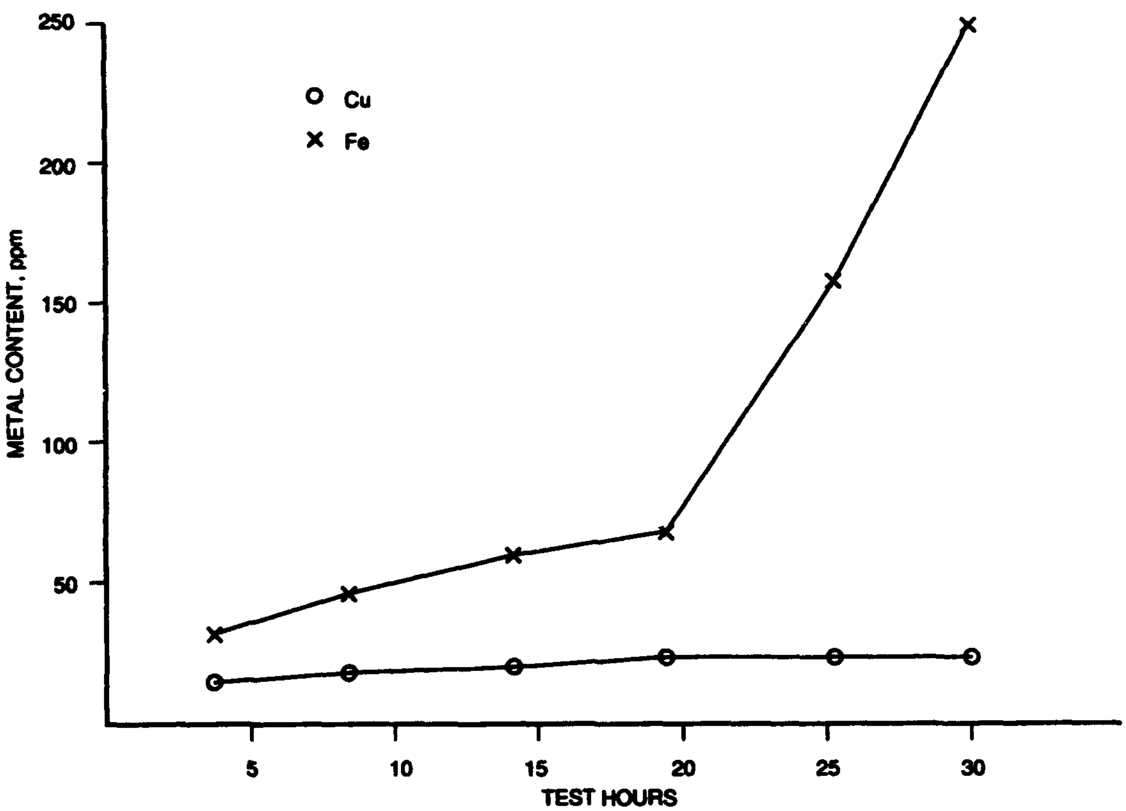

Figure 2. Unacceptable performance, Type 1

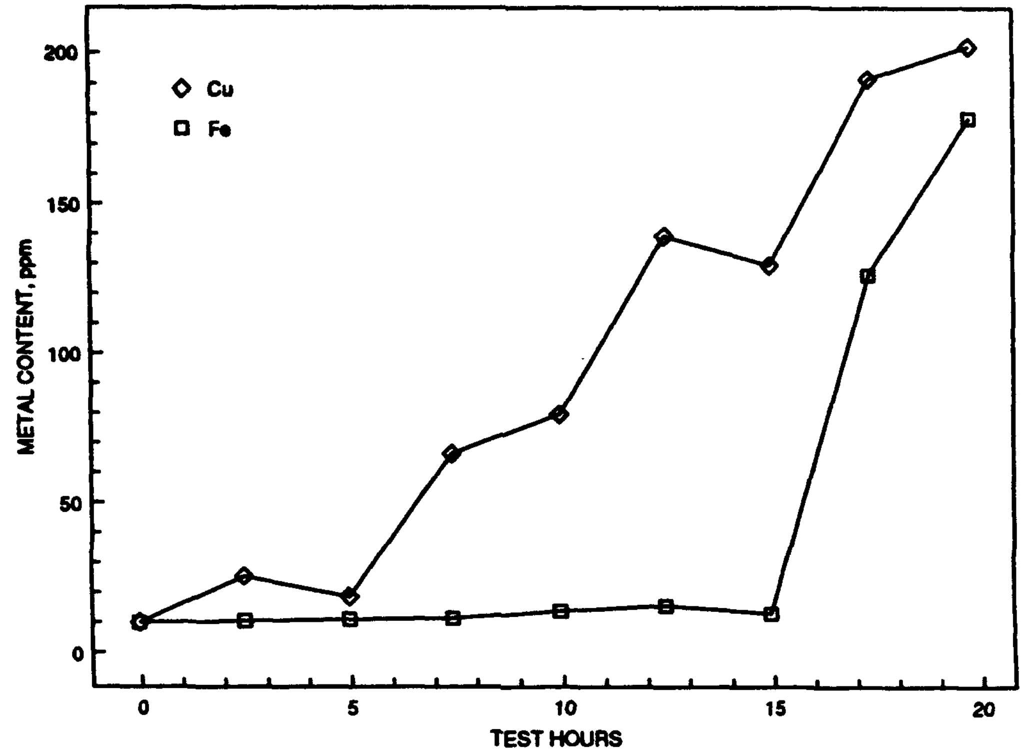

Figure 3. **Unacceptable performance, Type 2**

Oil A, the MIL-L-2104D SAE 30 viscosity grade Army Reference Oil, was evaluated at a variety of oil sump temperatures. Initial evaluations of Oil A were conducted at HT-A conditions (TABLE 9) in which the OST was the same at 2200 and 2800 rpm. Oil A had acceptable 50-hour engine screening performance at 121°/121°/96°C (250°/250°/205°F) conditions with slightly higher used oil copper content than expected. When evaluated at 127°/127°/102°C (260°/260°/215°F) conditions, Oil A completed only 24 hours. Three cylinders had liner scuffing greater than 30 percent, and the used oil iron content was high (315 ppm). During the program, HT-B conditions (TABLE 9), in which the OST at 2200 rpm was 6°C (10°F) lower than OST at 2800 rpm, were adopted. This OST spread was consistent with temperatures observed in regular FTM 355 runs. Several evaluations of Oil A were conducted at 121°/116°/88°C (250°/240°/190°F) conditions. In all cases, Oil A had acceptable performance. In fact, these conditions with Oil A were used as a baseline run to check engine integrity throughout the program. When conditions were raised to 127°/121°/93°C (260°/250°/200°F), the evaluation was stopped at 32.5 hours because of high used oil wear metals (Cu = 140 ppm, Fe = 555 ppm). This evaluation resulted in Type 2 unacceptable behavior (TABLE 10). At 20 to 30 test hours,

TABLE 11. 6V-53T Engine Screening Summarized Results

Lubricant (SAE Viscosity Grade)	Test No.	Test Hr	Fe, ppm	Cu, ppm	K. Vis, 100°C, cSt	Liner Scuffing and Comments
Oil A (SAE 30)						
121°/116°/80°C	44 H	45	34	<10	11.93	Normal (N)
(250°/240°/190°F)	44 J	45	47	<10	11.83	2-N; 4 at 30% est.
	44 L	45	<10	<10	11.52	5-N; 1 at 15% est.
	46	45	24	<10	11.60	N
121°/116°/102°C (250°/240°/215°F)	44 N	45	38	<10	12.10	N
121°/121°/96°C	44	45	84	44	12.06	5-N; 1 at 15% est.
(250°/250°/205°F)	44 B	45	42	52		N
	44 E	45	68	21	11.94	4-N; 2 at 25% est.
127°/121°/93°C (260°/250°/200°F)	46 B	32.5	555	140	11.58	Avg = 19; incl. 1 at 53%
127°/127°/102°C (260°/260°/215°F)	44 F	24	315	39	11.58	Avg = 28; incl. 36, 60, 53%
Oil B (SAE 30)						
121°/116°/80°C (250°/240°/190°F)	44 K	10	492	<10	11.39	Avg = 45; incl. 99, 76, 40%
Oil C (SAE 30)						
121°/116°/80°C	48	45	31	18	12.25	N
(250°/240°/190°F)	52	45	46	12	11.95	N

TABLE 11. 6V-53T Engine Screening Summarized Results (Cont'd)

Lubricant (SAE Viscosity Grade)	Test No.	Test Hr	Fe, ppm	Cu, ppm	K. Vis, 100°C, cSt	Liner Scuffing and Comments
Oil D (SAE 40)						
127°/121°/93°C (260°/250°/200°F)	53 B	45	45	<10	13.01	2-N; 2 at 25% est., 2 at 5% est.
135°/129°/102°C (275°/265°/215°F)	53 C	12.5	380	12	13.47	Avg = 30.5; incl. 31, 23, 67, 33%
Oil E (SAE 15W-40)						
121°/116°/80°C (250°/240°/190°F)	44 I	17	227	82	12.46	Avg = 25; 1 at 85%
	44 P	16	87	205	12.16	4-N; 1 at 30% est., 1 at 10% est.
	46 C	45	42	<10	12.32	3-N; three "scuffed"
121°/121°/96°C (250°/250°/205°F)	42	34	278	34	11.08	Avg = 51; incl. 2 at 100%, 67, 35
	44 A	10	912	99	12.18	Avg = 67; incl. 100, 94, 72, 62, 47
129°/129°/104°C (265°/265°/220°F)	43	16	470	207	11.75	Avg = 41; incl. 94, 93, 47
Oil F (SAE 15W-40)						
121°/121°/96°C (250°/250°/205°F)	44 C	10	363	11	12.20	Avg = 42; incl. 35, 78, 37, 32
Oil G (SAE 15W-40)						
121°/116°/180°C (250°/240°/190°F)	44 M	45	155	<10	11.80	3N; 1 at 90, 1 at 75, 1 at 50 est. Avg = 36

TABLE 11. 6V-53T Engine Screening Summarized Results (Cont'd)

Lubricant (SAE Viscosity Grade)	Test No.	Test Hr	Fe, ppm	Cu, ppm	K. Vis, 100°C, cSt	Liner Scuffing and Comments
Oil J (SAE 10W-30)						
121°/116°/180°C (250°/240°/190°F)	46 A	45	27	<10	9.04	6N
127°/121°/93°C (260°/250°/200°F)	46 B	45	28	<10	8.93	5N; 1 at 20 est.

the used oil copper increased, which was followed by a large iron increase at 30 to 32.5 test hours. Pin bushing distress followed by liner scuffing were the causes for test termination. Finally, the effect of raising only the COT by +14°C (+25°F) over baseline conditions was determined. At 121°/116°/102°C (250°/240°/215°F) conditions, Oil A had acceptable performance, equivalent to that of baseline conditions.

The effect of OST increase with Oil A is presented in Fig. 4 for liner scuffing and in Fig. 5 for used oil iron content. Overall, Oil A was not acceptable for use above 121°C (250°F) oil sump temperature in the two-cycle diesel engine.

Oil B, which is a MIL-L-2104D qualified 75 VI, SAE 30-grade viscosity oil, was evaluated at 121°/116°/88°C (250°/240°/190°F) conditions. The evaluation was stopped at 10 hours because of extremely high used oil iron content (492 ppm). Three cylinders experienced heavy scuffing; however, no piston pin bushing distress was present. No further evaluation was attempted using Oil B.

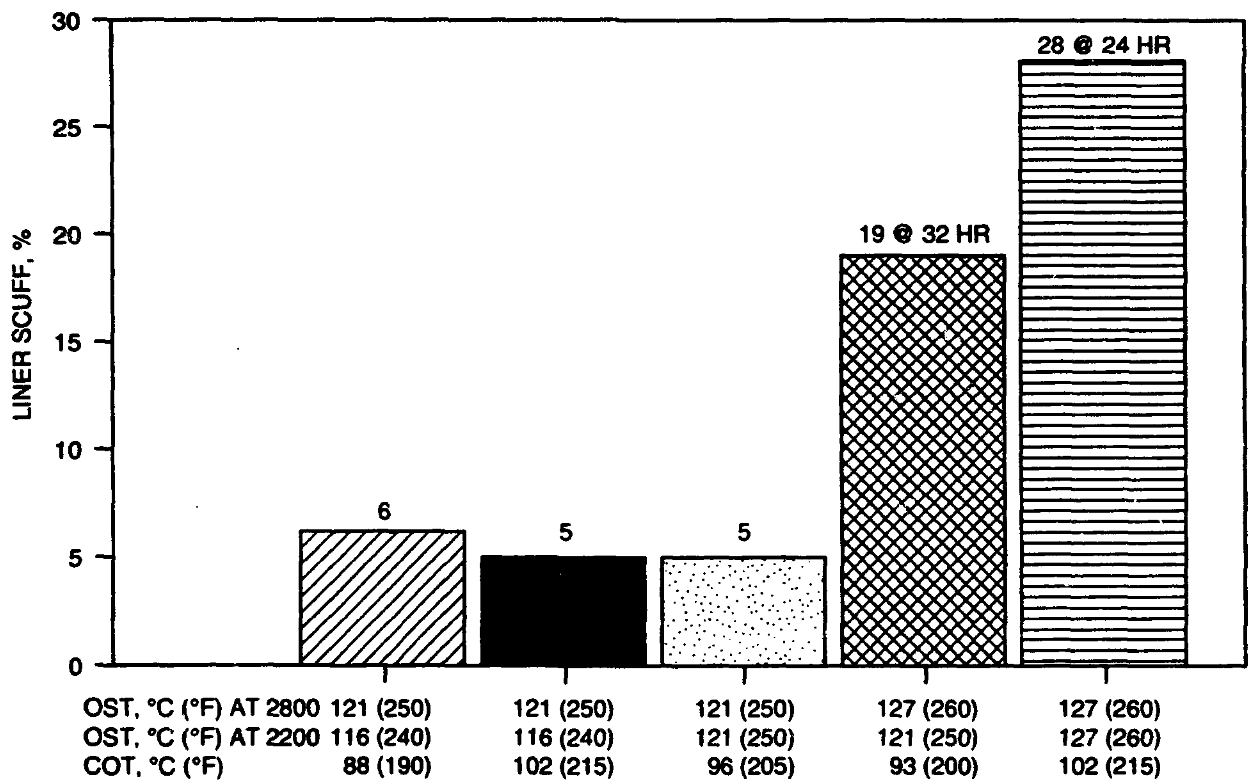

Figure 4. **<u>Effect of OST on liner scuffing with Oil A</u>**

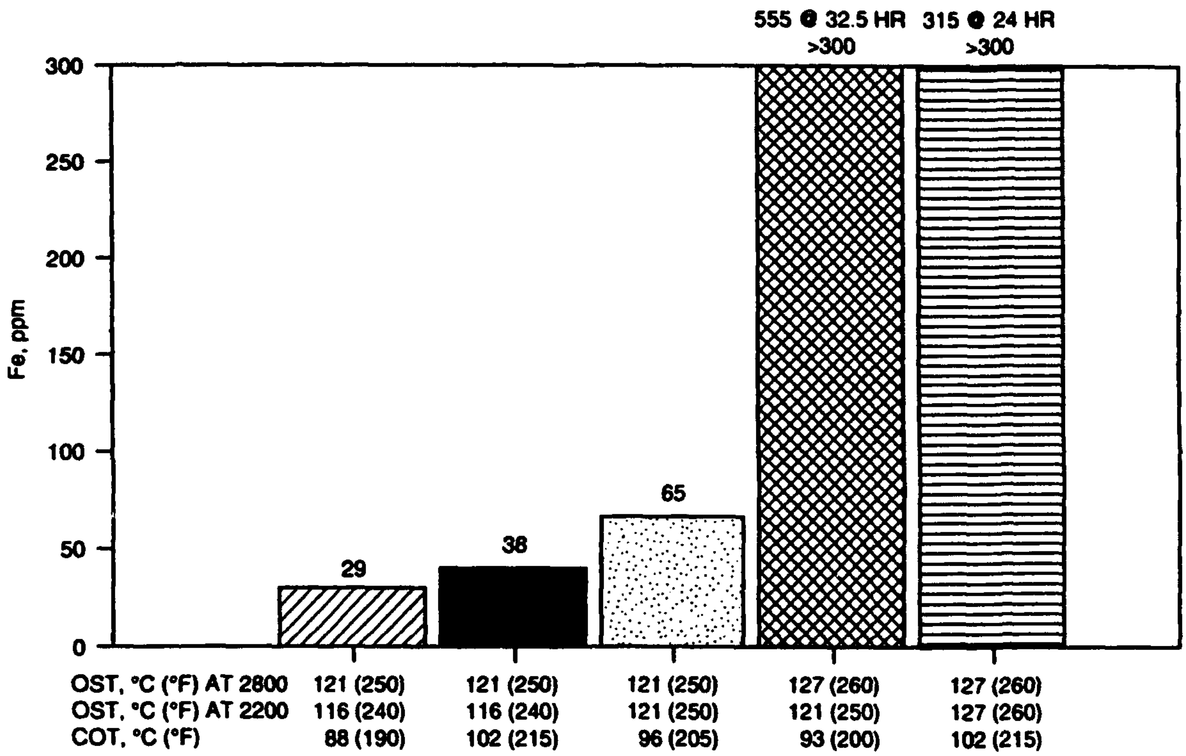

Figure 5. <u>Effect of OST on used oil iron content with Oil A</u>

Oil C is an SAE 30 viscosity grade oil that serves as the reference oil for FTM 355 (REO-203). Two separate evaluations of Oil C were made at 121°/116°/88°C (250°/240°/190°F) conditions, and each evaluation resulted in acceptable performance.

Oil J is an SAE 10W-30 viscosity grade, synthetic-based diesel engine oil. This oil was evaluated at 121°/116°/88°C (250°/240°/190°F) and 127°/121°/93°C (260°/250°/200°F) conditions. In both cases, acceptable performance was observed with no liner distress. These results confirm earlier work (4) that oil volatility is an important consideration in satisfying the requirements of the two-cycle diesel engine. Fig. 6 shows the liner scuffing at 121°C (250°F) OST for various SAE 30-grade oils, while Fig. 7 shows used oil iron content for these SAE 30 oils.

Oil D is an SAE 40 viscosity grade oil, MIL-L-2104D Army Reference Oil. This oil gave marginally acceptable performance at 127°/121°/93°C (260°/250°/200°F) conditions during the 45-hour screening evaluation in the 6V-53T engine. Two cylinders had approximately 25 percent

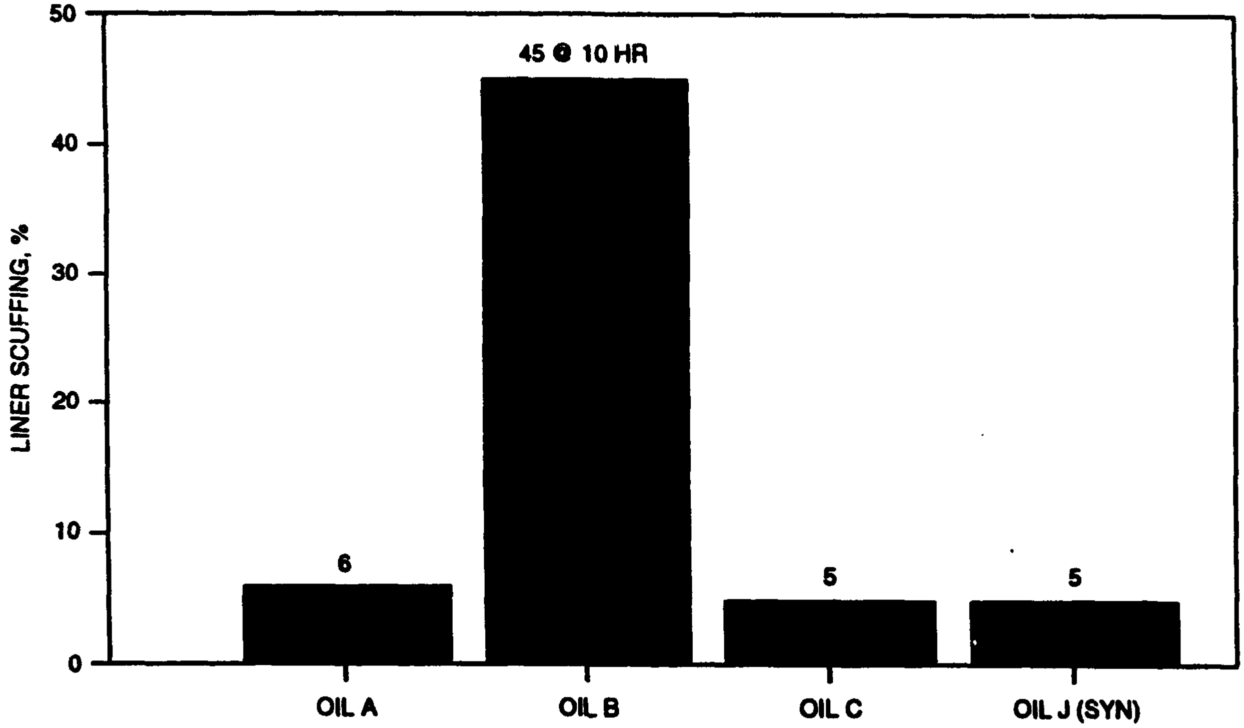

Figure 6. Liner scuffing for SAE 30-grade oils at 121°C (250°F) OST

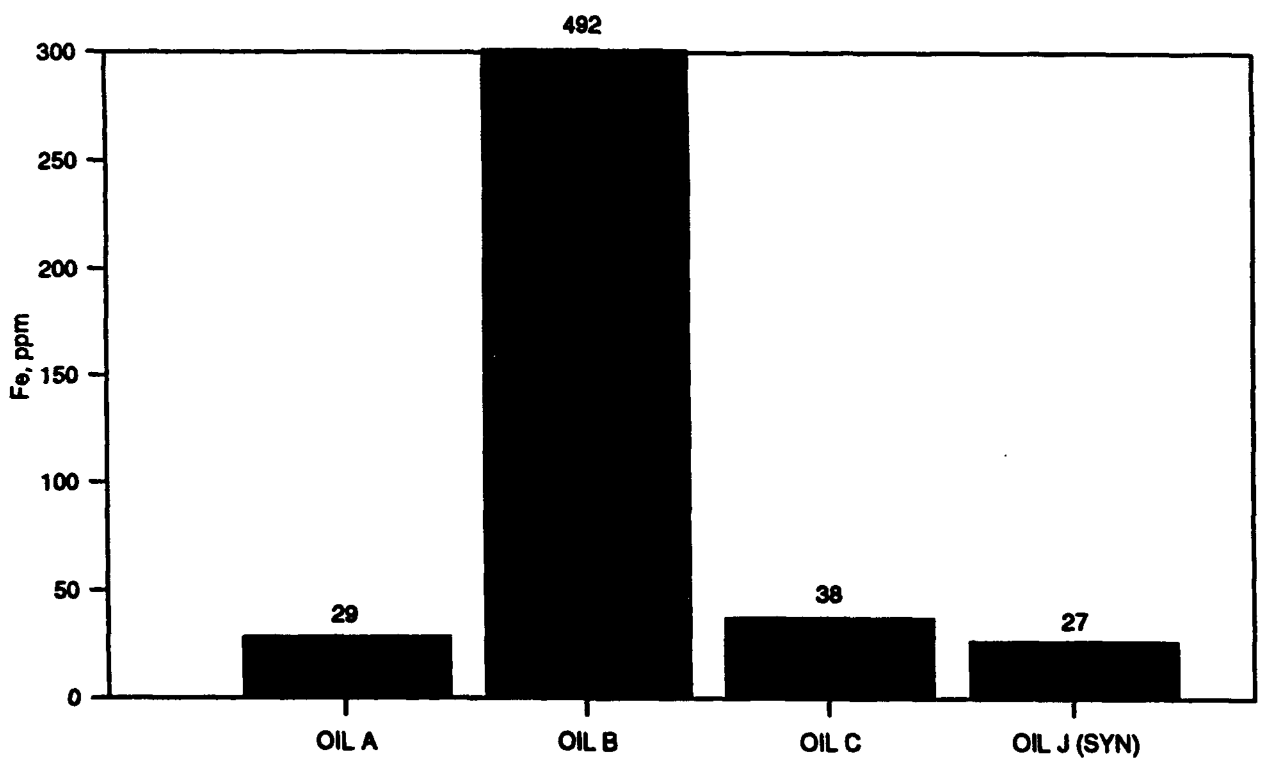

Figure 7. Used oil iron content for SAE 30-grade oils at 121°C (250°F) OST

scuffing. It was also evaluated at 135°/129°/102°C (275°/265°/215°F) conditions and completed only 12.5 hours when the test was stopped because of increasing blowby and high used oil iron content (380 ppm). Overall, the SAE 40-grade petroleum oil had marginally acceptable performance at 127°C (260°F) OST. The effect of OST on liner scuffing with Oil D is shown in Fig. 8, with the effect of OST on used oil iron content shown in Fig. 9.

The effect of oil viscosity and volatility on liner scuffing at 127°C (260°F) OST is shown in Fig. 10. The petroleum SAE 40-grade oil, which has higher viscosity and lower volatility than the petroleum SAE 30-grade, caused less liner scuffing. However, the synthetic SAE 30-grade oil had the least liner scuffing.

Early in the program, Oil E (Army Reference Oil MIL-L-2104D, SAE 15W-40) was evaluated at HT-A conditions of 121°/121°/96°C (250°/250°/205°F). One evaluation was stopped at 10 hours because of extremely high used oil iron content (912 ppm). Severe scuffing was found in five of the six cylinders. A second run under the same conditions was terminated at 34 hours because of high used oil iron content (278 ppm), and three cylinders were found to have substantial liner scuffing. This test was typical Type 1 unacceptable behavior as no connecting rod pin bushing distress was noted.

Oil E was evaluated at 129°/129°/104°C (265°/265°/220°F) conditions. At 16 hours, the evaluation was terminated because of high iron (470 ppm) and copper (207 ppm) in the used oil. This evaluation exhibited Type 2 behavior as the used oil copper increase preceded the iron increase. Engine disassembly revealed connecting rod pin bushing distress and three severely scuffed cylinders.

Three evaluations of Oil E were conducted at 121°/116°/88°C (250°/240°/190°F) (HT-B conditions). Two evaluations were stopped at 16 and 17 hours because of connecting rod pin bushing distress. Discussions with the engine manufacturer led to the hypothesis that the connecting rod pin bushing distress was caused by insufficient break-in operation. BFLRF was following the published engine break-in procedure, but, at the manufacturer's recommendation,

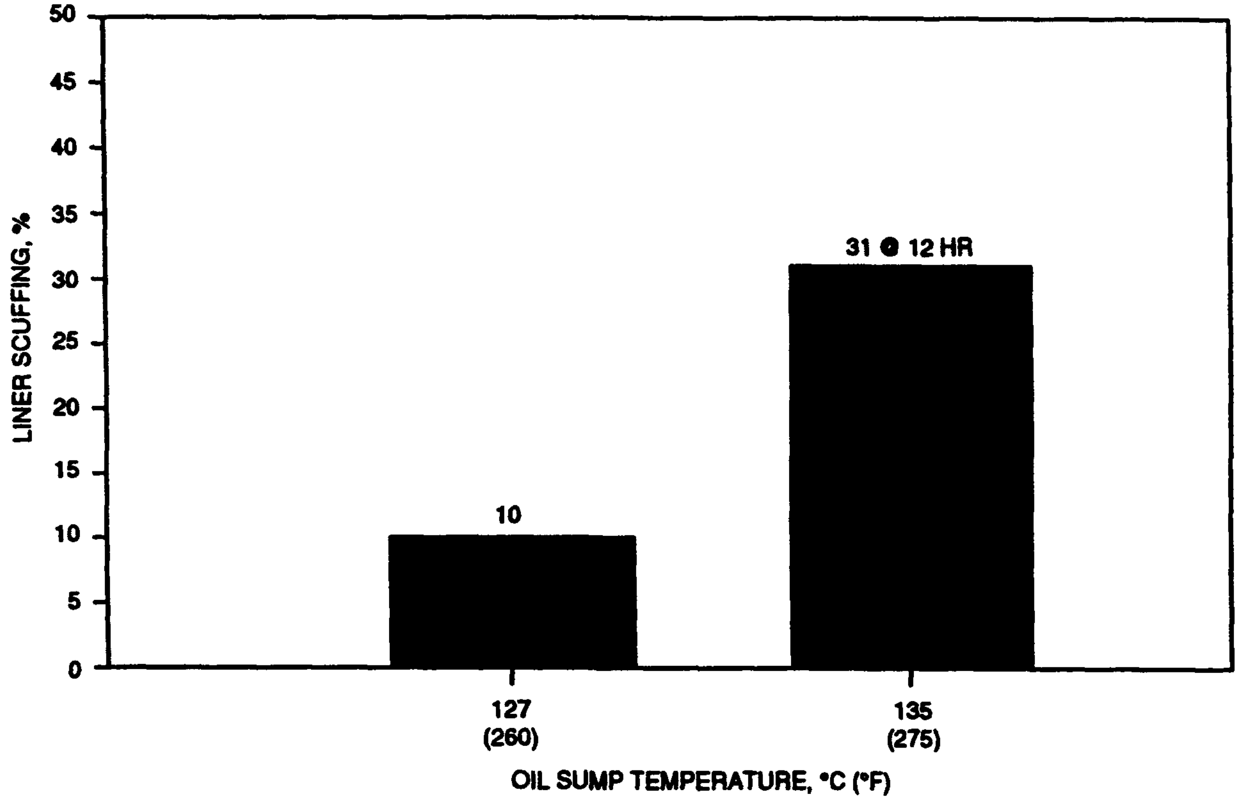

Figure 8. Effect of OST on liner scuffing with Oil D

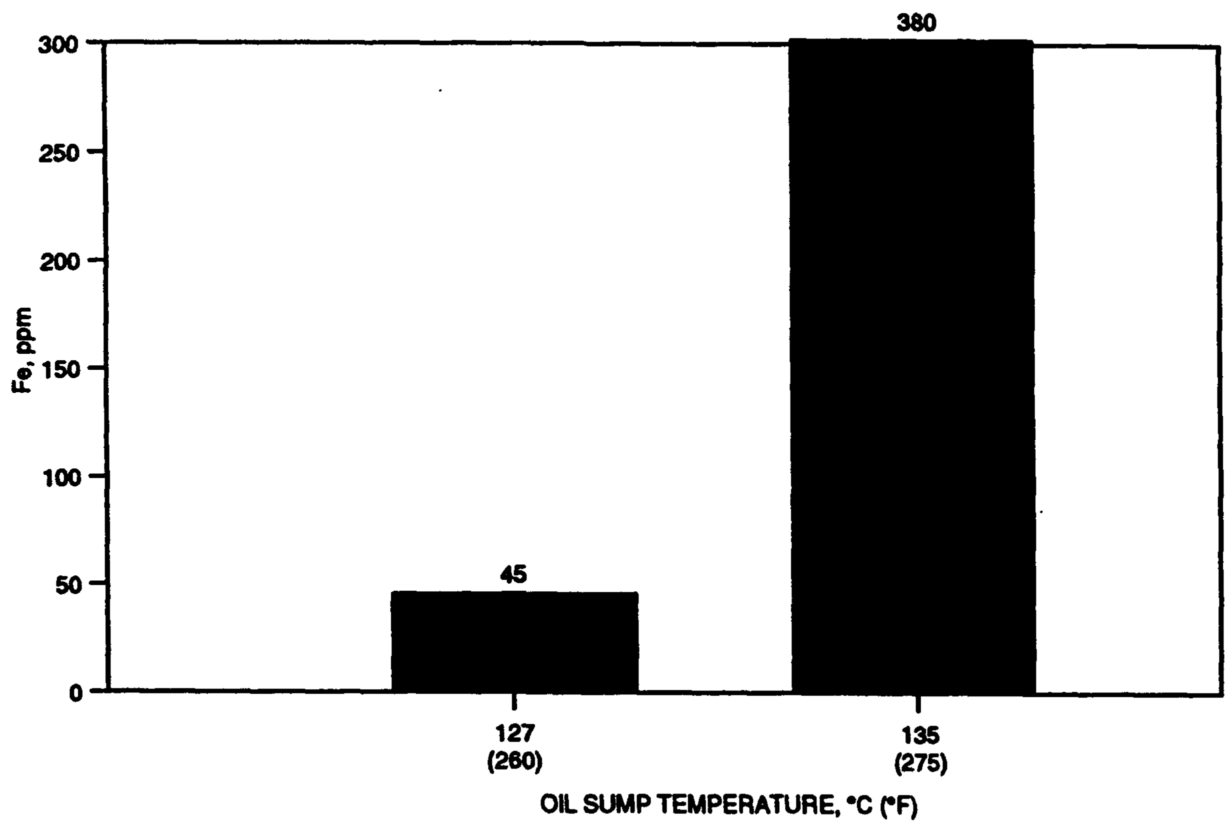

Figure 9. Effect of OST on used oil iron content with Oil D SAE 40

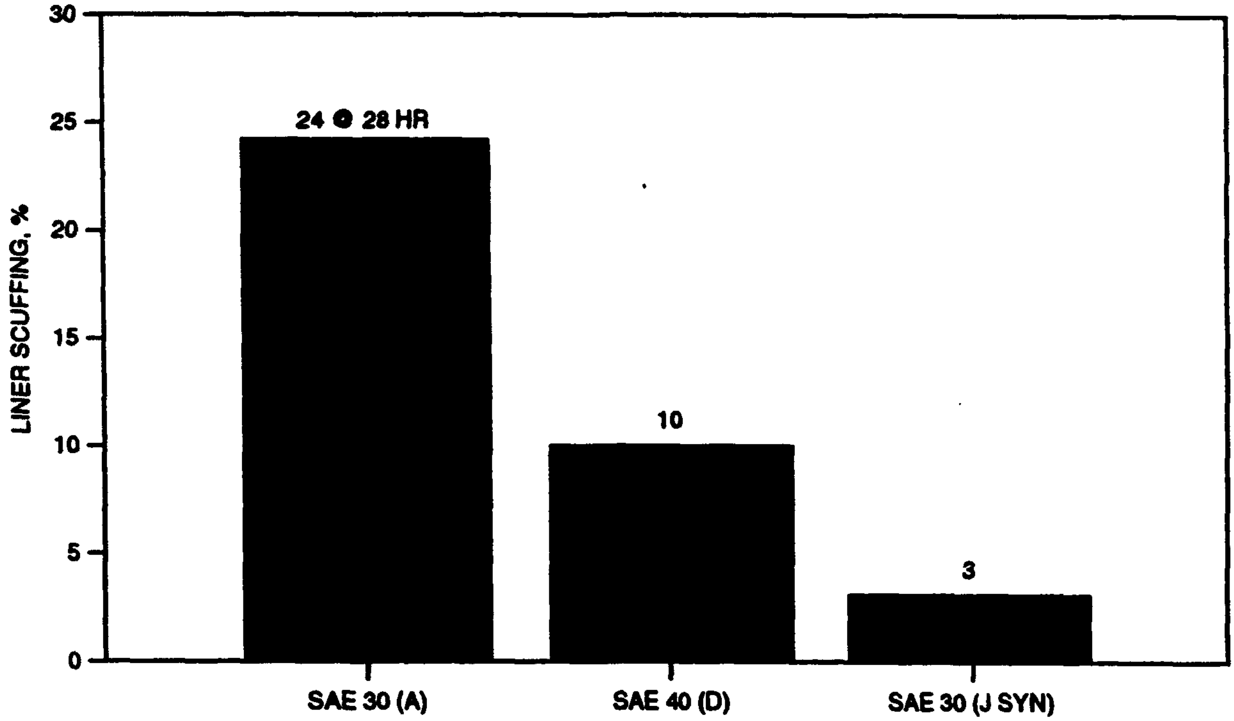

Figure 10. Effect of viscosity on liner scuffing at 127°C (260°F) OST

the run-in procedure was modified to be conducted at 2800 rpm, no load conditions to 3 hours. This change in procedure eliminated most instances of the premature connecting rod pin bushing distress. One evaluation of Oil E at 121°/116°/88°C (250°/240°/190°F) conditions completed the 45 hours and had only minor scuffing in three cylinders.

Two other SAE 15W-40 viscosity grade oils (Oils F and G) were evaluated at 121°/116°/88°C (250°/240°/190°F) conditions. Oil F completed only 10 hours when the test was stopped because of high used oil iron content (363 ppm), and two cylinders were found to have severe liner scuffing. Oil G completed the 45-hour screening procedure with marginal (borderline) results. Three cylinders had substantial scuffing, and three were normal, with the overall average scuffing at 36 percent. Overall, the performance of SAE 15W-40 grade oils at 121°/116°/88°C (250°/240°/190°F) conditions was borderline at best. Disregarding the evaluations where parts or run-in duration were factors, for the three SAE 15W-40 petroleum-based oils, one each had acceptable (Oil E), borderline (Oil G), and unacceptable (Oil F) performance. Petroleum-based SAE 15W-40 oils should not be operated at OSTs of greater than 121°C (250°F) in U.S. Army two-cycle diesel equipment.

In summary, based on the evaluations in the 6V-53T engine, which has trunk-type pistons, U.S. Army two-cycle diesel engines using MIL-L-2104 engine oil should not be operated continuously at >121°C (250°F) OST. Note that two-cycle diesel engines with crosshead-type pistons would be expected to be slightly less sensitive to oil sump temperature increase. It appears that most, but not all, petroleum-based SAE 30-grade oils should be acceptable at 121°C (250°F) OST. Synthetic SAE 30 and petroleum-based SAE 40 appear to be acceptable for continuous operation at 127°C (260°F) OST. Not all petroleum-based SAE 15W-40 oils had acceptable performance at 121°C (250°F) OST, and none would be recommended for use above 121°C.

V. FOUR-CYCLE GM 6.2L DIESEL ENGINE LUBRICANT SCREENING

A. Engine

Engine dynamometer evaluations were conducted at increased oil sump and coolant temperatures in the GM 6.2L diesel engine (5) to determine high-temperature use limits for various Army engine oils. A description of the GM 6.2L engine is presented in TABLE 12, and a photograph of the engine dynamometer installation is shown in Fig. 11. For this evaluation, an engine in the High Mobility Multipurpose Wheeled Vehicle (HMMWV) configuration (145 hp) was used. The GM 6.2L engine is widely used in large numbers in U.S. Army combat and tactical equipment as shown in TABLE 13.

B. Test Cycle

The engine test cycle used in this portion of the program was a modified version of the Army/CRC 210-hour Wheeled-Vehicle (WV) endurance cycle (TABLE 14). This cycle has been correlated to 32,185 kilometers (20,000 miles) of proving ground experience.(3) For high-temperature use limit evaluations, the following 50-hour modified WV procedure was used:

TABLE 12. GM 6.2L Engine Specifications

Engine Type:	Naturally Aspirated, Ricardo Swirl Precombustion Chamber, Four-Stroke, Compression Ignition
No. of Cylinders, Arrangement:	8, V-Configuration
Displacement, liters (in.^{3}):	6.2 (379)
Bore × Stroke, mm (in.):	101 × 97 (3.98 × 3.82)
Compression Ratio:	21.3:1
Rated Power, kW (BHP):	96.6 (130) CUCV, 107.7 (145) HMMWV
Rated Torque, Nm (ft-lb):	325 (240)
Oil Capacity, liters (gal.):	6.62 (1.75)
Engine Structure:	Cast Iron Head and Block (No Cylinder Liners) Aluminum Pistons
Injection System:	Stanadyne DB-2 F/I Pump with Bosch Pintle Injectors

	Time	OST, °F	COT, °F
Max power, 3600 rpm	2 hr	250 + x	190 + x
Idle	1 hr	140	100

where x = increase in °F over standard baseline conditions.

For this evaluation, 14 hours per day test operation was achieved by starting with the 2-hour maximum power condition and alternating 1-hour idle periods for four repetitions, and then completing the day with 2 hours maximum power. The engine was thoroughly flushed between tests but was not disassembled during this program. Oil performance was determined by monitoring used oil wear elements, viscosity, soot content, and oxidation by IR.

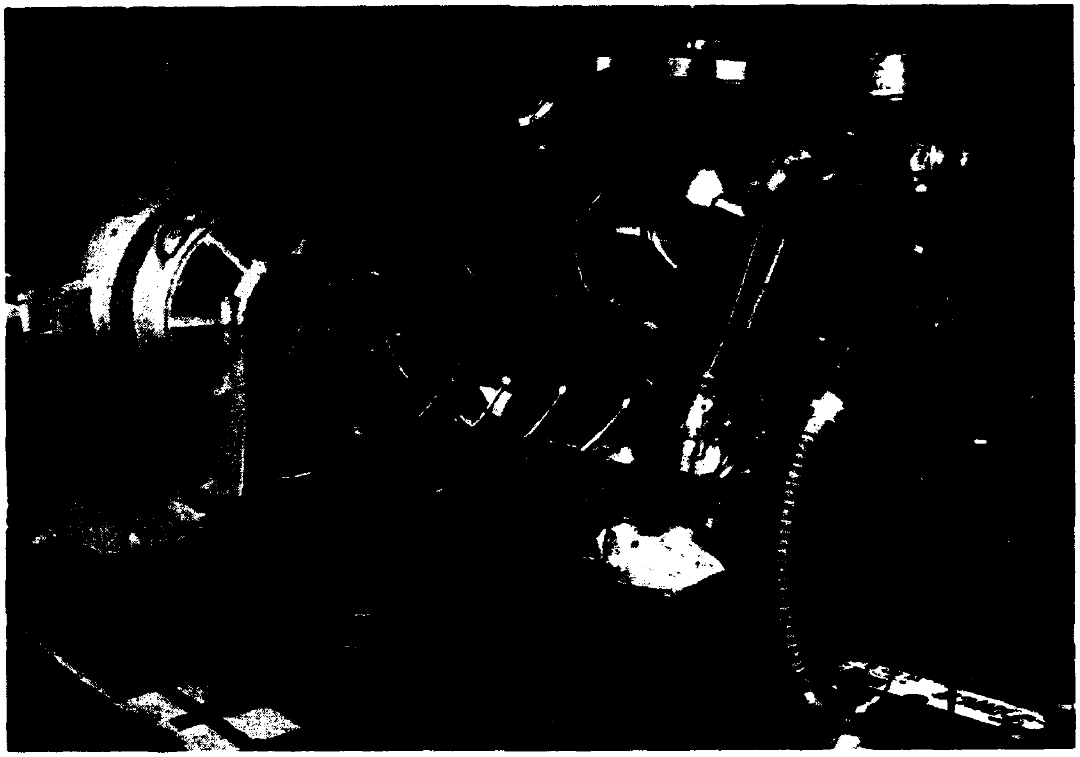

Figure 11. Installation of GM 6.2L engine

TABLE 13. U.S. Army Vehicles Powered by the General Motors 6.2L Diesel Engine

Designation	Description
M996	Truck, Ambulance: 2-Liter, HMMWV
M997	Truck, Ambulance: 4-Liter, HMMWV
M1010	Truck, Ambulance: TAC, 5/4 Ton
M1008	Truck, Cargo: Tactical, 5/4 Ton
M1008A1	Truck, Cargo: Tactical, 5/4 Ton
M1028	Truck, Cargo: Tactical, 5/4 Ton
M1025	Truck, Utility: 4 × 4, 1 1/4 Ton
M1026	Truck, Utility: 4 × 4, 1 1/4 Ton
M1038	Truck, Utility: C60, 1 1/4 Ton
M998	Truck, Utility: C60, 1 1/4 Ton
M1037	Truck, Utility: S250, HMMWV
M1009	Truck, Utility: Tactical, 3/4 Ton
M966	Truck, Utility: Tow Carrier, HMMWV

TABLE 14. Army/CRC 210-Hour Wheeled-Vehicle Endurance Cycle

Period*	Time, hr	Rack/Throttle Setting
1	2	5 min idle followed by slow acceleration to maximum power
2	1	Idle
3	2	Maximum Power
4	1	Idle
5	2	Maximum Power
6	1	Idle
7	2	Maximum Power
8	1	Idle
9	2	Maximum Power
10	10	5 min idle followed by shutdown

* These ten periods yield 14 hours of running with a 10-hour shutdown; this cycle is repeated 15 times for a total test time of 210 hours.

C. Discussion

Three different qualified MIL-L-2104 engine oils (Oils A, B, and E) were evaluated in the GM 6.2L diesel engine at a variety of oil sump temperatures. Properties of Oils A, B, and E are presented in TABLE 2. Summarized results of the high-temperature 6.2L engine lubricant evaluations are presented in TABLE 15. Plots of used oil viscosity and iron wear metal versus time are presented in Appendix B. The performance of each lubricant will be discussed individually, and then comparisons between oils will be made.

Oil A, the MIL-L-2104D, SAE 30 viscosity grade Army Reference Oil, was evaluated at 121°, 127°, 135°, and 143°C (250°, 260°, 275°, and 290°F) OSTs. For each test, coolant-out temperature was held 33°C (60°F) below the OST. Fig. 12 shows the effect of increasing oil sump temperature on used oil viscosity. At 135°C (275°F) OST/102°C (215°F) COT, used oil viscosity experienced a 62-percent increase in 50 hours. At 143°C (290°F) OST/110°C (230°F) COT, the viscosity increase was 79 percent in 50 hours. As shown in Fig. 13, used oil iron content at 50 hours also increased with increasing oil sump temperature. TAN increase was experienced for each test above 121°C (250°F) OST. The evaluation at 143°C (290°F) OST was

TABLE 15. 6.2L High-Temperature Test Results

Test	HT1	HT1A	HT1B	HT1C	HT1C	HT1D	HT1E	HT1F	HT1F	HT1G
Oil, AL-	15212	15212	15212	15212	EOT	14180	14180	14180	EOT	13804
Oil Code	A	A	A	A	A	E	E	E	E	B
OST, °C (°F)	121 (250)	127 (260)	135 (275)	143 (290)	143 (290)	121 (250)	135 (275)	143 (290)	143 (290)	143 (290)
COT, °C (°F)	88 (190)	93 (200)	102 (215)	110 (230)	110 (230)	88 (190)	102 (215)	110 (230)	110 (230)	110 (230)
Hours	50	50	50	50	102	50	50	50	182	50
K. Vis, at 100°C, cSt	16.65	16.87	18.44	20.30	52.47	21.16	19.57	20.48	83.68	25.51
K. Vis, % increase	47	49	62	79	362	56	42	51	516	124
TAN	2.2	6.6	20.2	9.9	15.3	5.6	7.4	7.6	16.4	7.6
TBN	4.0	6.4	0.7	4.5	2.3	3.3	3.3	3.3	1.0	8.6
Soot, wt%	2.2	2.3	2.5	3.5	6.2	2.6	2.9	3.3	8.6	3.6

Test	HT1	HT1A	HT1B	HT1C	EOT1C	HT1D	HT1E	HT1F	EOT1F	HT1G
IR, Absorb/cm										
Oxidation	40	38	207	79	173	35	24	46	77	472
Nitration	5	4	0	0	0	4	0	ND*	12	3
ICP, ppm										
Fe	73	80	104	125	374	99	124	133	546	131
Cr	2	2	4	5	12	4	5	6	3	7
Pb	14	20	76	94	342	10	14	16	<1	16
Cu	14	14	15	14	25	16	19	27	31	18
Sn	12	18	16	24	55	8	10	13	37	9
Al	14	9	8	5	12	5	5	8	17	8
Ni	3	4	3	5	13	6	7	7	ND	ND
Si	16	11	30	12	42	21	24	27	47	27
B	8	8	10	11	10	107	124	<1	ND	ND
Na	4	ND	ND	ND	ND	ND	ND	ND	ND	ND

*ND = Not Determined

TABLE 15. 6.2L High-Temperature Test Results (Cont'd)

Test	HT1	HT1A	HT1B	HT1C	EOT1C	HT1D	HT1E	HT1F	EOT1F	HT1G
ICP, ppm										
Mo	10	11	15	18	42	19	31	35	ND	ND
Mg	1,469	1,968	2,126	2,181	2,295	772	829	903	ND	ND
Ca	19	16	ND	17	ND	ND	ND	ND	3,300	4,600
Ba	5	7	7	7	9	1	1	<1	1	1
P	1,211	1,411	1,520	1,495	1,603	1,610	1,755	1,953	2,500	2,000
Zn	1,597	1,747	1,828	1,875	2,028	2,004	2,269	2,535	2,300	1,600

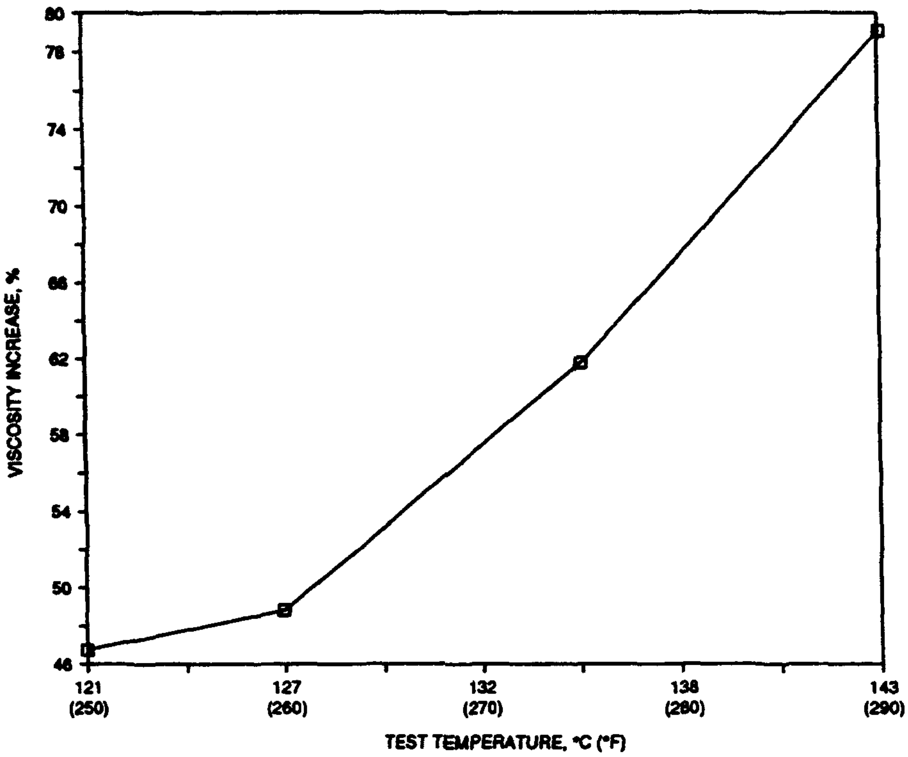

Figure 12. **Effect of increasing sump temperature in 6.2L engine**

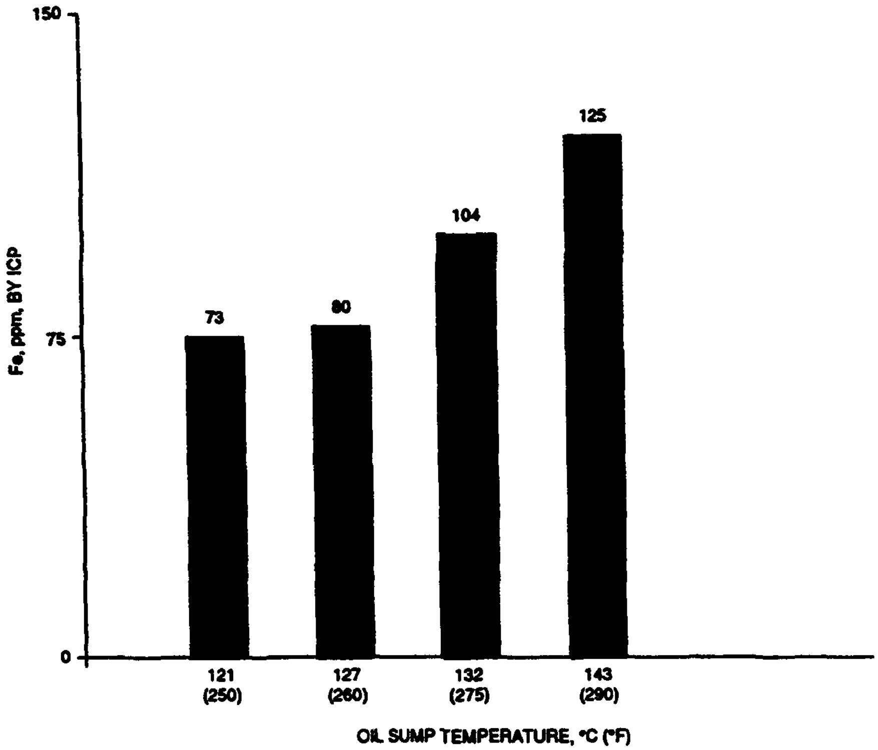

Figure 13. **Used oil iron content at 50 hours (Oil A)**

continued beyond 50 hours and eventually terminated at 102 hours with a viscosity increase of 362 percent and a used oil iron content of 374 ppm, with a total acid number of 15.3. Despite the severely degraded used oil having a large viscosity increase and high TAN and iron contents, it is significant to note that no catastrophic engine distress was observed. The used oil iron content indicates substantial engine wear occurred, and a shortened engine life would be expected.

The differential IR analysis for oxidation and nitration are presented in TABLE 15 for information and general trends only. These determinations were manually calculated from spectra obtained from an old instrument and, as such, are subject to error. Very slight differences in manually picking differential absorption units can result in vastly different oxidation values. Overall, it is estimated that the 6.2L engine starting with fresh Oil A could be operated at up to 143°C (290°F) OST for brief periods of time, not to exceed 50 hours.

Oil E, the MIL-L-2104D, SAE 15W-40 viscosity grade Army Reference Oil was evaluated at 121°, 135°, and 143°C (250°, 275°, and 290°F) OST, with the coolant-out temperature held 33°C (60°F) below the OST. As shown in Fig. 14, approximately the same viscosity increase was experienced in 50 hours at 121°, 135°, and 143°C (250°, 275°, and 290°F) OST. It appears that the complex relationships of factors that influence used oil viscosity increase--oxidation, soot content, viscosity decrease from Viscosity Index Improver (VII) shear, and fuel dilution--contributed to the nearly constant viscosity increase at increasing OSTs. Fig. 15 shows the increase in used oil iron content with increasing OST. At each set of operating conditions, the used oil TAN increased above a conservative oil drain limit of 5.0.

The evaluation of Oil E at 143°C (290°F) was continued beyond 50 hours and eventually terminated at 182 hours. At this point, the used oil viscosity had increased 516 percent, and the total acid number was 16.4, with 546 ppm of iron content. As with Oil A at 143°C (290°F) OST, Oil E at 143°C (290°F) OST degraded substantially in 182 hours; however, no catastrophic engine distress was observed. The high used oil iron content indicated substantial engine wear had occurred, and a shortened engine life would be expected. Overall, it is felt that the 6.2L

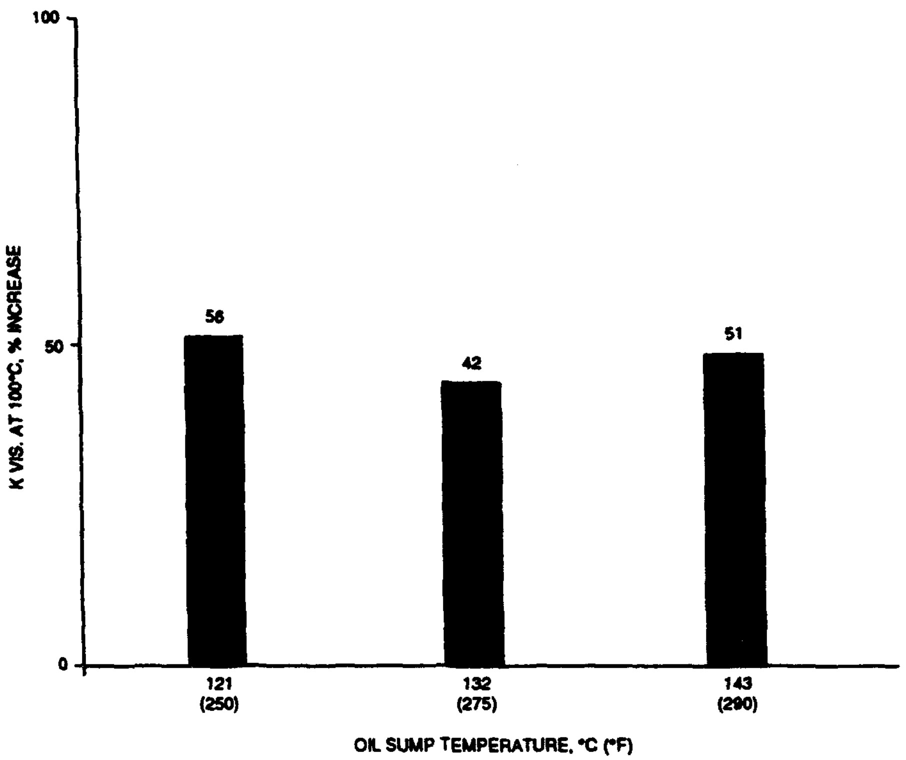

Figure 14. Viscosity increase versus oil sump temperature at 50 hours (Oil E) in 6.2L engine

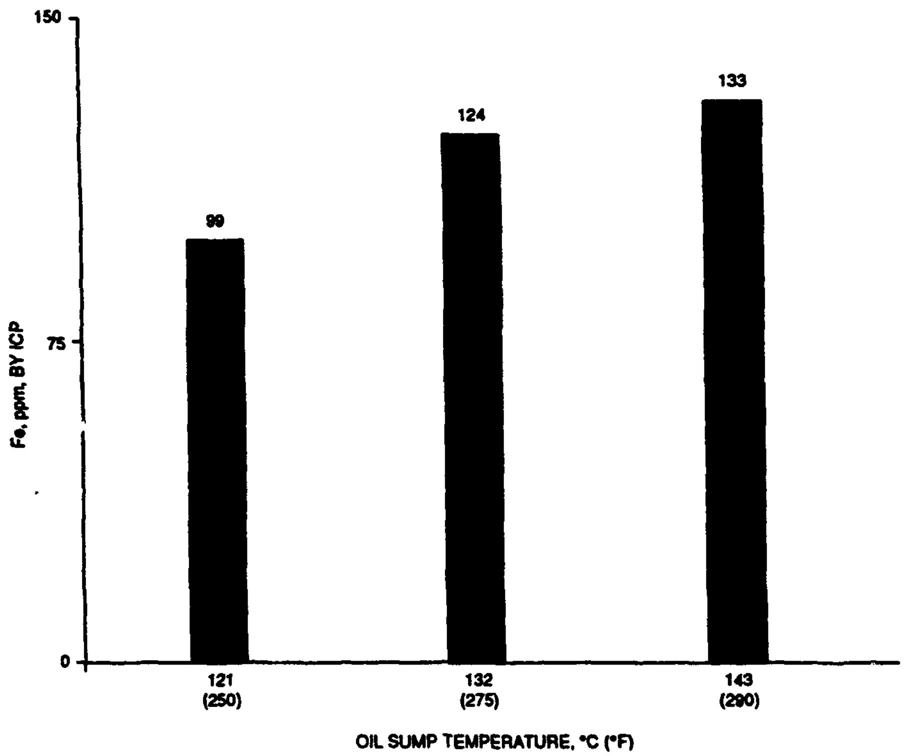

Figure 15. Used oil iron content at 50 hours (Oil E) in 6.2L engine

engine and fresh Oil E could be operated at up to 143°C (290°F) OST for brief periods of time not to exceed 50 hours.

Oil B, which is a MIL-L-2104D qualified product (SAE 30 viscosity grade), was evaluated at only 143°C (290°F) OST in the 6.2L engine. At 50 hours, Oil B had experienced a 124-percent viscosity increase and had a 131-ppm iron content.

Fig. 16 shows comparative used oil iron contents for Oils A, B, and E at 290°F OST, while Fig. 17 shows the percent viscosity increases. The used oil iron contents at 50 hours were nearly the same for all three oils. The viscosity increases show Oil B to have the least oxidation stability, with a 220-percent viscosity increase at 50 hours. Extrapolating from Fig. 17, Oil A took 68 hours to reach this viscosity increase, and Oil E took nearly 100 hours. At 10 hours, Oil B had approximately the same viscosity increase as Oils A and E had at 50 to 75 hours.

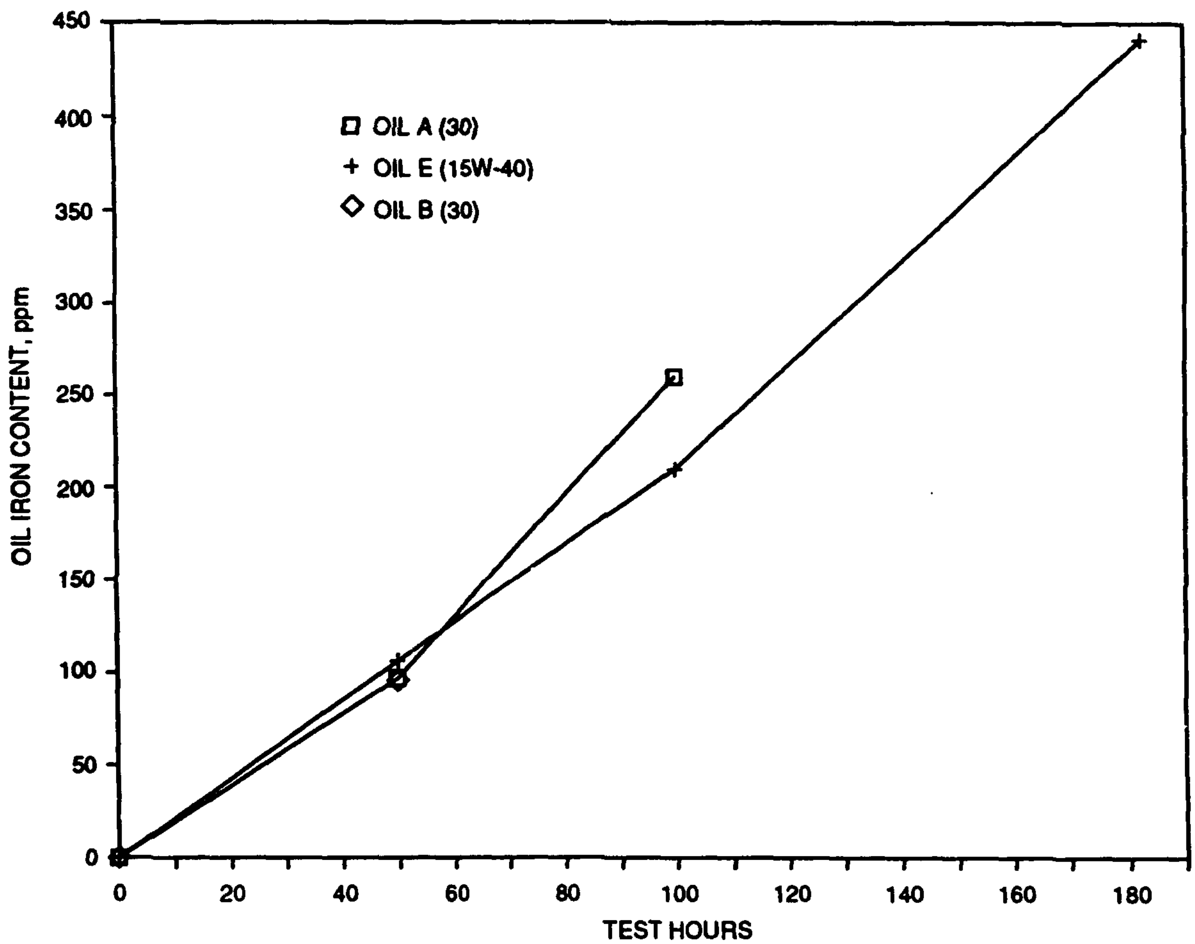

Figure 16. Used oil iron contents at 143°C (290°F) OST for Oils A, B, and E

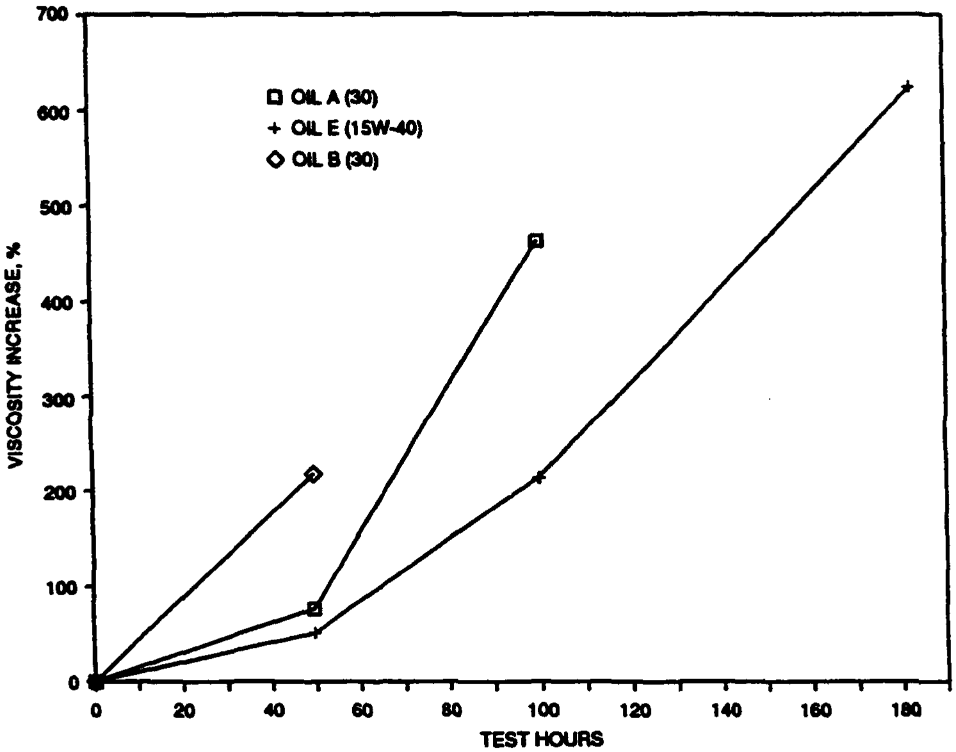

Figure 17. Viscosity increases at 143°C (290°F) OST for Oils A, B, and E

Based on viscosity increase (starting with fresh oil), it is estimated that even the least oxidatively stable of these oils (Oil B) could be operated at 290°F OST for perhaps a maximum of 10 hours without serious problems in the 6.2L engine. Overall, it is felt that MIL-L-2104D engine oils can safely operate continuously in the 6.2L diesel engine at OSTs greater than 250°F.

VI. FOUR-CYCLE CUMMINS VTA-903T DIESEL ENGINE LUBRICANT SCREENING

A. Engine

Engine dynamometer evaluations were conducted at increased oil sump and coolant temperatures in the Cummins VTA-903T engine to determine high-temperature use limits for various Army engine oils. A description of the Cummins VTA-903T engine is presented in TABLE 16, and a photograph of the engine dynamometer installation is shown in Fig. 18. Army equipment powered by V-903 series engines are listed in TABLE 17 and include Bradley Fighting Vehicles, the Armored Combat Earthmover, and the carrier for the Multiple Launch Rocket System (MLRS).

TABLE 16. Engine Specifications for the Cummins VTA-903T Engine

Model:	VTA-903T
Engine Type:	Four-Cycle, Compression Ignition, Direct Injection
Cylinders:	8, V-Configuration
Displacement, liters ($in.^3$)	14.8 (903)
Bore, cm (in.)	14.0 (5.5)
Stroke, cm (in.)	12.1 (4.75)
Compression Ratio:	15.5:1
Fuel Injection:	Cummins PT
Rated Power, kW (BHP)	373 (500) at 2600 rpm
Rated Torque, Nm (ft-lb)	1369 (1010) at 2400 rpm

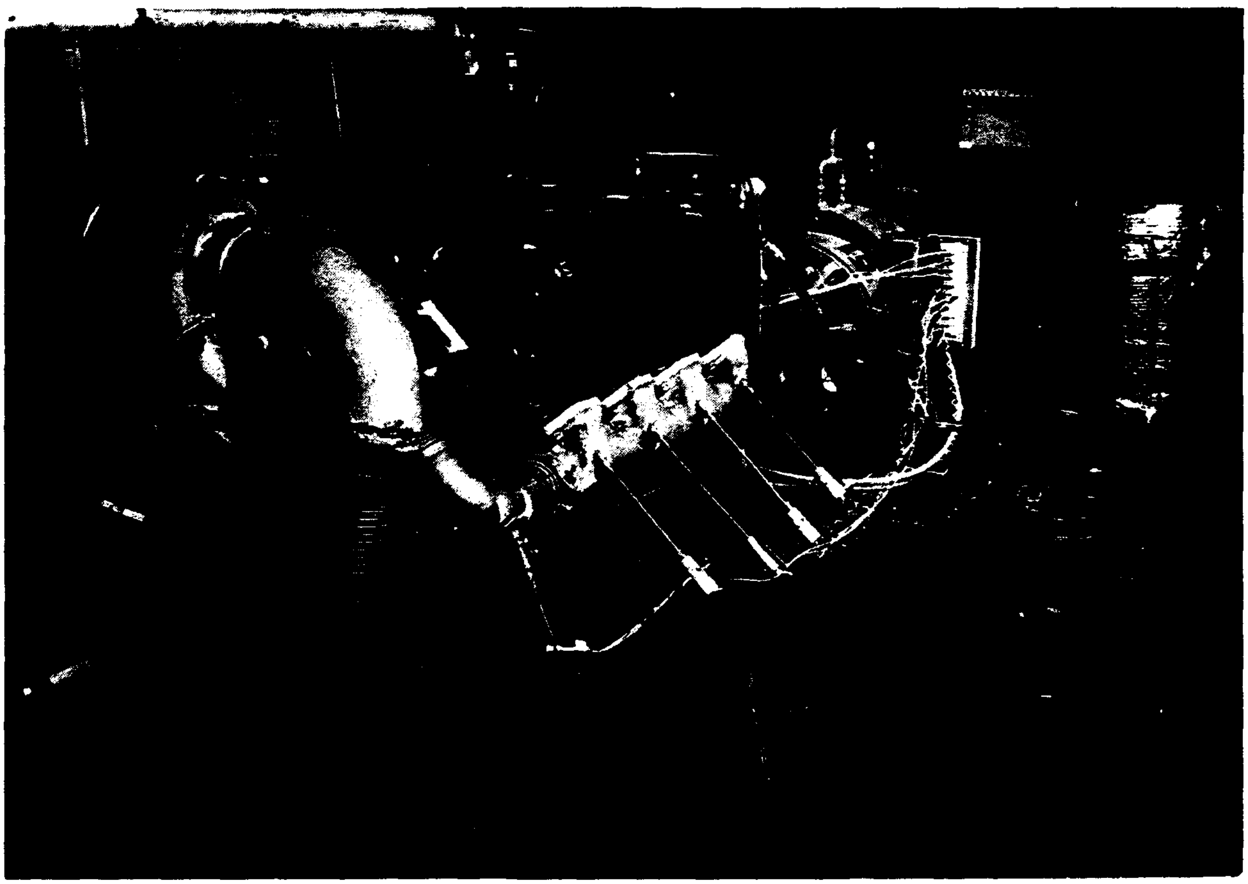

Figure 18. VTA-903T engine dynamometer installation

TABLE 17. Army Equipment With Cummins V-903 Engines

End Item/Nomenclature	Engine
M2 INF Fighting Vehicle	VTA-903T
M3 CAV Fighting Vehicle	VTA-903T
M9 Armored Combat Earthmover	VTA-903
M993 Carrier MLRS	VTA-903T
9125TC 140T Crane	V-903
M320RT 20T Crane Carrier	V-903

B. Test Cycle

The engine test cycle used in this portion of the program was the modified version of Method 355 (2) as described in TABLES 8 and 9, except for the maximum power point of the VTA-903T being at 2600 rpm. As discussed in Section IV of this report, the engine operating variables are presented in the following format:

OST, °C (°F) at 2600 rpm/OST, °C (°F) at 2200 rpm/COT, °C (°F).

The generalized formula for the VTA-903T operating conditions is:

$$x°F \, / \, x\text{-}10°F \, / \, x\text{-}60°F$$

where x = OST, °F at 2600 rpm. A 50-hour screening test procedure was used with the VTA-903T engine (10 × 5 hours, Period 1 from TABLE 8). During each test, oil samples were withdrawn and analyzed at 5-hour intervals. Between evaluations, the used oil was flushed, and fresh oil was charged to the engine. The engine was rebuilt as needed.

C. Discussion

Six different engine oils were evaluated in the VTA-903T engine at various oil sump temperatures. Oils A, D, E, F, H, and I from TABLE 2 were included. TABLE 18 presents a listing of the test conditions for each oil evaluated. Summarized results of the high-temperature VTA-903T engine lubricant evaluations are presented in TABLE 19. Plots of used oil viscosity and iron content versus time are presented in Appendix C.

Excessive intake and exhaust valve guide wear was a continuing problem during these evaluations in the VTA-903T engine. The wear occurred during normal operating temperature baseline tests as well as during higher temperature runs. A revised test cell installation that reduced engine vibration was investigated; however, valve guide distress was not reduced. New and used valve guides were examined to determine the wear mechanism. Two used and one new valve guide were cut on the longitudinal axis and examined at 10 to 40× magnifications. The guides have a spiral threadlike groove on the inner diameter that showed severe wear on the used guide. In the worst case, the "thread" had been completely worn until flush with the underlying surface. The wear seems to represent side-thrust loading since wear, in all cases, was more severe in two zones separated by 180° rotation. In one of the lesser worn guides, it was noted that the metal was being deformed in one preferential longitudinal direction. This deformation would indicate that the greatest loading of this zone was occurring during valve opening and lesser loads were involved during valve closing. Overall, the valve guide wear did not appear to be lubricant related.

The performance of each lubricant is discussed individually, and then comparisons between the oils are made. Oil A, the MIL-L-2104D, SAE 30 viscosity grade Army Reference Oil, was evaluated at 121°, 135°, 143°, and 154°C (250°, 275°, 290°, and 310°F) oil sump temperature at maximum power conditions (2600 rpm). Oil A completed each of these 50-hour evaluations. The end-of-test viscosities at 100°C are compared to the new oil viscosity in Fig. 19, and a plot of viscosity (K. Vis, 100°C) with test hours is presented in Fig. 20. Used oil viscosity had minor increases, except for the trial at 154°C (310°F) oil sump temperature, which encountered a 25-percent increase and appeared to be approaching a "breakpoint" of rapid viscosity increase. Used oil total acid number increases for the four tests are plotted in Fig. 21 and also show a relatively large TAN increase (+4.7) for the 154°C (310°F) OST run. Overall, Oil A appears to have acceptable performance at up to 143°C (290°F) OST for at least 50 hours.

TABLE 18. Oil Evaluations in the VTA-903T Engine

Oil	Max OSTs, °C (°F)
A	121 (250) 135 (275) 143 (290) 154 (310)
D	143 (290)
E	135 (275) 143 (290)
F	143 (290)
H	143 (290)
I	143 (290)

Oil D, the U.S. Army MIL-L-2104D, SAE 40 viscosity grade reference oil, was evaluated at 143°C (290°F) OST. Oil D completed the scheduled 50 hours at 143°/138°/110°C (290°/280°/230°F) conditions, with minimal viscosity and TAN increase. Overall, Oil D would be projected to perform adequately at 143°C (290°F) OST in the VTA-903T engine for greater than 50 hours.

Oil E is the U.S. Army MIL-L-2104D, SAE 15W-40 viscosity grade reference oil. Evaluations were conducted at 135°C (275°F) and 143°C (290°F) maximum OST. The evaluation at 135°/129°/102°C (275°/265°/215°F) completed the scheduled 50 test hours, and used oil degradation was minimal. The trial at 143°/138°/110°C (290°/280°/230°F) was stopped at 12.5 hours to investigate the reason for high exhaust temperature. The heads were removed, and several worn exhaust valve guides and some exhaust valve seal distress were observed. These conditions were not believed to be lubricant related. Overall, Oil E would be projected to perform adequately at 135°C (275°F) OST in the VTA-903T for greater than 50 hours. Performance at 143°C (290°F) was not fully defined.

TABLE 19. VTA-903T Engine Summary of Results

Test No.	Oil	Oil Code	SAE Grade	Test Hr	OST, °C (°F) at 2600	OST, °C (°F) at 2200	COT, °C (°F)	K. Vis, 100°C, cSt	TAN	TBN	Soot, wt% by TGA	Fe, ppm	Cu, ppm	Pb, ppm	Sn, ppm	Cr, ppm	Al, ppm	Oxidation, A/cm by DIR
CHT-1	AL-15689	A	30	50	135 (275)	129 (265)	102 (215)	12.10	4.0	5.0	0.25	74	56	43	22	12	8	15
CHT-1A	AL-15689	A	30	6.5	143 (290)	138 (280)	110 (230)	11.64	ND*	ND	ND	ND	ND	ND	ND	ND	ND	ND
** Engine Rebuilt **																		
CHT1A1	AL-15689	A	30	50	143 (290)	138 (280)	110 (230)	12.36	4.6	6.2	0.05	55	58	22	26	8	5	27
CHT-1B	AL-16215	E	15W-40	24	135 (275)	129 (265)	102 (215)	12.71	ND	ND	ND	26	ND	ND	ND	ND	ND	ND
CHT-1C	AL-16215	E	15W-40	50	135 (275)	129 (265)	102 (215)	13.15	3.0	3.5	0.07	33	9	3	4	4	2	21
CHT-1D	AL-16215	E	15W-40	12.5	143 (290)	138 (280)	110 (230)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CHT-2	AL-15689	A	30	50	121 (250)	116 (240)	88 (190)	11.55	4.2	5.0	0.15	39	11	31	<15	8	<1	17
CHT-2A	AL-15689	A	30	50	121 (250)	116 (240)	88 (190)	6.61	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CHT-3	AL-14570	F	15W-40	50	143 (290)	138 (280)	110 (230)	12.67	3.1	5.5	0.42	51	19	9	<15	6	7	20
CHT-4	AL-19013	D	40	50	143 (290)	138 (280)	110 (230)	14.41	3.6	3.2	0.45	50	13	9	<15	14	7	13
CHT-5	AL-15689	A	30	24.8	154 (310)	149 (300)	121 (250)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
** Engine Rebuilt **																		
CHT-5A	AL-19230	A	30	50	121 (250)	116 (240)	88 (190)	11.42	3.6	3.3	0.16	89	64	<60	<15	15	6	5
CHT-6	AL-19230	A	30	50	154 (310)	149 (300)	121 (250)	14.21	7.7	2.9	ND	42	11	18	<15	9	7	60
CHT-7	AL-19475	H	15W-40	50	143 (290)	138 (280)	110 (230)	13.85	6.9	5.3	ND	71	64	24	1	16	5	24
CHT-8	AL-19424	I	15W-40	50	143 (290)	138 (280)	110 (230)	13.77	3.4	2.1	ND	51	31	6	<1	8	7	18

*ND = Not Determined

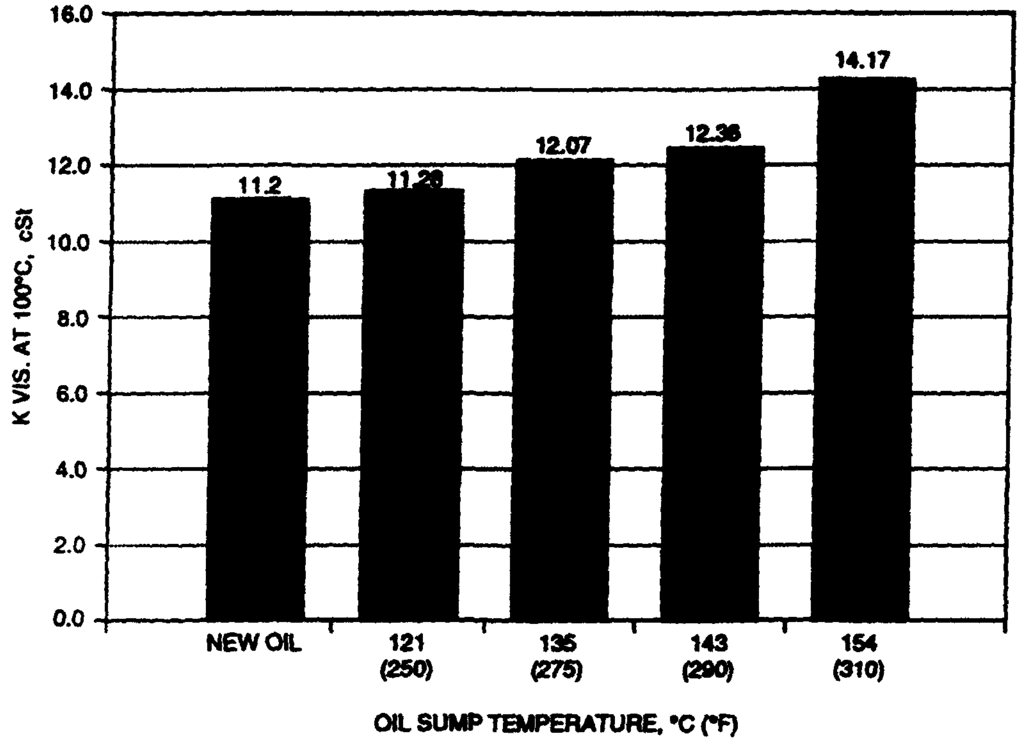

Figure 19. End-of-test viscosity at 100°C for Oil A (50 hours) in a VTA-903T engine

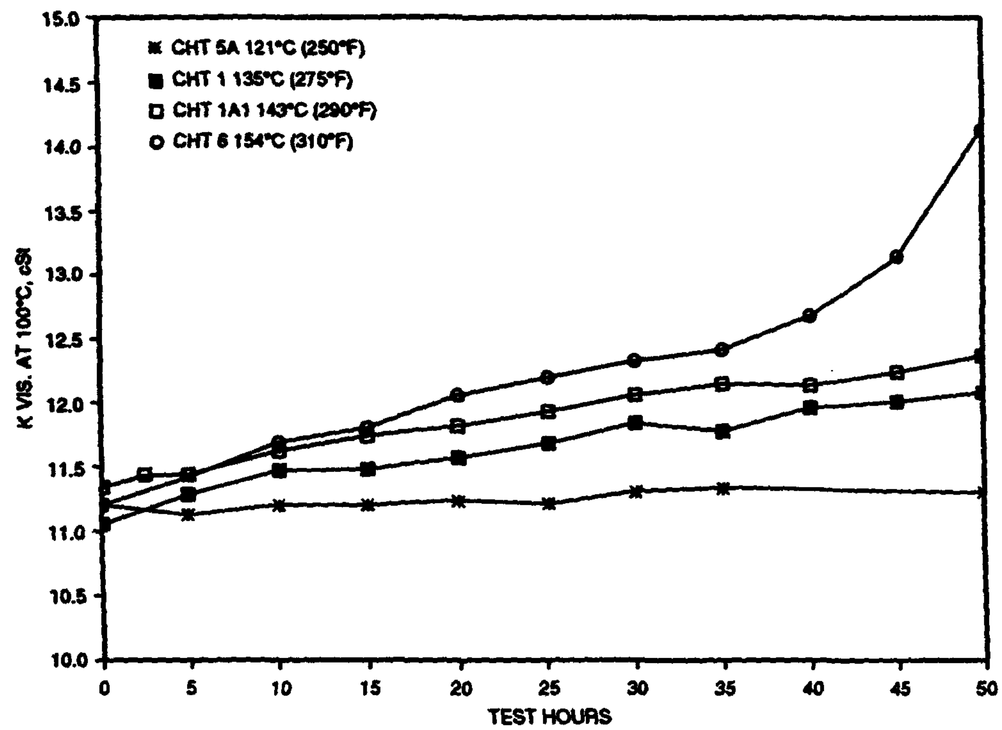

Figure 20. Kinematic viscosity at 100°C versus test hours (Oil A) in a VTA-903T engine

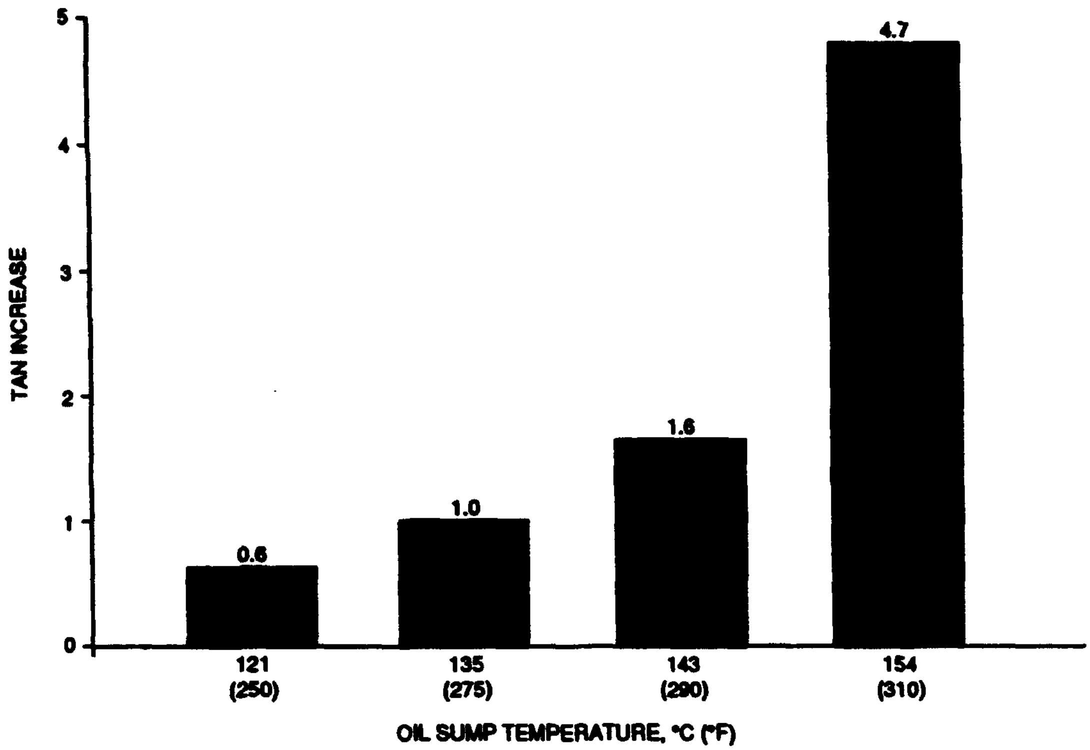

Figure 21. Total acid number increase at 50 hours (Oil A) in a VTA-903T engine

Three commercially available, SAE 15W-40 viscosity grade oils (Oils F, H, and I) were evaluated in the VTA-903T engine at 143°/138°/110°C (290°/280°/230°F) conditions. Oil F met oil performance classifications for MIL-L-2104D and API CD, while Oils H and I were classified API CE. All three oils completed the scheduled 50 hours at 143°/138°/110°C (290°/280°/230°F) with no problems. End-of-test used oil condition of the three oils revealed some differences. Oils F and I had very minor viscosity changes, similar iron and copper wear metal accumulations, and TAN increases of 0.3 (Oil F) and 1.0 (Oil I). Oil H had a TAN increase of 3.7 and higher iron and copper wear metals, while only a minor viscosity decrease occurred. Overall, Oils F and I would be expected to perform adequately for greater than 50 hours at 143°C (290°F) OST, while Oil H would not be recommended for greater than 50 hours at 143°C (290°F) OST because of acid number increase.

Test CHT-8 (Oil I) at 143°/138°/110°C (290°/280°/230°F) was conducted beyond 50 hours to confirm longer term operation at the increased oil sump temperature. At 89 hours, the engine failed when the piston in cylinder 2R fractured. Also, the piston in cylinder 2L had a hole in the piston crown. A recurring problem at elevated temperatures with this engine has been the seal between the copper injector tube and the fire deck. This seal would loosen, allowing coolant to leak into the cylinders; thus, it is felt that the two piston failures were related to coolant leaking past the injector tubes into the cylinders. This leakage was confirmed by a loss of 19 liters (5 gallons) of coolant from the 53-liter (14-gallon) system. Most of these 19 liters was lost to the sump, with the remainder leaving via blowby breather as steam. Because of the coolant leakage, it is felt that failures of the pistons were not lubricant related. This test completed the scheduled evaluations in the VTA-903T engine.

Overall, starting with fresh oil, MIL-L-2104 and commercial API CD and CE engine oils had adequate performance in the VTA-903T for up to 50 hours at 143°/138°/110°C (290°/280°/230°F) conditions. Engine hardware problems such as injector cup seal failure preclude extended operation at increased operating temperatures in the VTA-903T engine.

VII. CONCLUSIONS

The high-temperature use limits for military and commercial diesel engine oils were found to be engine specific. The two-cycle 6V-53T engine with trunk-type pistons was the most sensitive of the three engines investigated with respect to oil properties such as viscosity grade and volatility. Catastrophic engine distress is probable if certain oils are used at increased operating temperatures in this engine. Operation of the 6.2L engine at increased temperatures caused oil degradation. Oil thickening from oxidation and soot accumulation was observed as was TAN increase. While the oil degraded substantially in the 6.2L engine, overall engine operation continued with no apparent problems. Long-term wear problems would be expected if the engine continued operation using the highly acidic, very viscous, degraded oil. The VTA-903T engine was not sensitive to the oil used, and oil degradation at increased temperatures was fairly mild. Unfortunately, operation of the VTA-903T engine at increased temperatures was limited by engine hardware problems that were not lubricant related.

Overall summarized results for the 45-hour 6V-53T engine tests are presented in TABLE 20 in terms of acceptable, borderline acceptable, and unacceptable performance. Unacceptable performance was defined as not completing the 45 hours and/or >45 percent liner scuffing. Most, but not all, petroleum-based SAE 30 viscosity grade oils should be acceptable at 121°C (250°F) OST. Synthetic SAE 30 and petroleum-based SAE 40 appear to be acceptable for continuous operation at 127°C (260°F) OST in excess of 45 hours. Not all petroleum-based SAE 15W-40 oils had acceptable performance at 121°C (250°F) OST, and none would be recommended for use above 121°C (250°F).

Summarized results for the 50-hour 6.2L engine tests are presented in TABLE 21. Unacceptable oil performance in this engine at increased operating temperatures consisted of high TAN (>10) and, during extended tests, viscosity increase. Oil viscosity grade of the unused oil was not a

TABLE 20. 6V-53T Engine Results Summary

Oil	SAE Grade	Max OST, °C (°F)	Overall Performance at 45 hours
A	30	121 (250) 127 (260)	Acceptable Unacceptable
B	30	121 (250)	Unacceptable
C	30	121 (250)	Acceptable
D	40	127 (260) 135 (275)	Acceptable Unacceptable
E	15W-40	121 (250) 129 (265)	BL Acceptable Unacceptable
F	15W-40	121 (250)	Unacceptable
G	15W-40	121 (250)	BL Acceptable
J (synthetic)	10W-30	121 (250) 127 (260)	Acceptable Acceptable

BL = Borderline
U = Unacceptable (<45 hours or scuffing)

TABLE 21. 6.2L Engine Results Summary

Oil	SAE Grade	Max OST, °C (°F)	Overall Oil Performance at 50 hours
A	30	121 (250)	Acceptable
		127 (260)	BL (TAN > 5)
		135 (275)	U (TAN > 10)
		143 (290)	BL (TAN > 5)
			(U at 102 hr - viscosity & TAN incr)
B	30	143 (290)	BL (TAN > 5, %vis incr > 100)
E	15W-40	121 (250)	BL (TAN > 5)
		135 (275)	BL (TAN > 5)
		143 (290)	BL (TAN > 5)
			(U at 182 hr - viscosity & TAN incr)

BL = Borderline Acceptable
U = Unacceptable

TABLE 22. VTA-903T Engine Results Summary

Oil	SAE Grade	Max OST, °C (°F)	Overall Oil Performance at 50 hours
A	30	121 (250)	Acceptable
		135 (275)	Acceptable
		143 (290)	Acceptable
		154 (310)	BL (TAN > 5)
D	40	143 (290)	Acceptable
E	15W-40	135 (275)	Acceptable
F	15W-40	143 (290)	Acceptable
H	15W-40	143 (290)	BL (TAN > 5)
I	15W-40	143 (290)	Acceptable

BL = Borderline Acceptable
U = Unacceptable

major factor in overall oil performance. The oils investigated had borderline acceptable performance for up to 50 hours at 143°C (290°F) OST. Operation of up to 182 hours at 143°C (290°F) OST was achieved; however, the used oil was severely degraded.

Summarized results for the 50-hour VTA-903T engine tests are presented in TABLE 22. Borderline oil performance was defined as TAN > 5. SAE oil grades 30, 40, and 15W-40 had approximately the same high-temperature performance in this engine. One SAE 15W-40 was borderline at 143°C (290°F) OST. The oils examined gave adequate performance for up to 50 hours at 143°C (290°F) OST.

VIII. RECOMMENDATIONS

Based on this work, the following recommendations are made:

- Potential high-temperature use limits (HTLIMs) should be defined for current MIL-L-2104F performance level lubricants in representative military diesel engines using 50-hour engine dynamometer screening tests.

- HTLIMs for engines that are new to the Army inventory should be investigated and defined. These engines include the Caterpillar 3116, which is being used in the family of medium tactical vehicles.

- Potential HTLIMs should be confirmed with 240-hour engine dynamometer endurance evaluations.

- Because of differing engine response to operation at increased temperature, the Army should consider setting engine/equipment specific HTLIMs for two-cycle and four-cycle diesel engines.

- Consideration should be given to raising the short-term excursion limit (15 min/hr) from 135°C (275°F) to 143°C (290°F) for <u>four-cycle diesel engines only</u>.

IX. REFERENCES

1. LePera, M.E., Letter to U.S. Army Yuma Proving Ground (Mr. Doebbler), 1 March 1985.

2. Federal Test Method Standard 791C, "Lubricants, Liquid Fuels, and Related Products: Methods of Testing," 30 September 1986.

3. Coordinating Research Council, Inc., "Development of Military Fuel/Lubricant/Engine Compatibility Test," Final Report, New York, NY, January 1967.

4. Stavinoha, L.L., J.R. Eichelberger, S.J. Lestz, and J.C. Tyler, "Lubricant Volatility Related to Two-Cycle Diesel-Engine Piston-Ring/Cylinder-Liner Wear," presented at ASLE/ASME Lubrication Conference, San Francisco, CA, August 1980. Preprint No. 80-LC-3C-1; also J. ASLE, Vol. 38, 1, pp. 11-22, January 1982.

5. Reilly, D.J. "The New GM 6.2L V8 Diesel Engine - Designed by Chevrolet," SAE Paper No. 820115, 1982.

APPENDIX A

Wear Metal Versus Test Hours

(6V-53T Engine Tests)

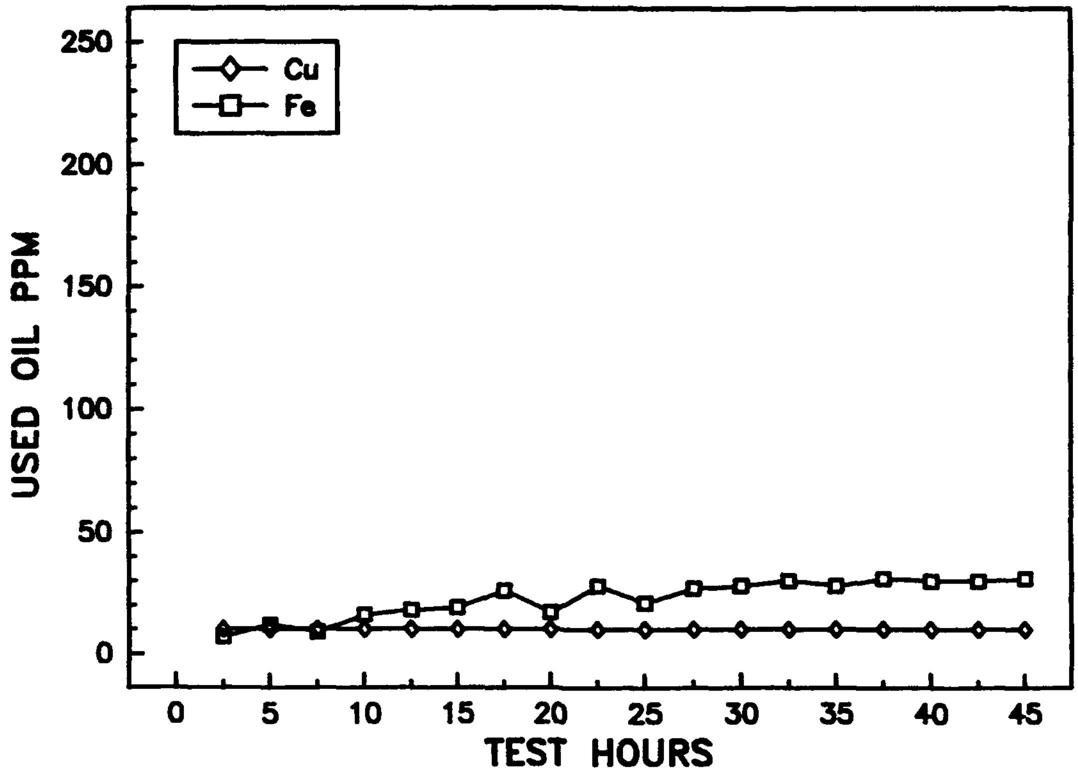

Figure A-1. **Oil A, Test No. 44H, 250°F max OST, wear metals, ppm**

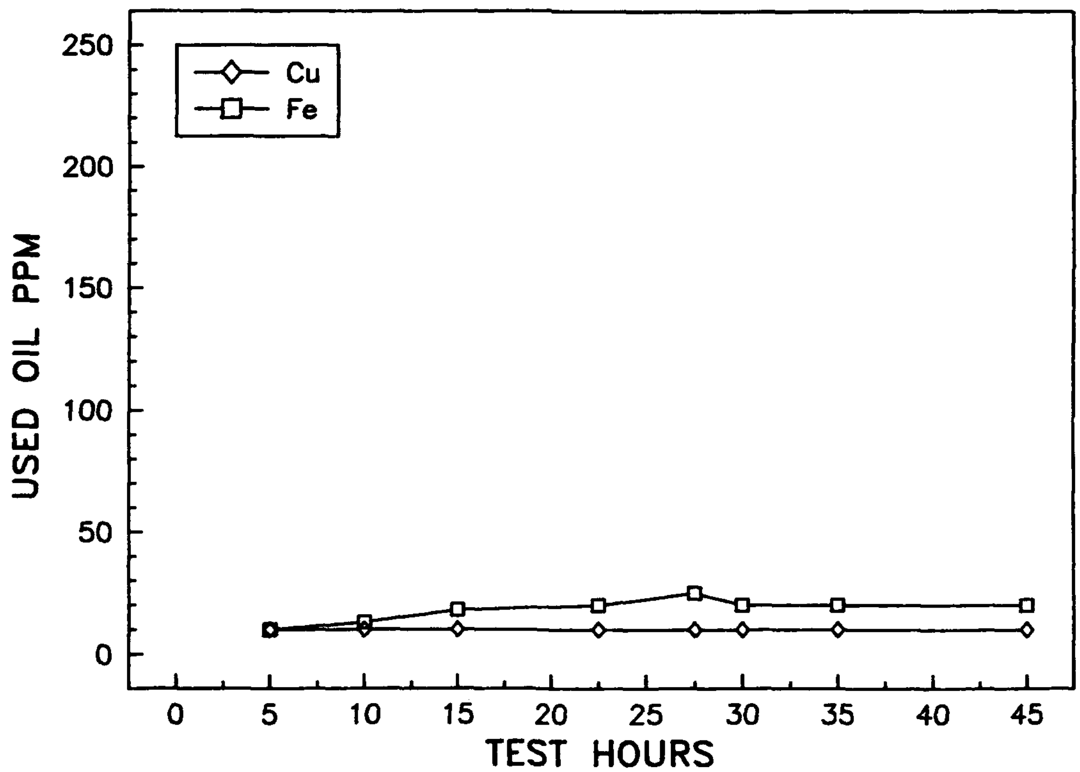

Figure A-2. **Oil A, Test No. 46, 250°F max OST, wear metals, ppm**

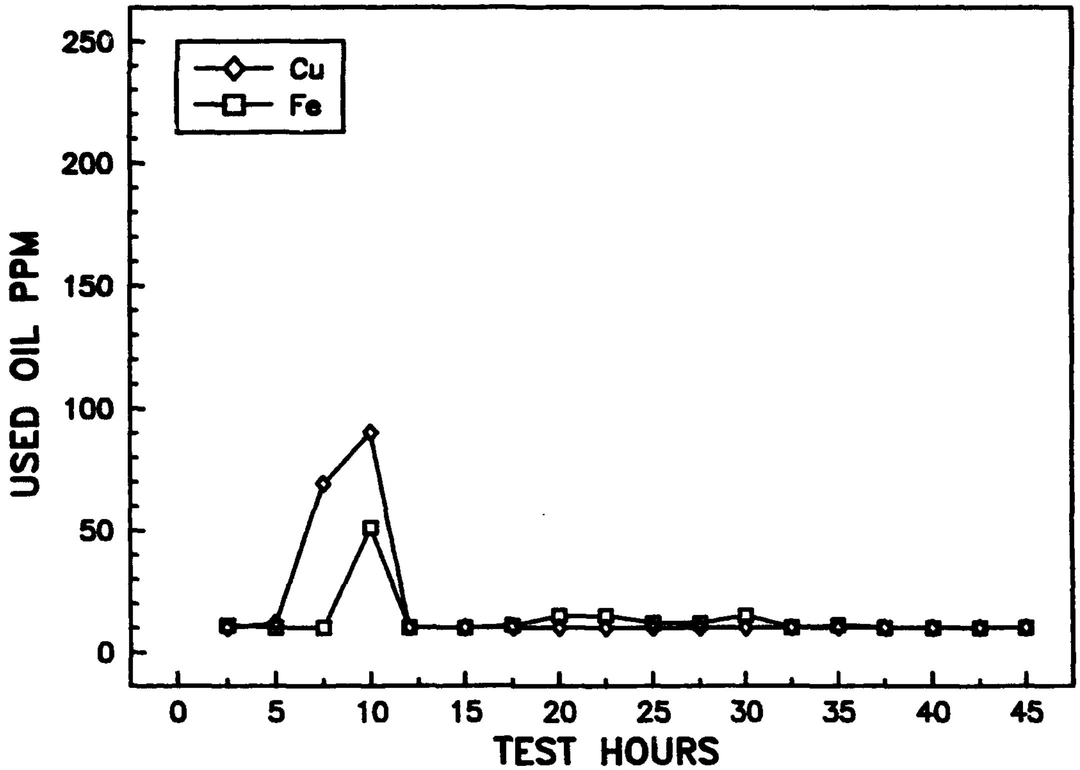

Figure A-3. <u>**Oil A, Test No. 44L, 250°F max OST, wear metals, ppm**</u>

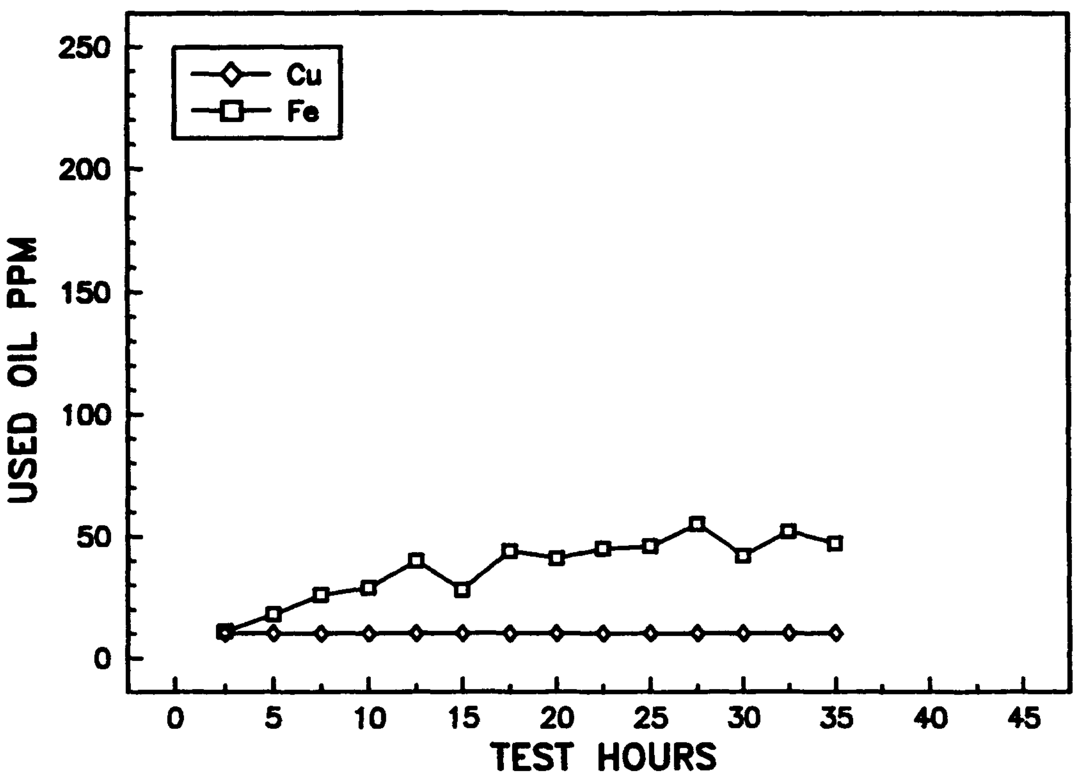

Figure A-4. <u>**Oil A, Test No. 44J, 250°F max OST, wear metals, ppm**</u>

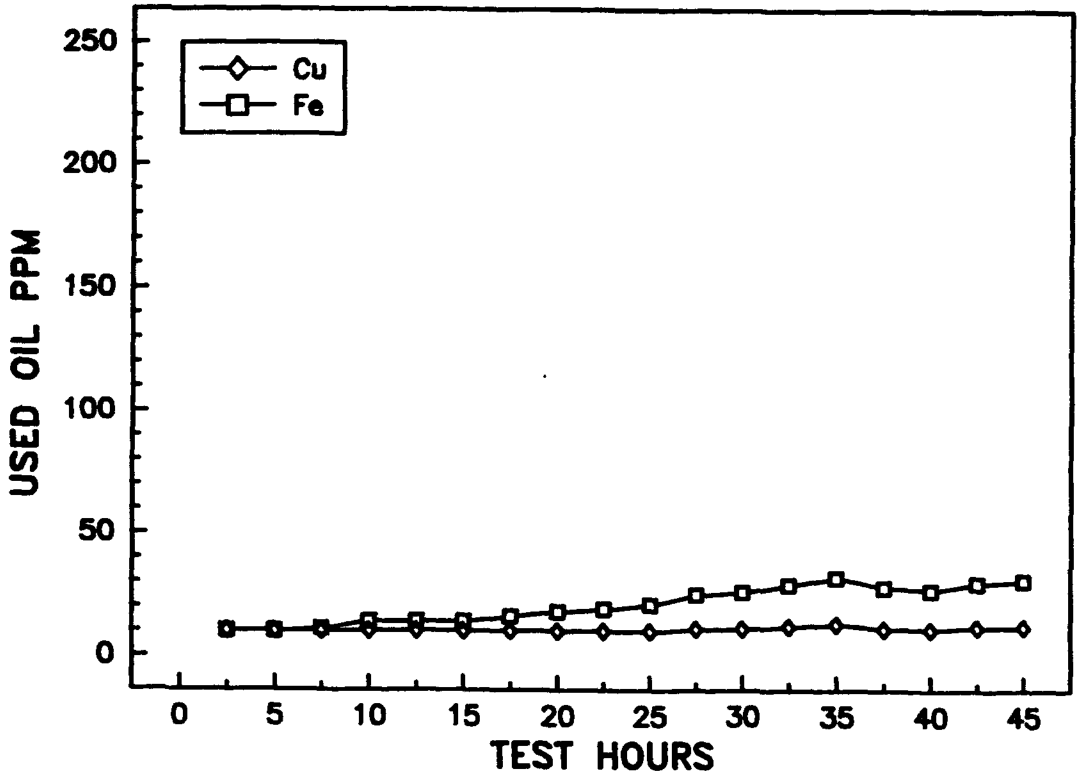

Figure A-5. Oil A, Test No. 44N, 250°F max OST, wear metals, ppm

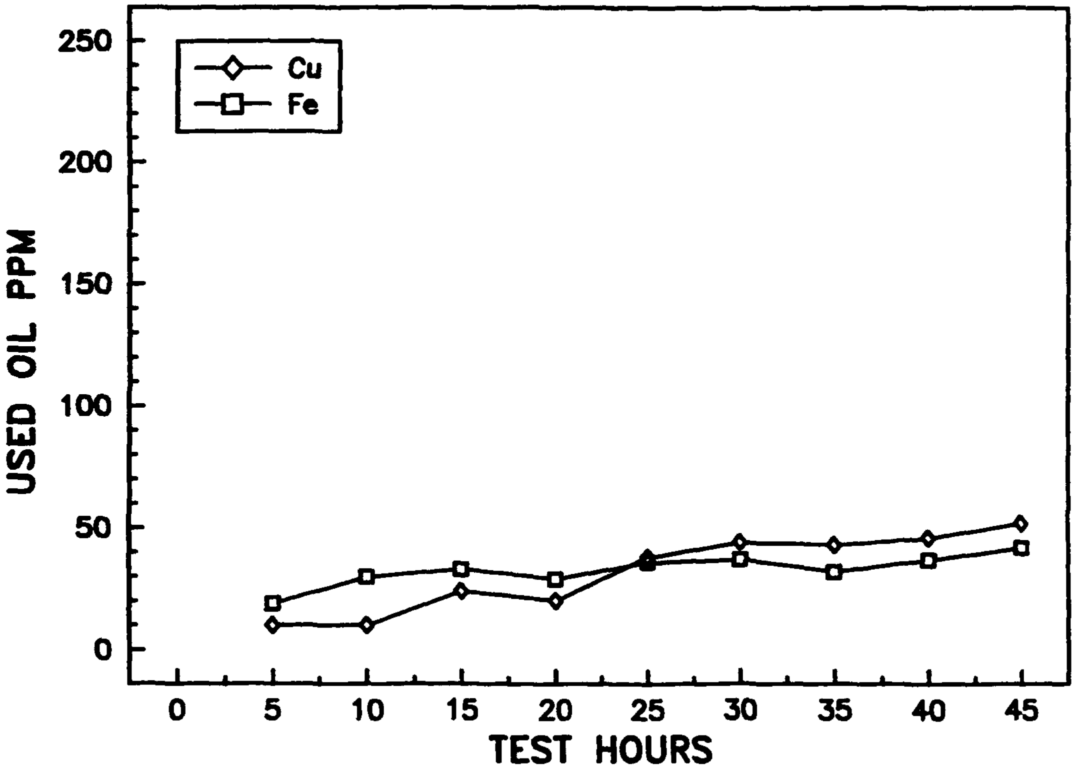

Figure A-6. Oil A, Test No. 44B, 250°F max OST, wear metals, ppm

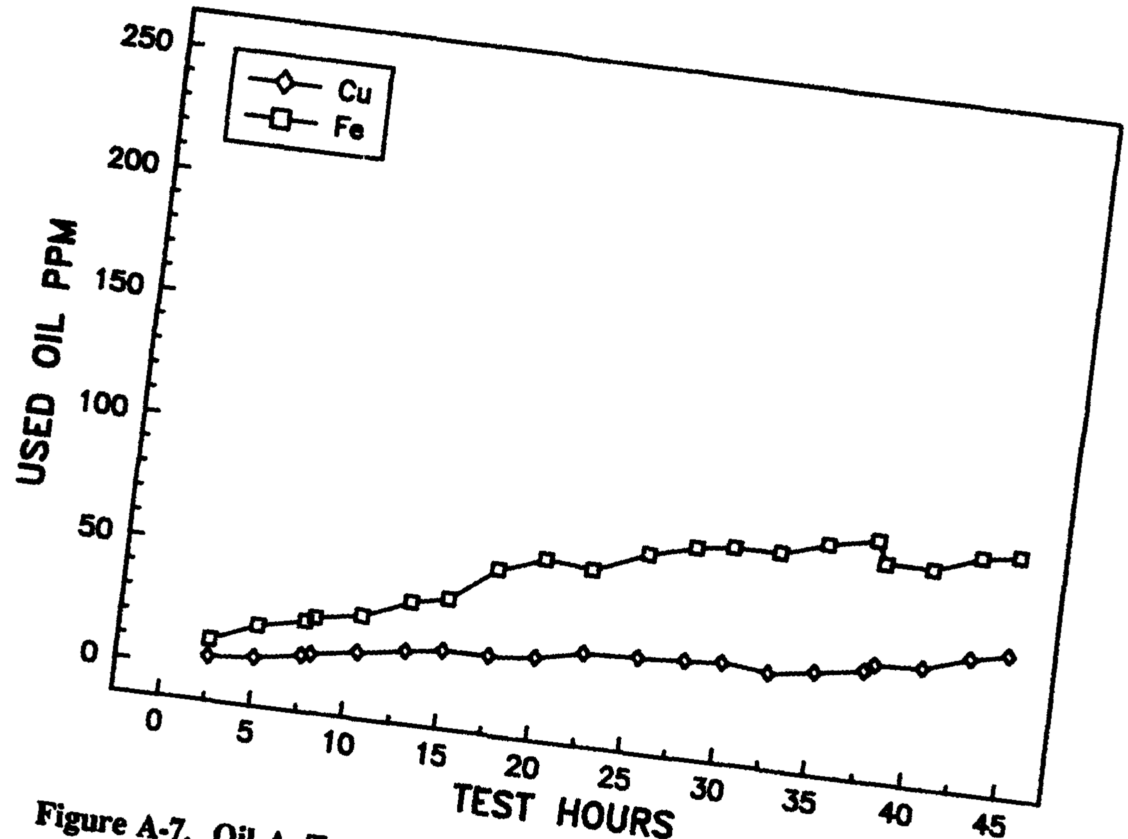

Figure A-7. Oil A, Test No. 44, 250°F max OST, wear metals, ppm

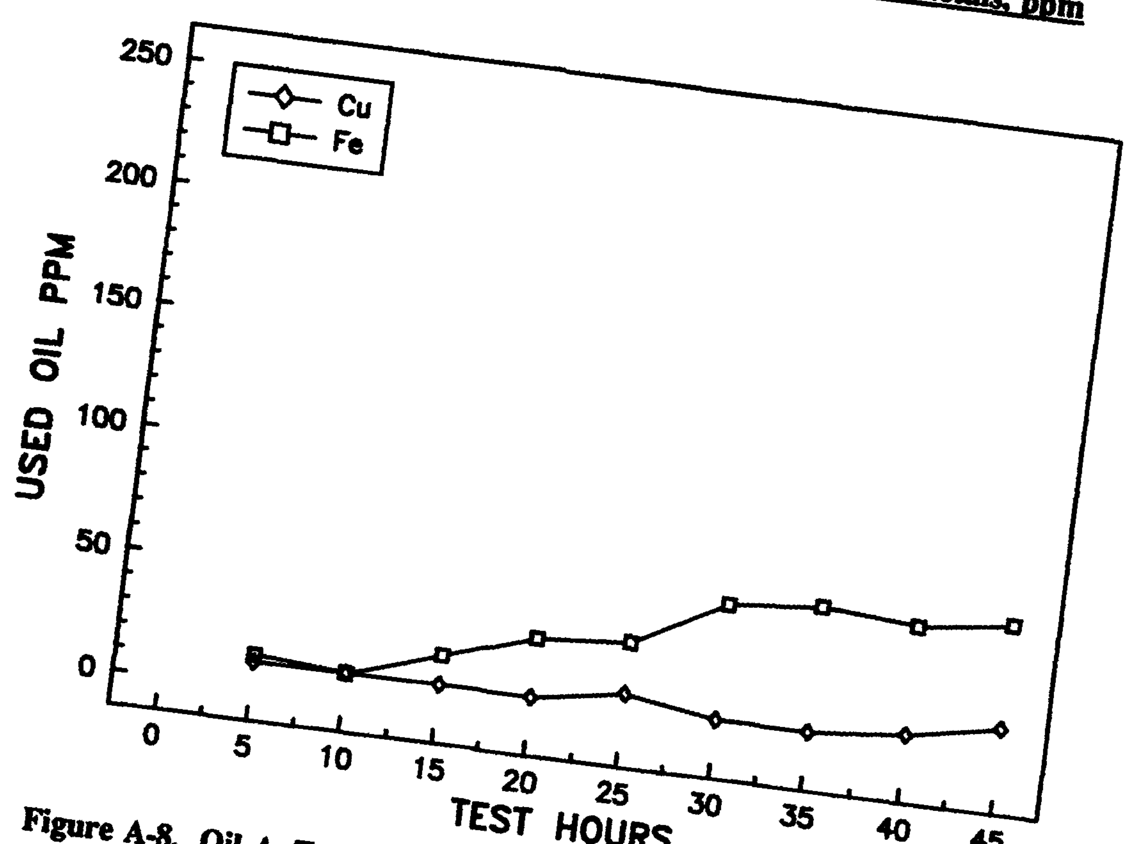

Figure A-8. Oil A, Test No. 44E, 250°F max OST, wear metals, ppm

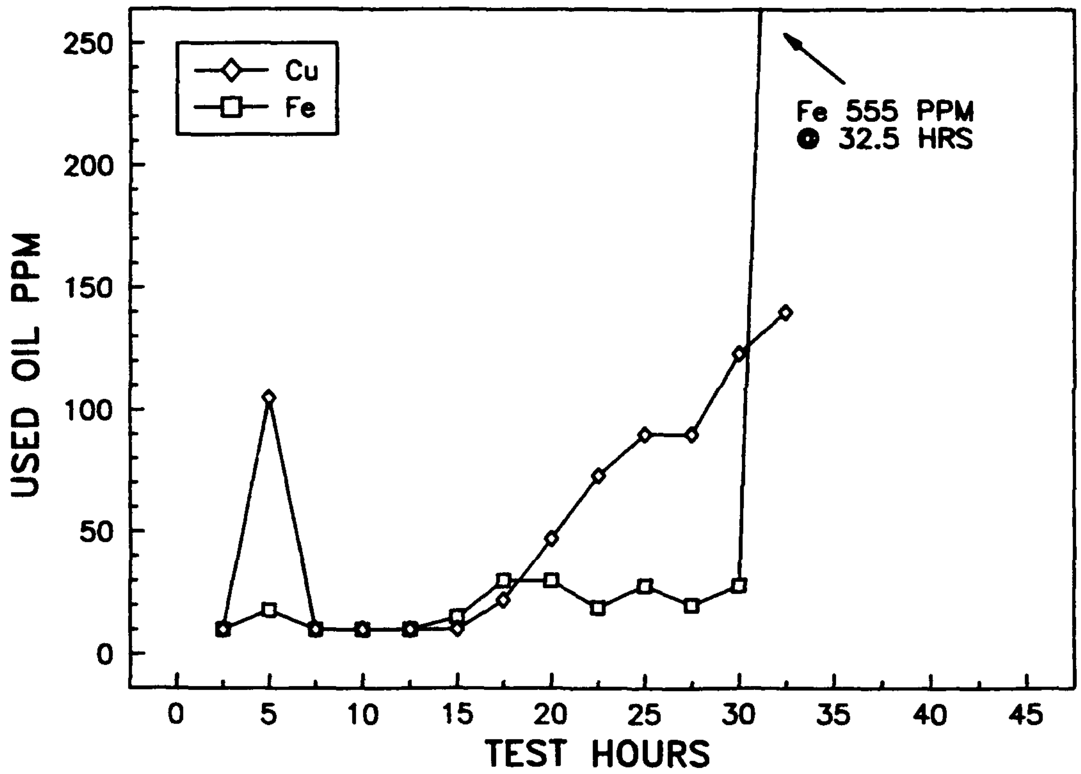

Figure A-9. Oil A, Test No. 46E, 260°F max OST, wear metals, ppm

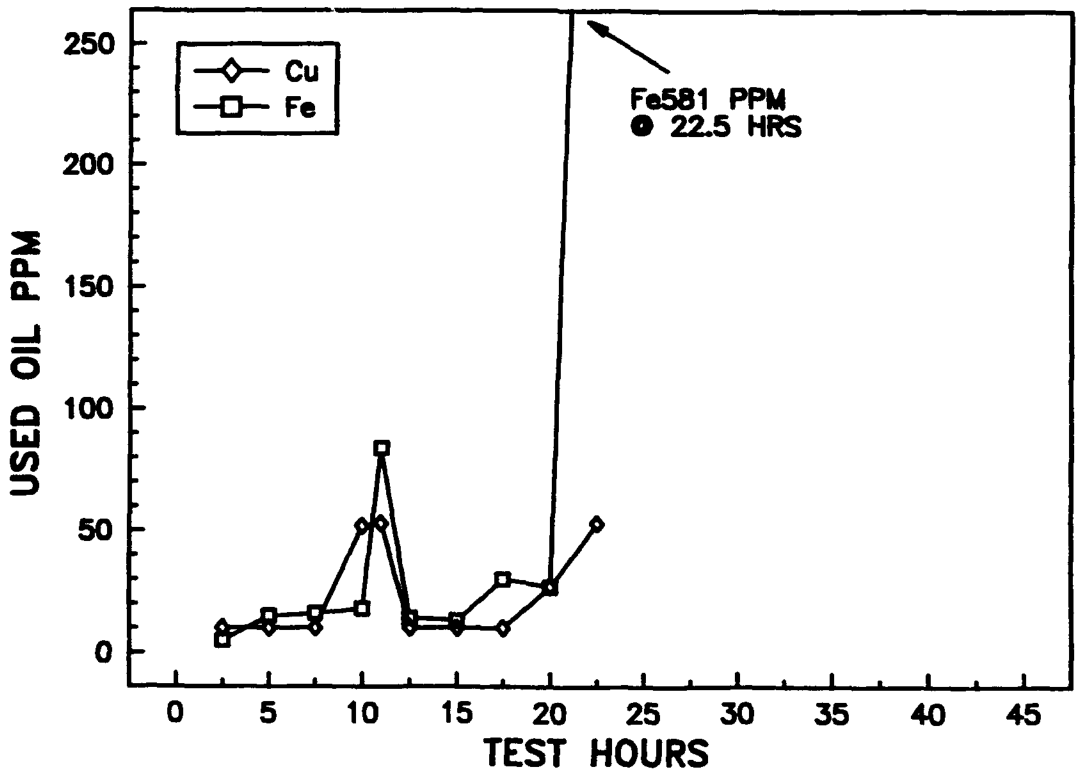

Figure A-10. Oil A, Test No. 44F, 260°F max OST, wear metals, ppm

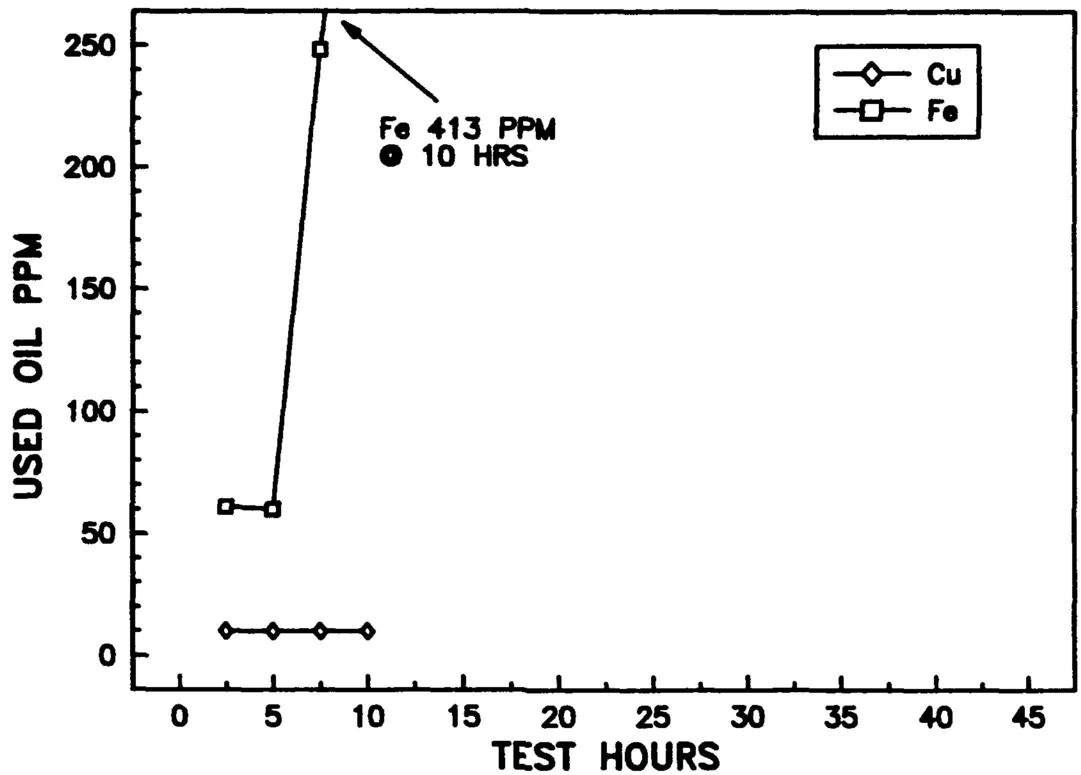

Figure A-11. <u>**Oil B, Test No. 44K, 250°F max OST, wear metals, ppm**</u>

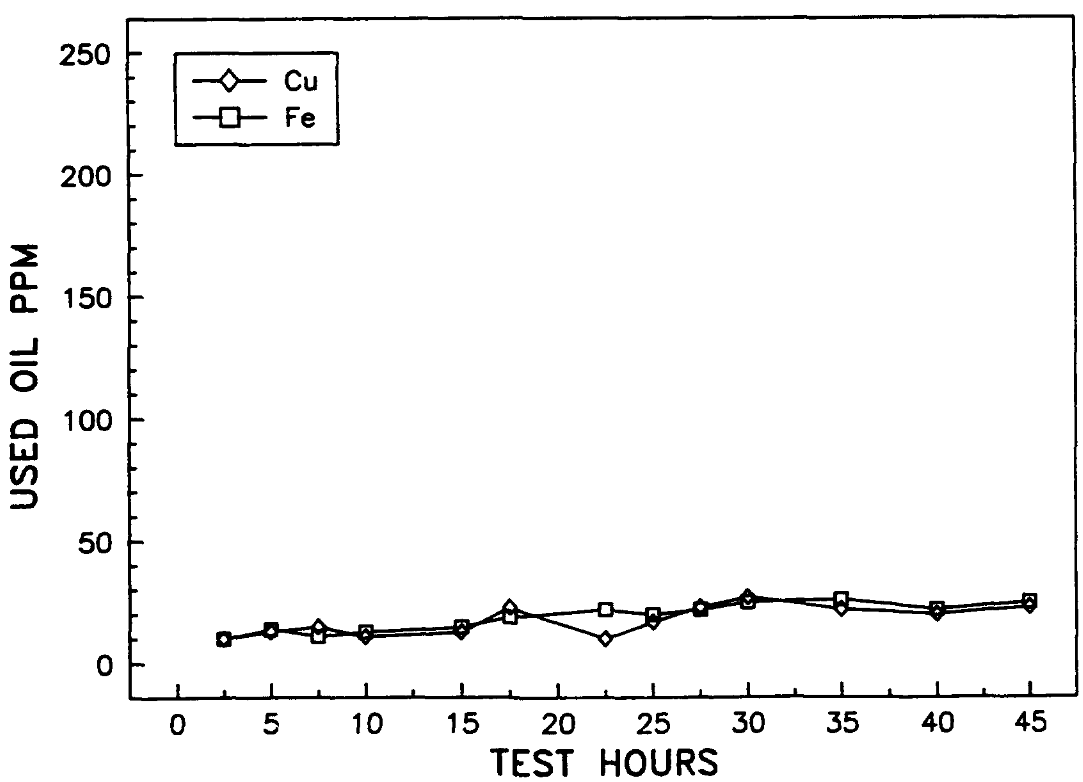

Figure A-12. <u>**Oil C, Test No. 48, 250°F max OST, wear metals, ppm**</u>

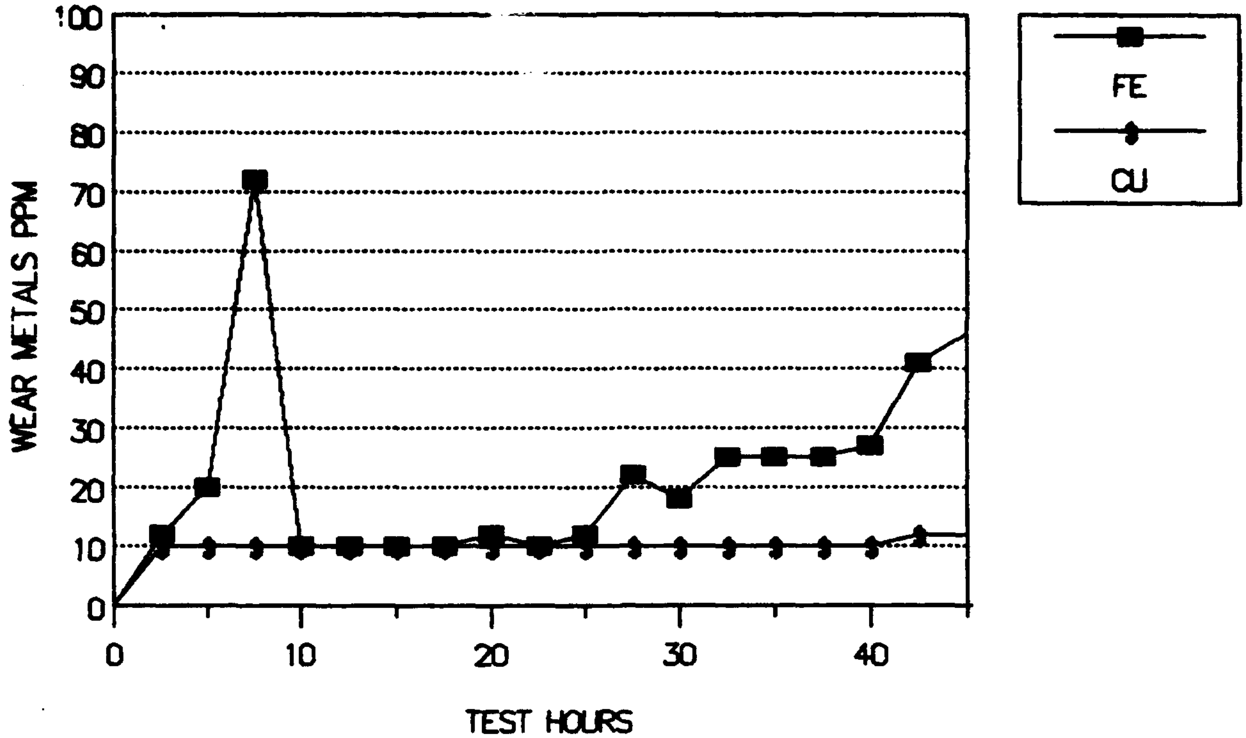

Figure A-13. Oil C, Test No. 52, 250°F max OST, wear metals, ppm

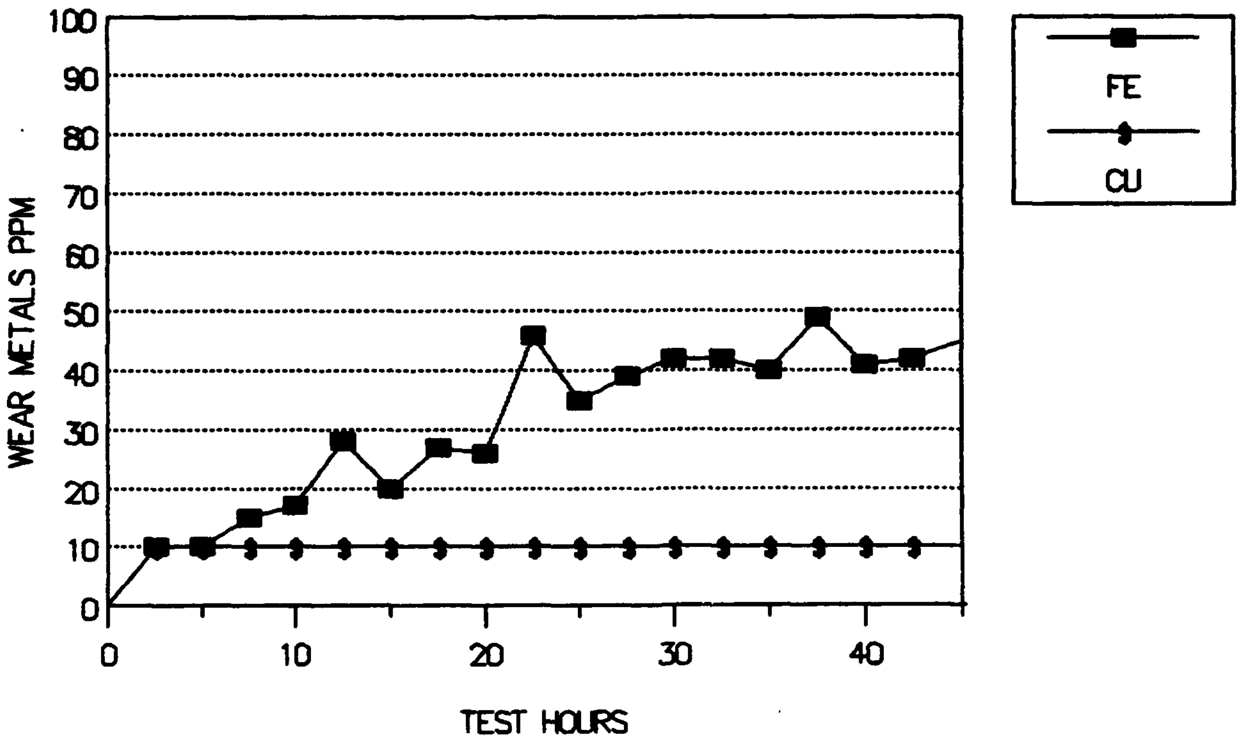

Figure A-14. Oil D, Test No. 53B, 260°F max OST, wear metals, ppm

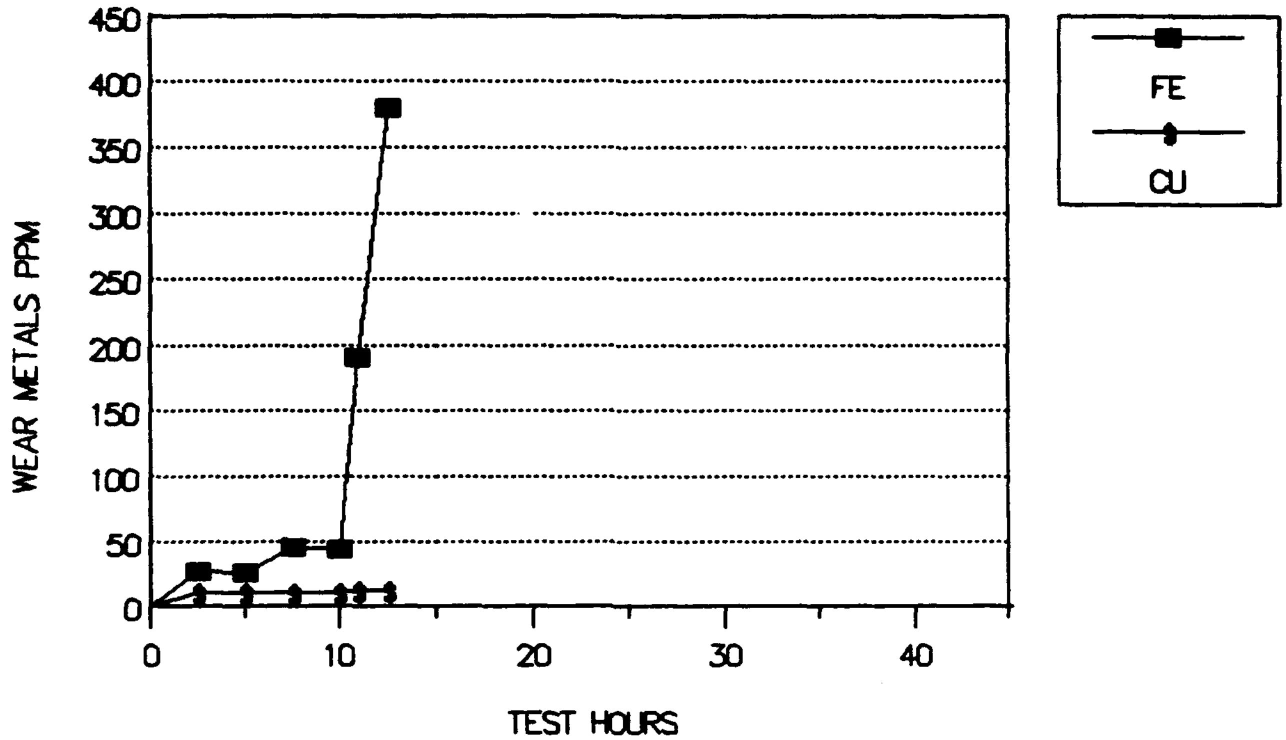

Figure A-15. Oil D, Test No. 53C, 275°F max OST, wear metals, ppm

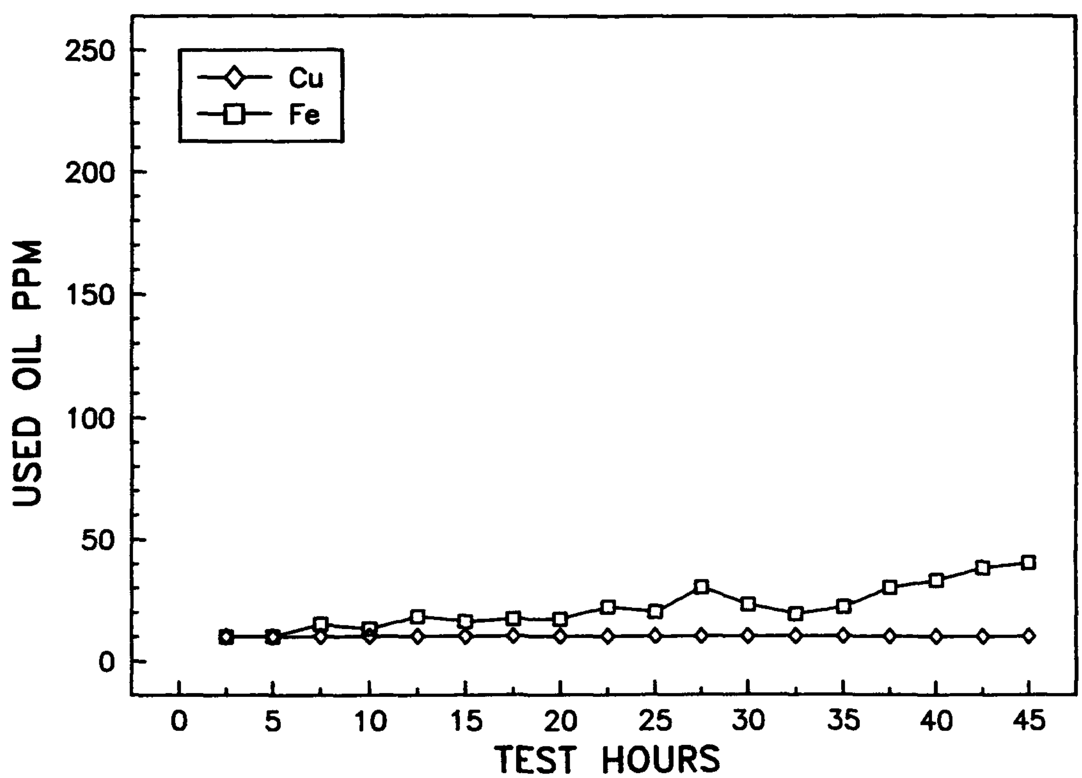

Figure A-16. Oil E, Test No. 46C, 250°F max OST, wear metals, ppm

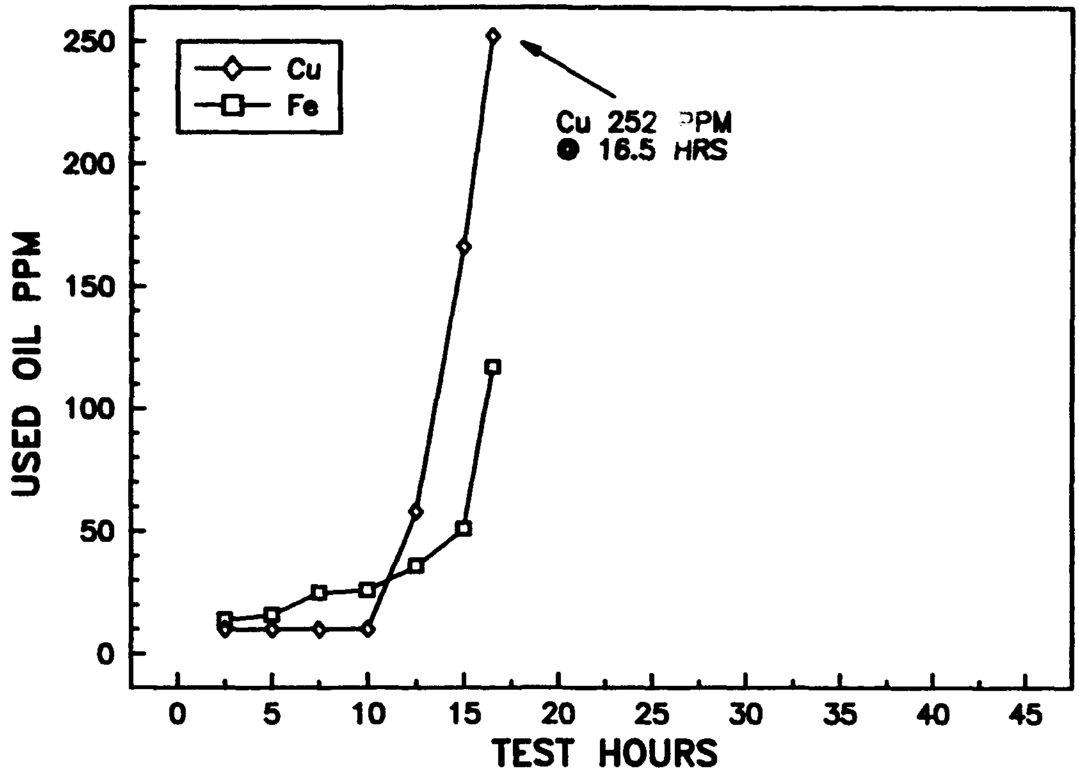

Figure A-17. Oil E, Test No. 44P, 250°F max OST, wear metals, ppm

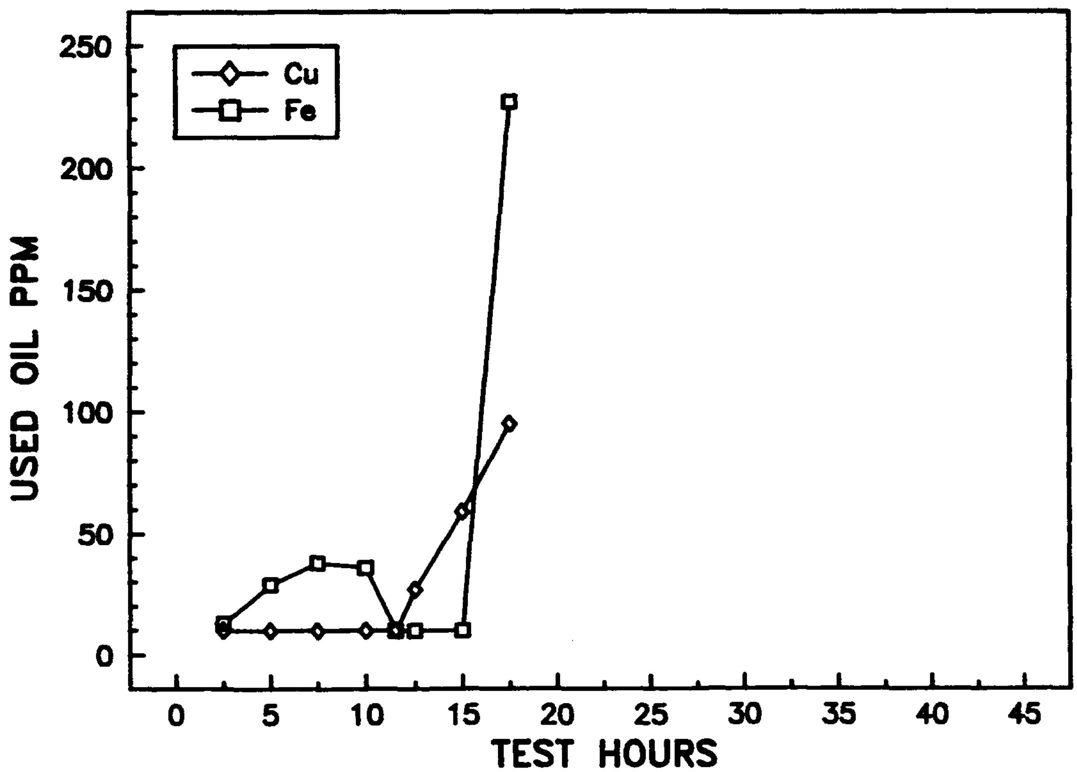

Figure A-18. Oil E, Test No. 44I, 250°F max OST, wear metals, ppm

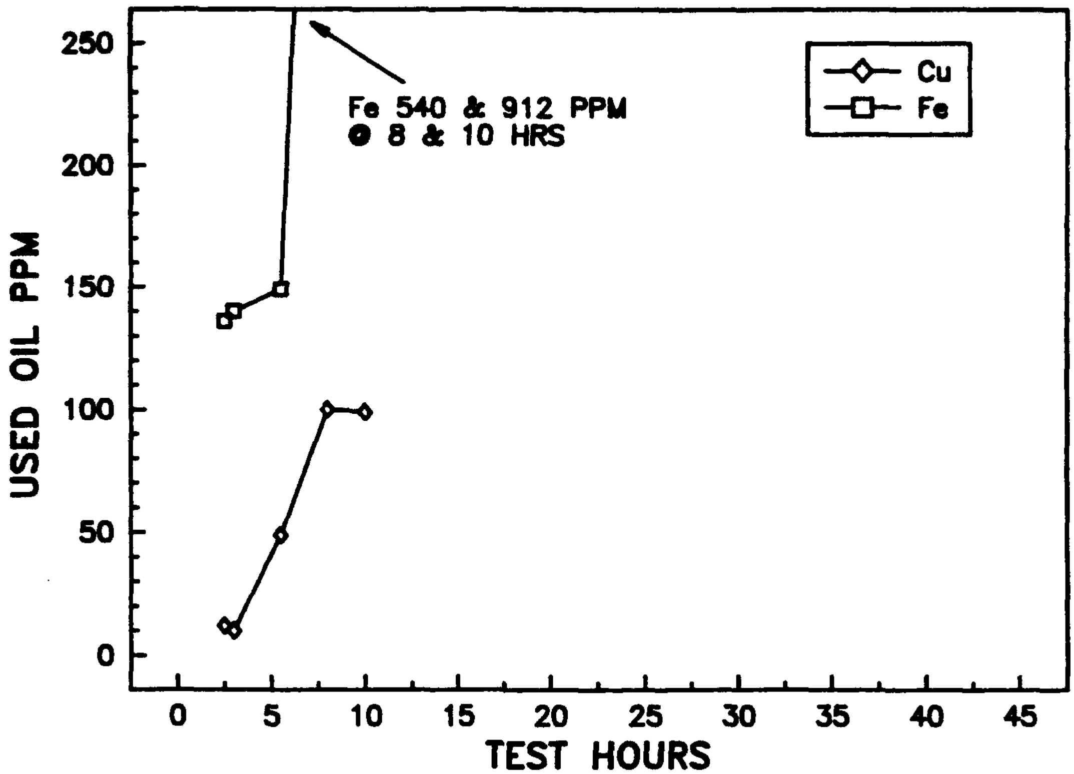

Figure A-19. Oil E, Test No. 44A, 250°F max OST, wear metals, ppm

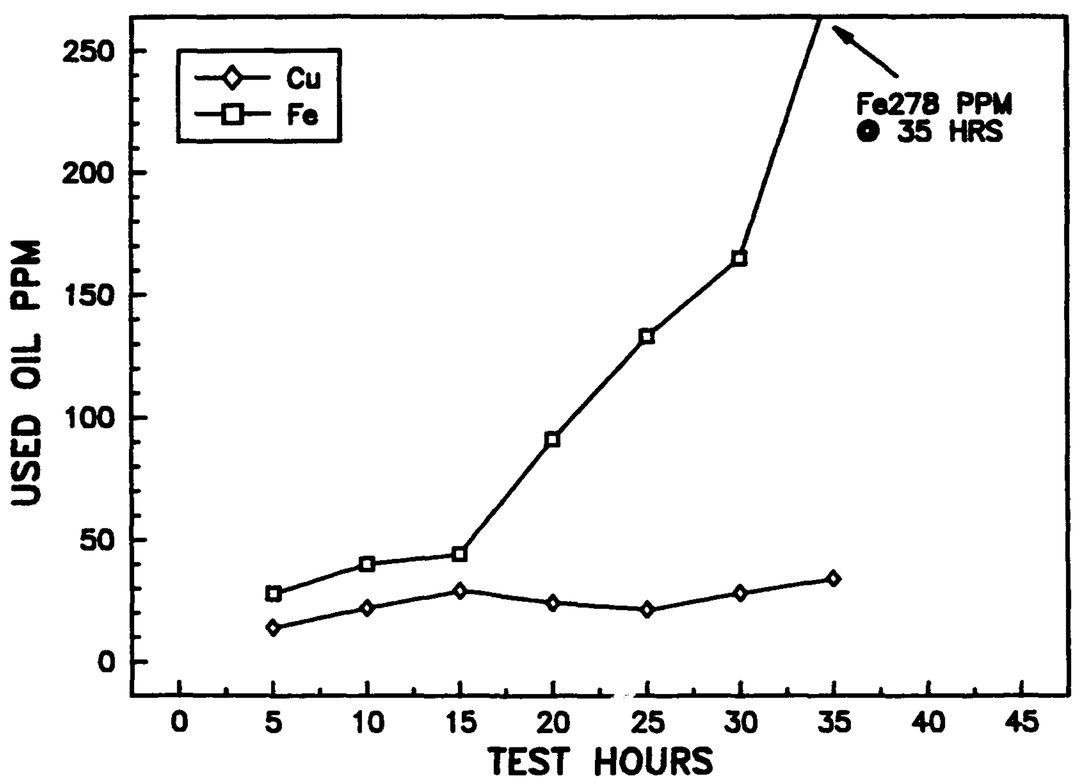

Figure A-20. Oil E, Test No. 42, 250°F max OST, wear metals, ppm

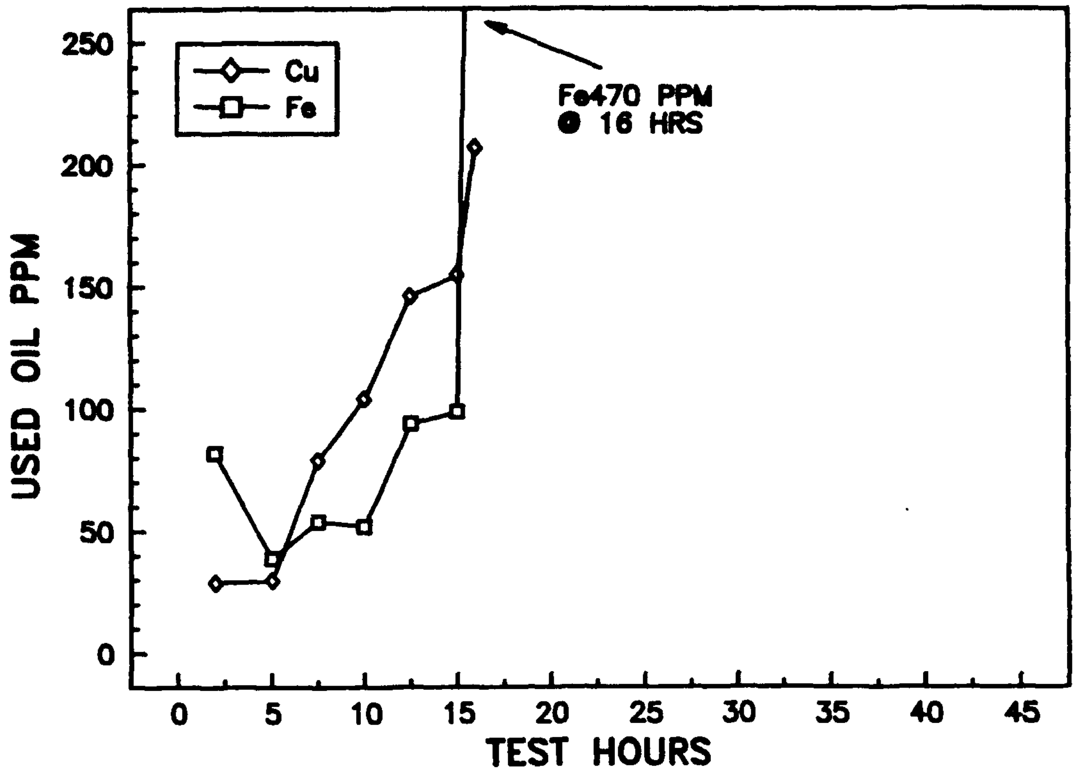

Figure A-21. Oil E, Test No. 43, 265°F max OST, wear metals, ppm

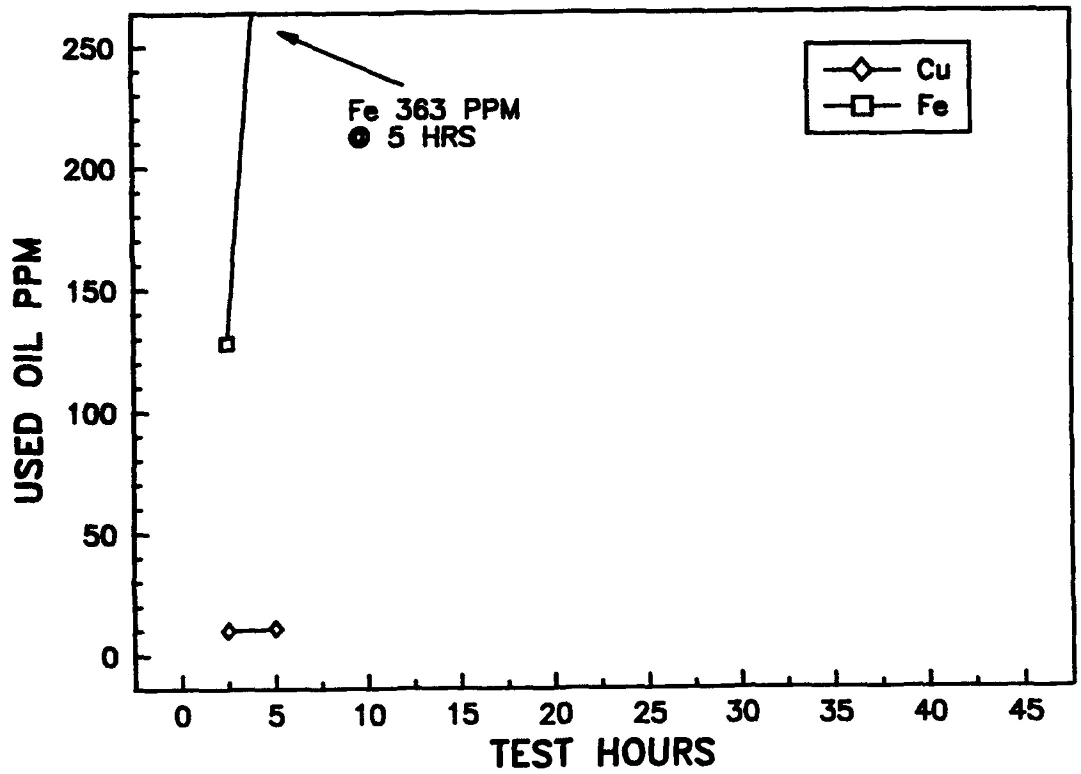

Figure A-22. Oil F, Test No. 44C, 250°F max OST, wear metals, ppm

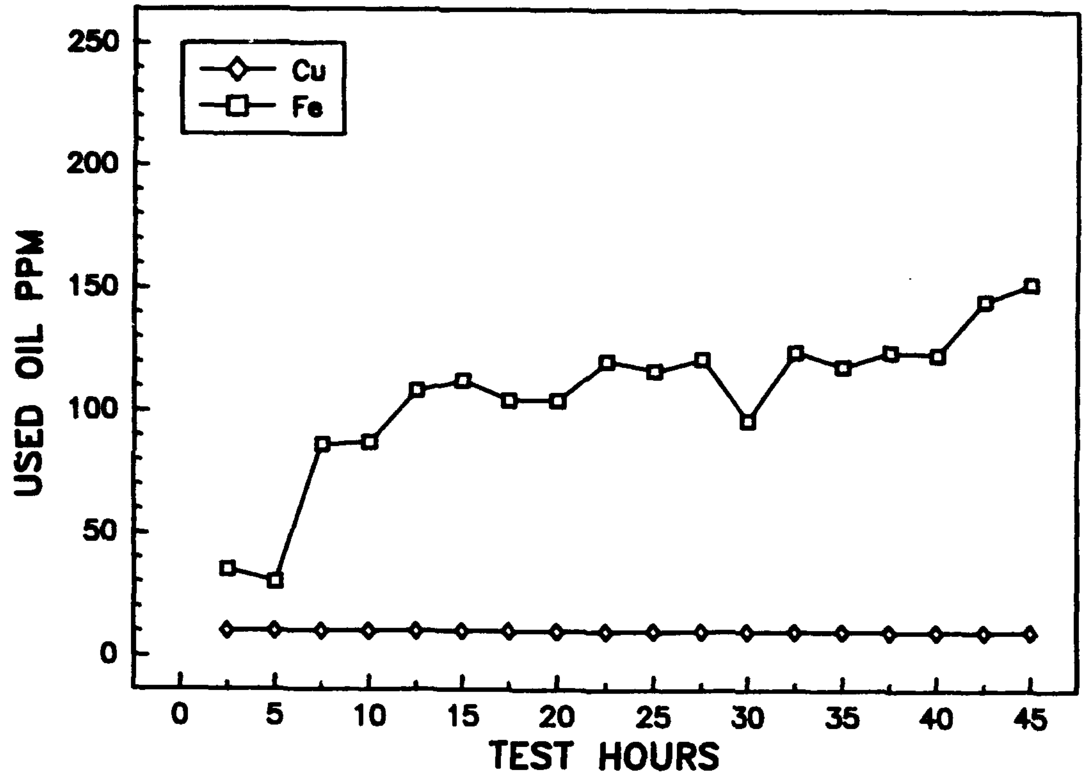

Figure A-23. Oil G, Test No. 44M, 250°F max OST, wear metals, ppm

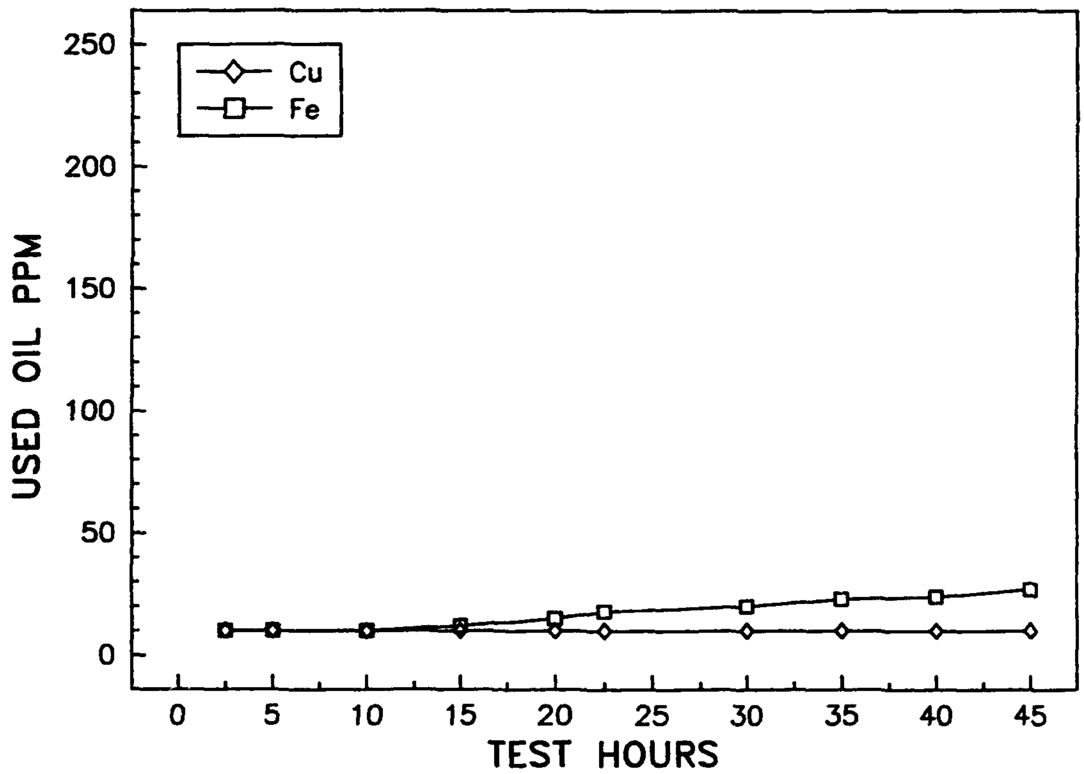

Figure A-24. Oil J, Test No. 46A, 250°F max OST, wear metals, ppm

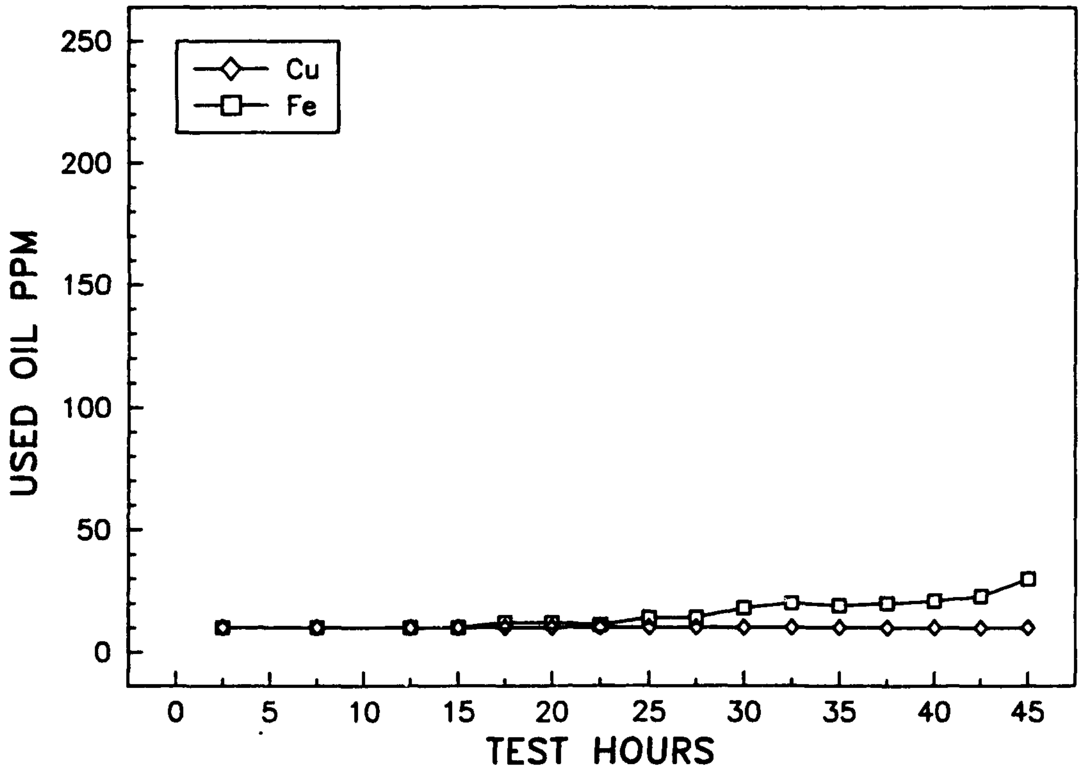

Figure A-25. Oil J, Test No. 46B, 260°F max OST, wear metals, ppm

APPENDIX B

Viscosity Versus Test Hours, Wear Metals Versus Test Hours

(6.2L Engine Tests)

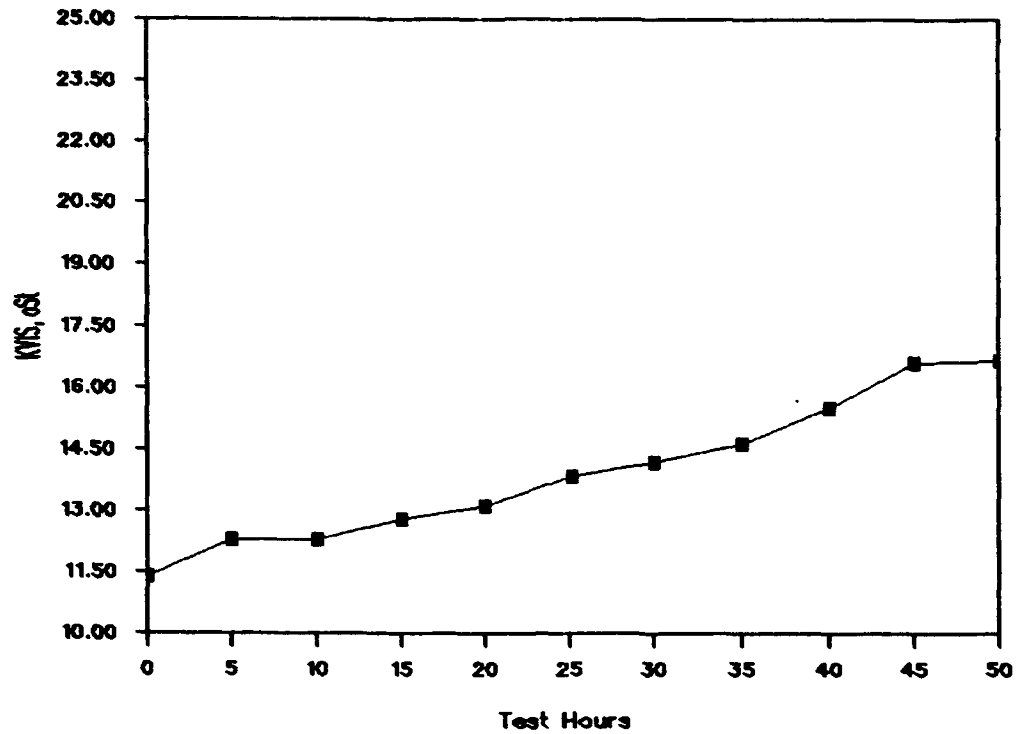

Figure B-1. <u>Oil A, Test No. HT1, 250°F OST, KVis. 100°C</u>

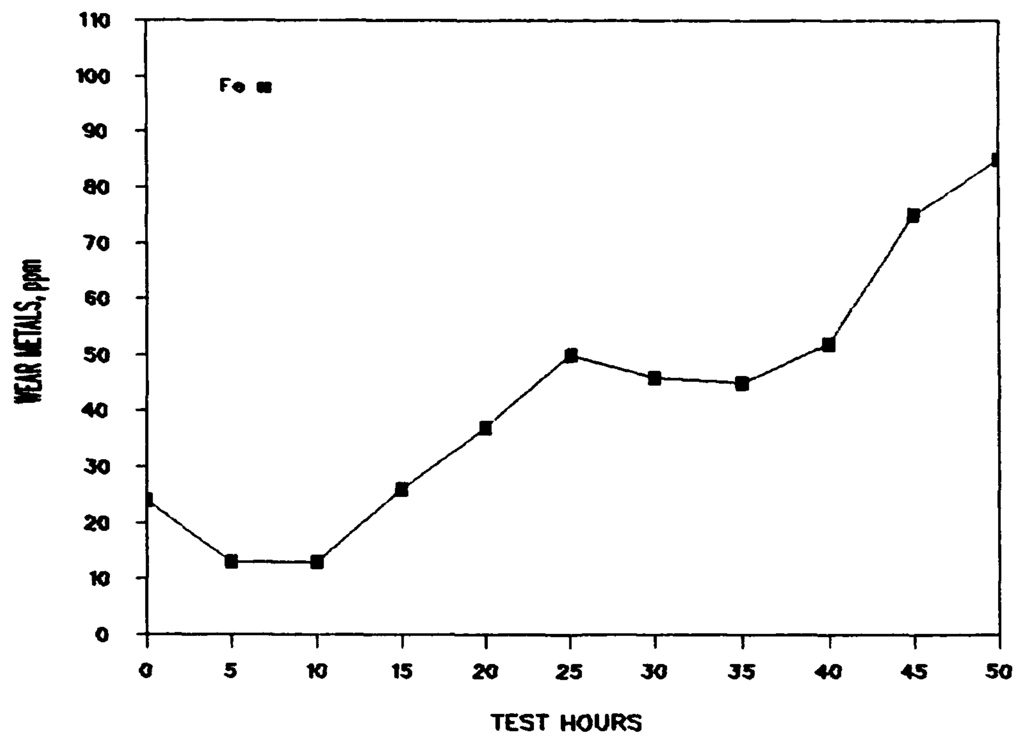

Figure B-2. <u>Oil A, Test No. HT1, 250°F OST, wear metals, ppm</u>

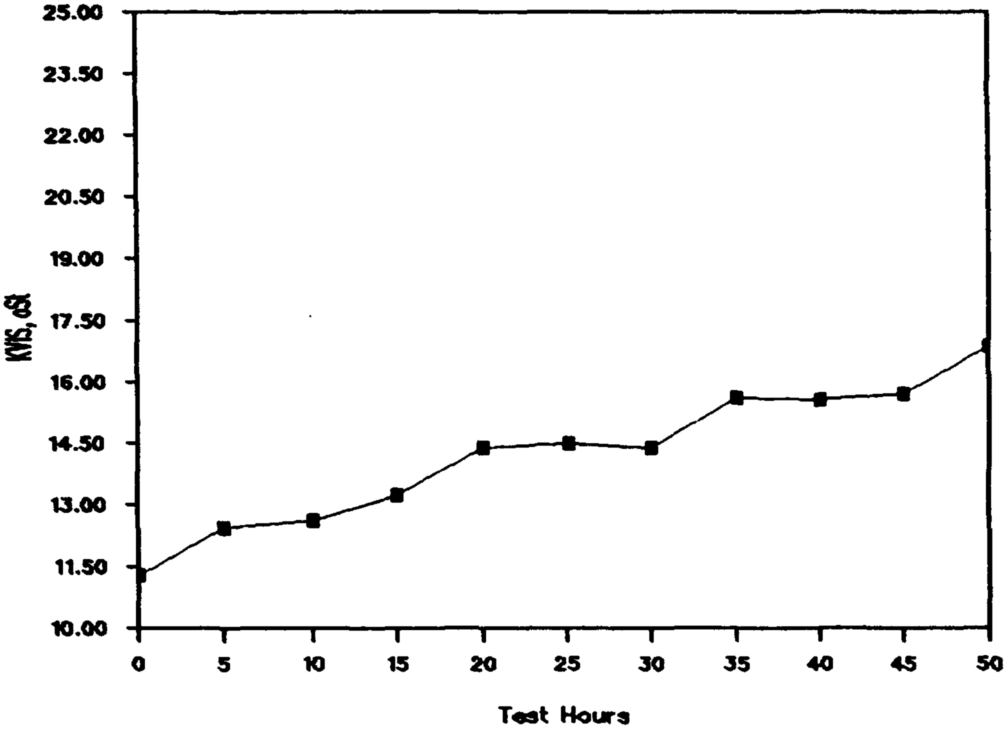

Figure B-3. __Oil A, Test No. HT1A, 260°F OST, KVis. 100°C__

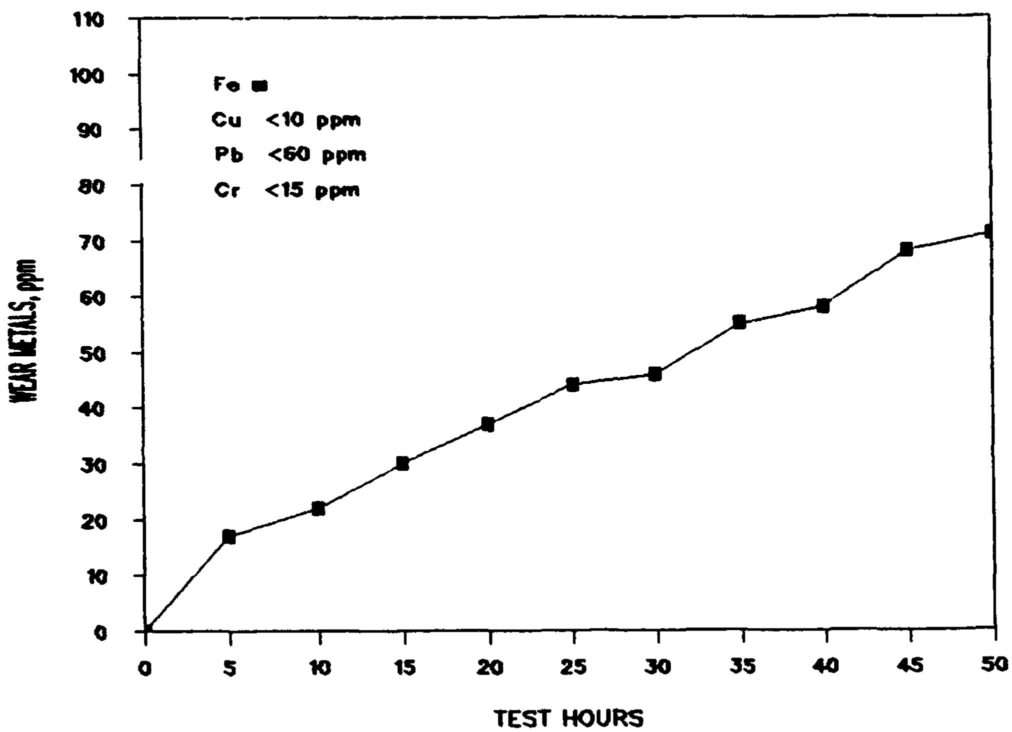

Figure B-4. __Oil A, Test No. HT1A, 260°F OST, wear metals, ppm__

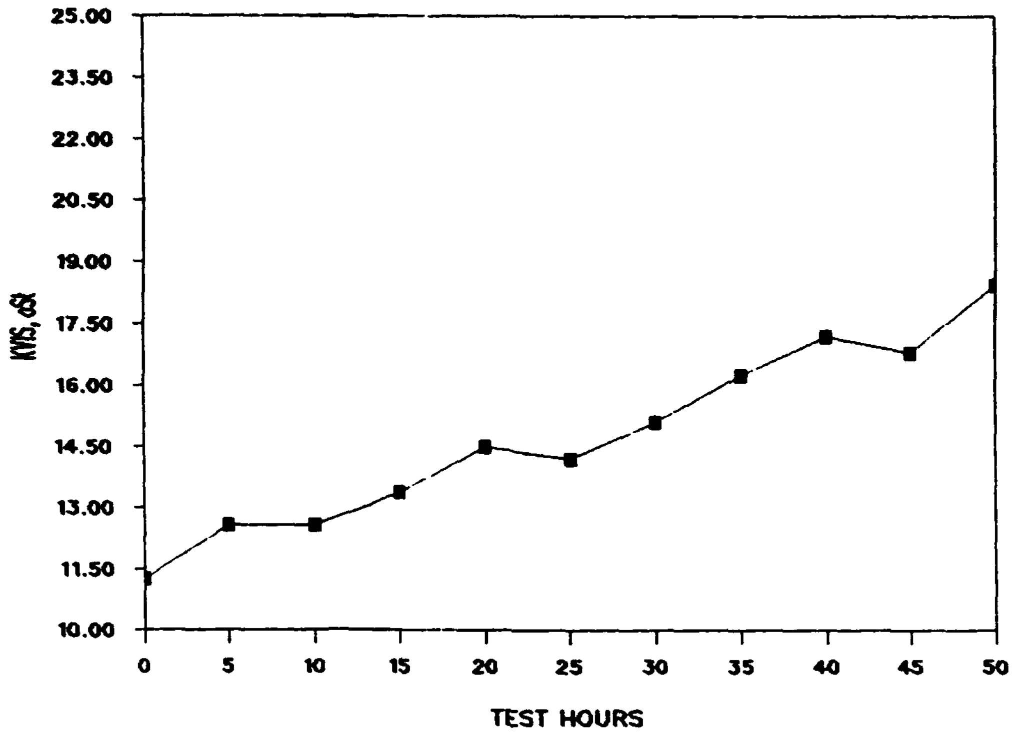

Figure B-5. __Oil A, Test No. HT1B, 275°F OST, KVis. 100°C__

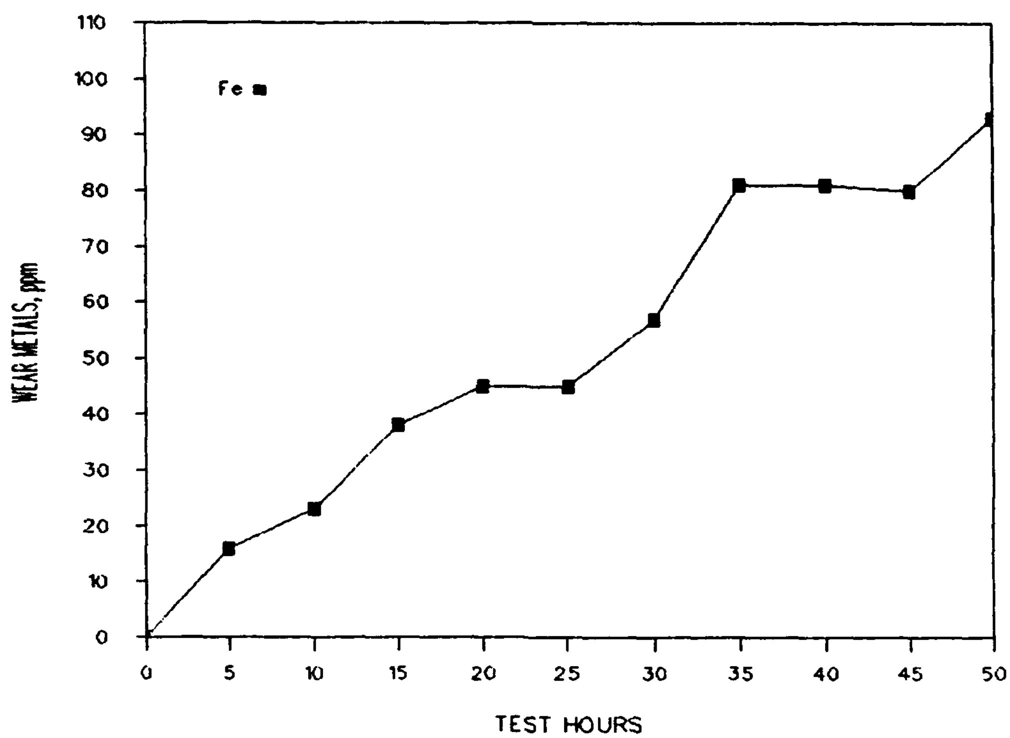

Figure B-6. __Oil A, Test No. HT1B, 275°F OST, wear metals, ppm__

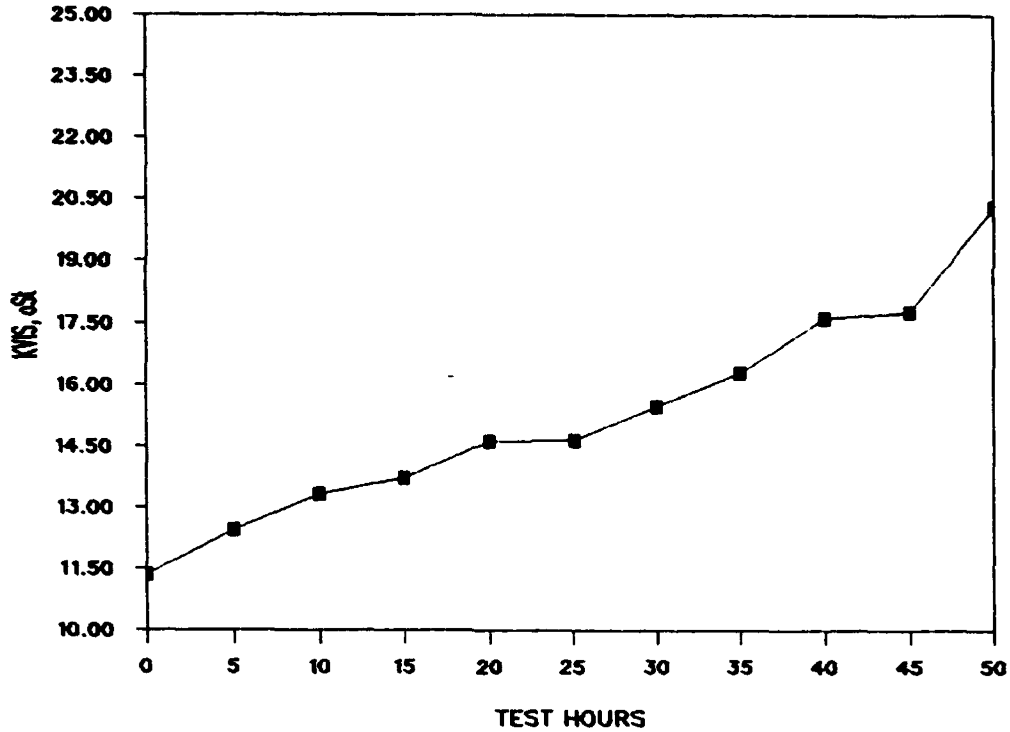

Figure B-7. <u>Oil A, Test No. HT1C, 290°F OST, KVis. 100°C</u>

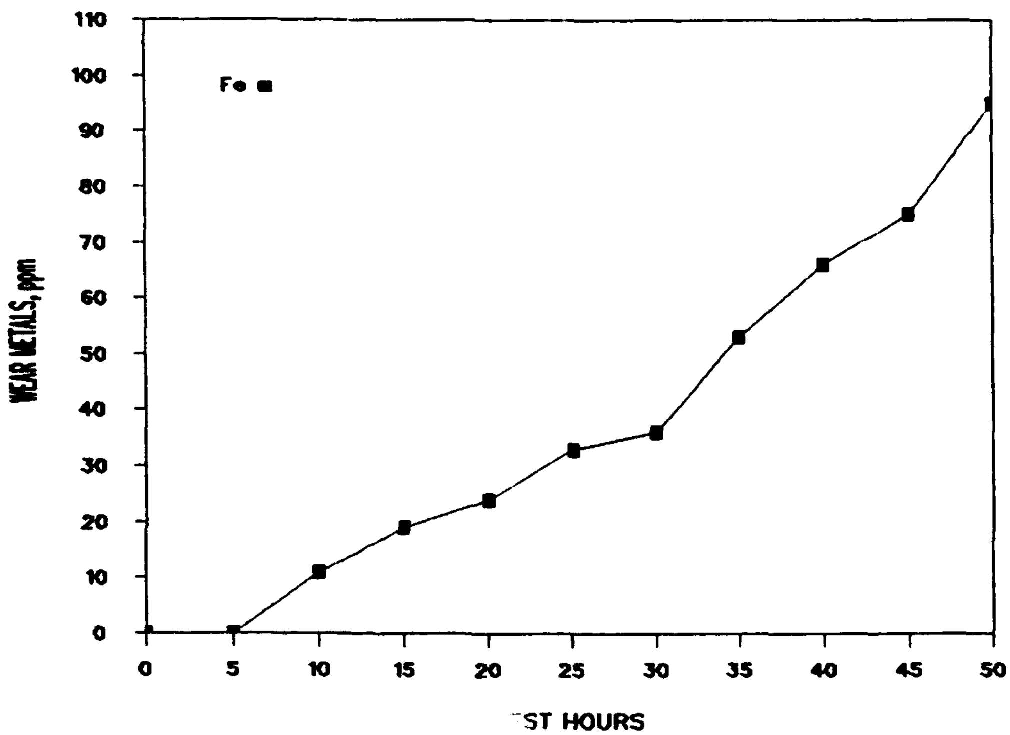

Figure B-8. <u>Oil A, Test No. H11C, 290°F OST, wear metals, ppm</u>

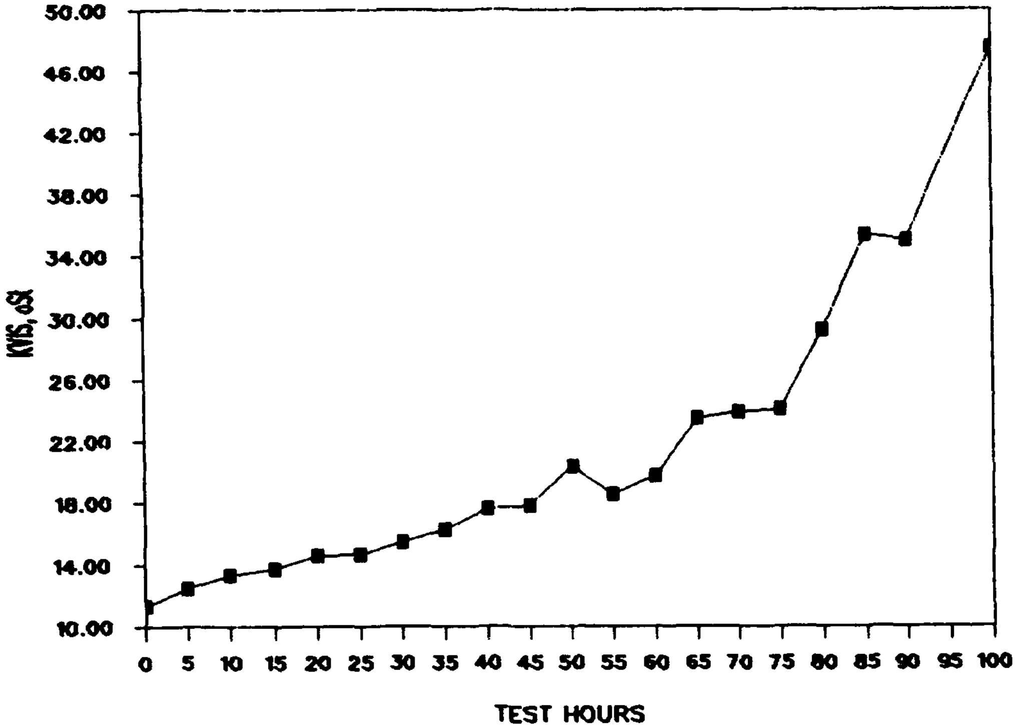

Figure B-9. __Oil A, Test No. HT1C, 290°F OST, KVis. 100°C__

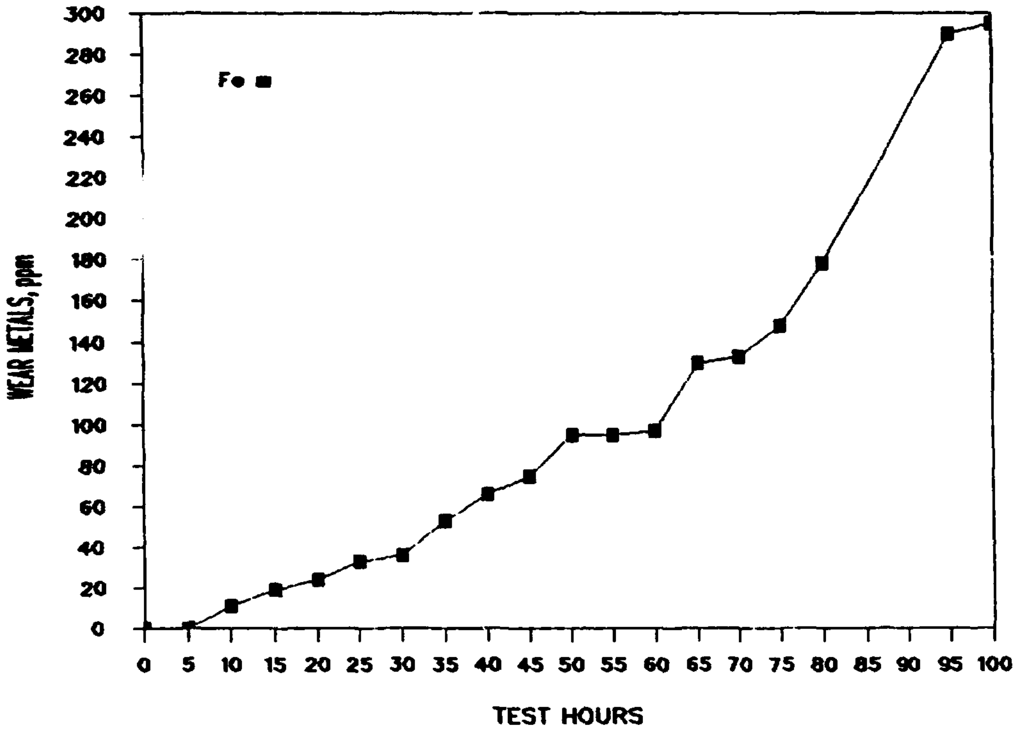

Figure B-10. __Oil A, Test No. HT1C, 290°F OST, wear metals, ppm__

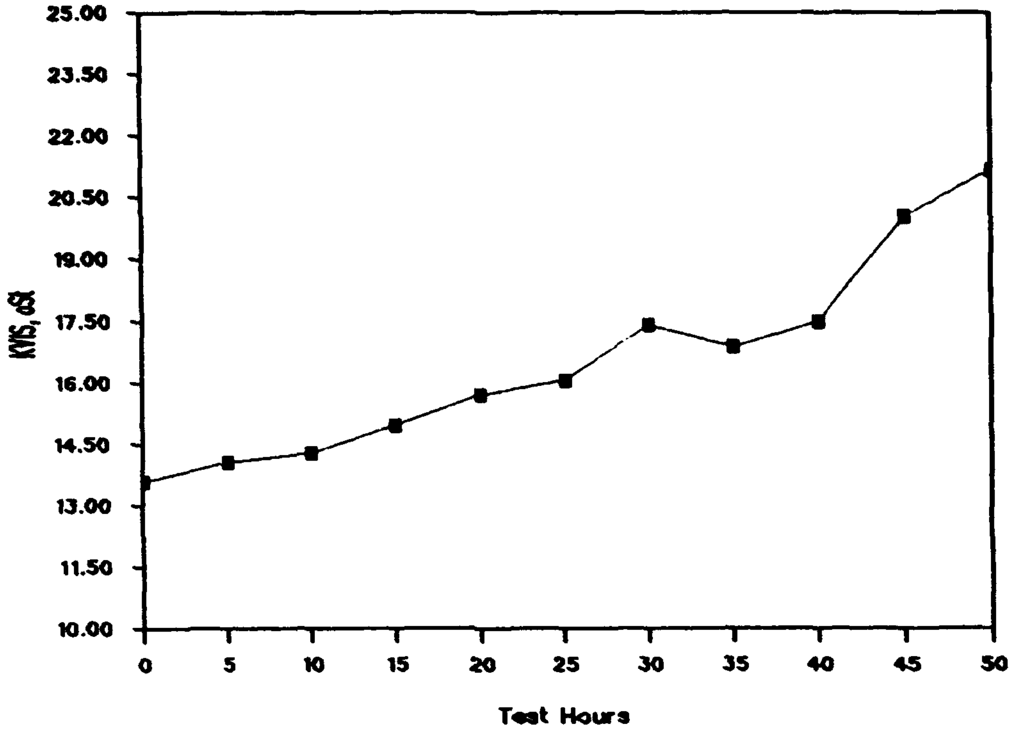

Figure B-11. <u>Oil E, Test No. HT1D, 250°F OST, KVis. 100°C</u>

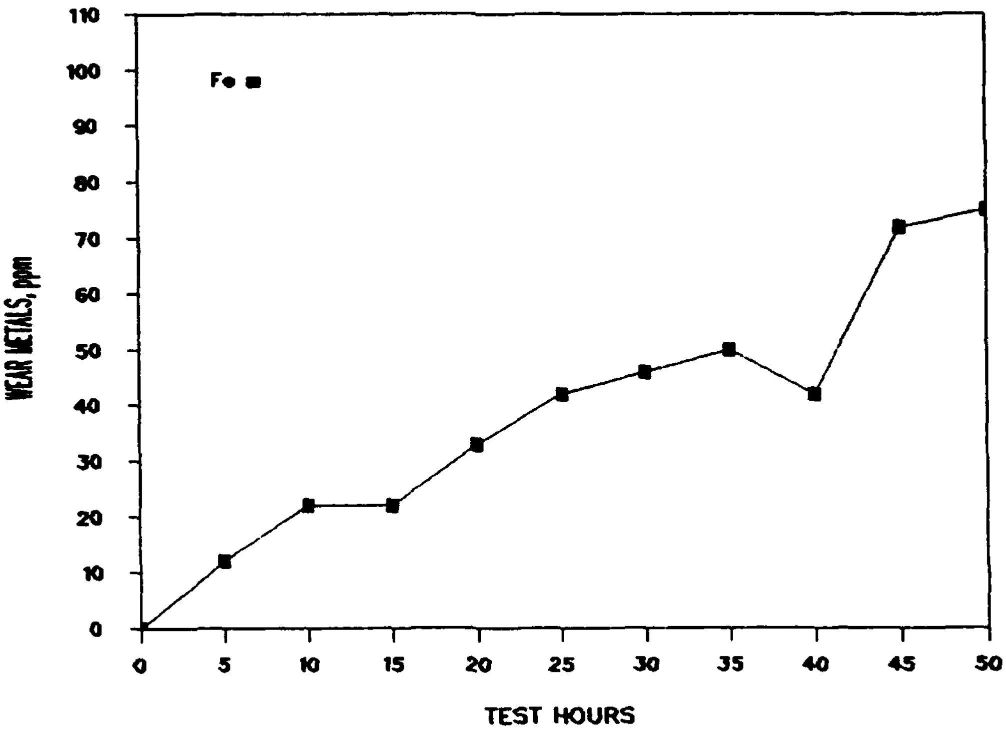

Figure B-12. <u>Oil E, Test No. HT1D, 250°F OST, wear metals, ppm</u>

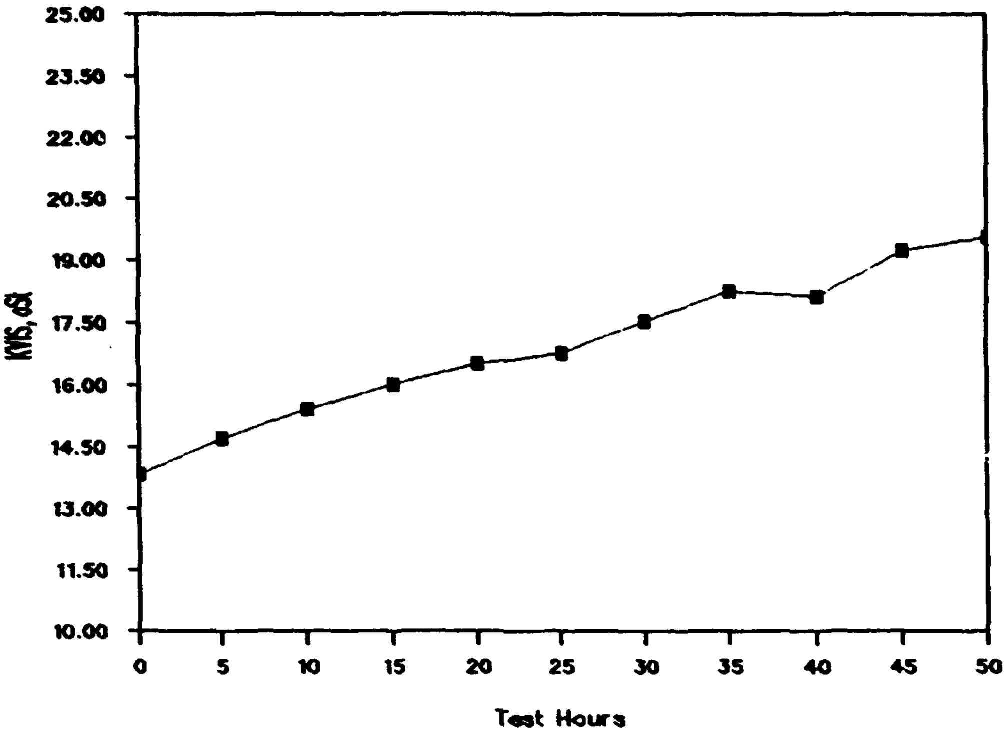

Figure B-13. <u>**Oil E, Test No. HT1E, 275°F OST, KVis. 100°C**</u>

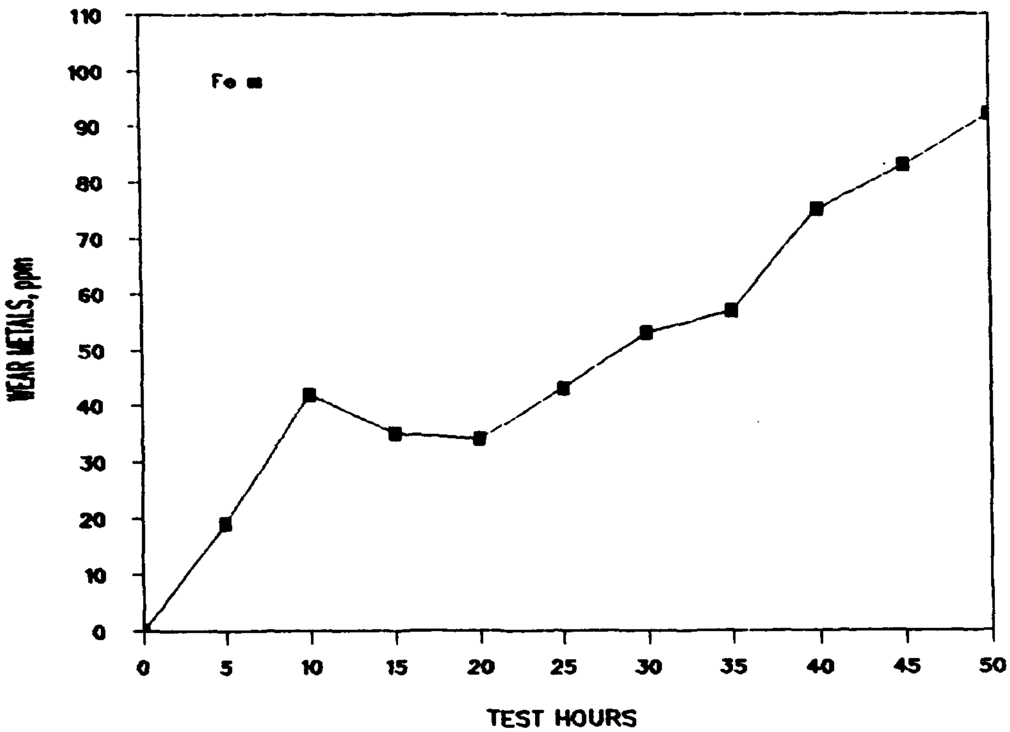

Figure B-14. <u>**Oil E, Test No. HT1E, 275°F OST, wear metals, ppm**</u>

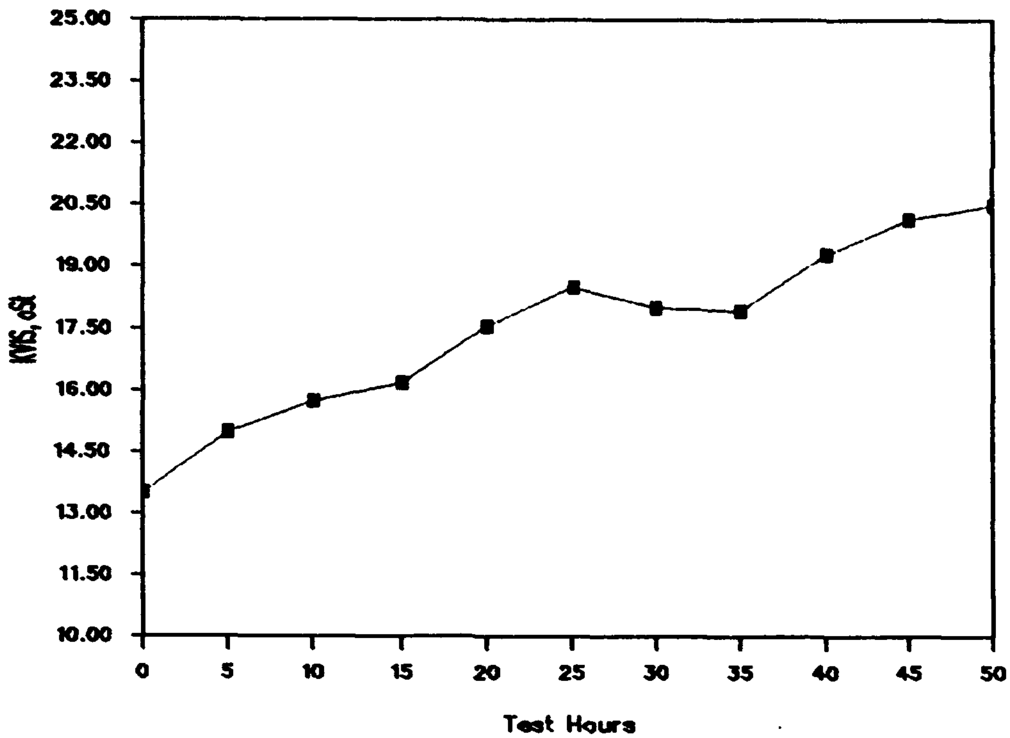

Figure B-15. Oil E, Test No. HT1F, 290°F OST, KVis. 100°C

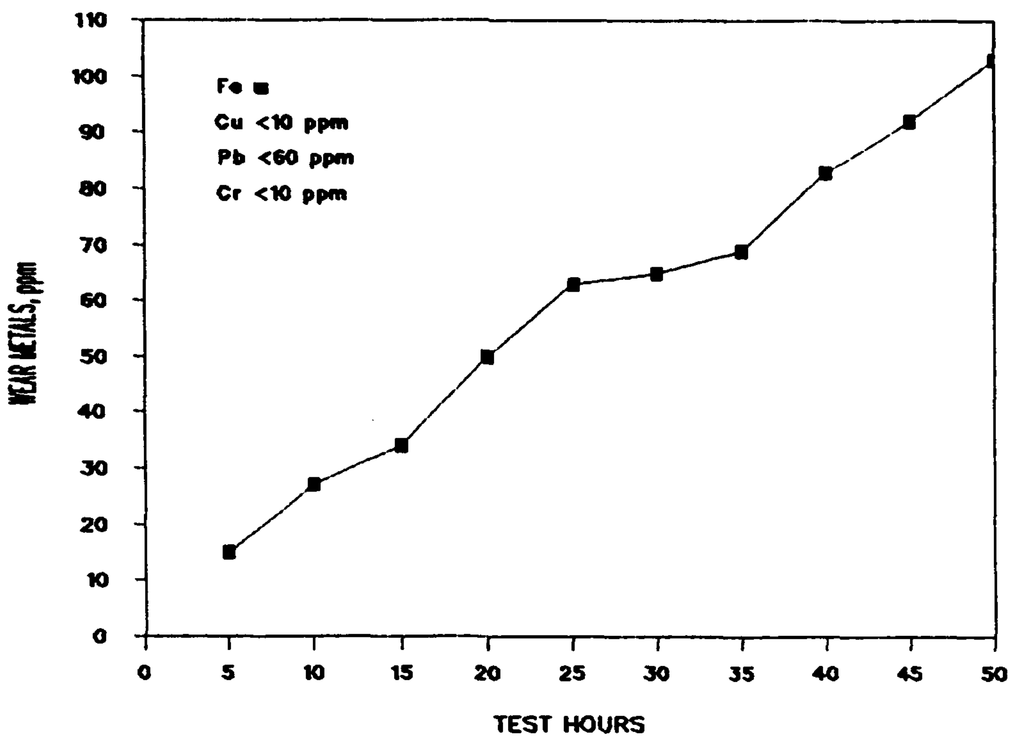

Figure B-16. Oil E, Test No. HT1F, 290°F OST, wear metals, ppm

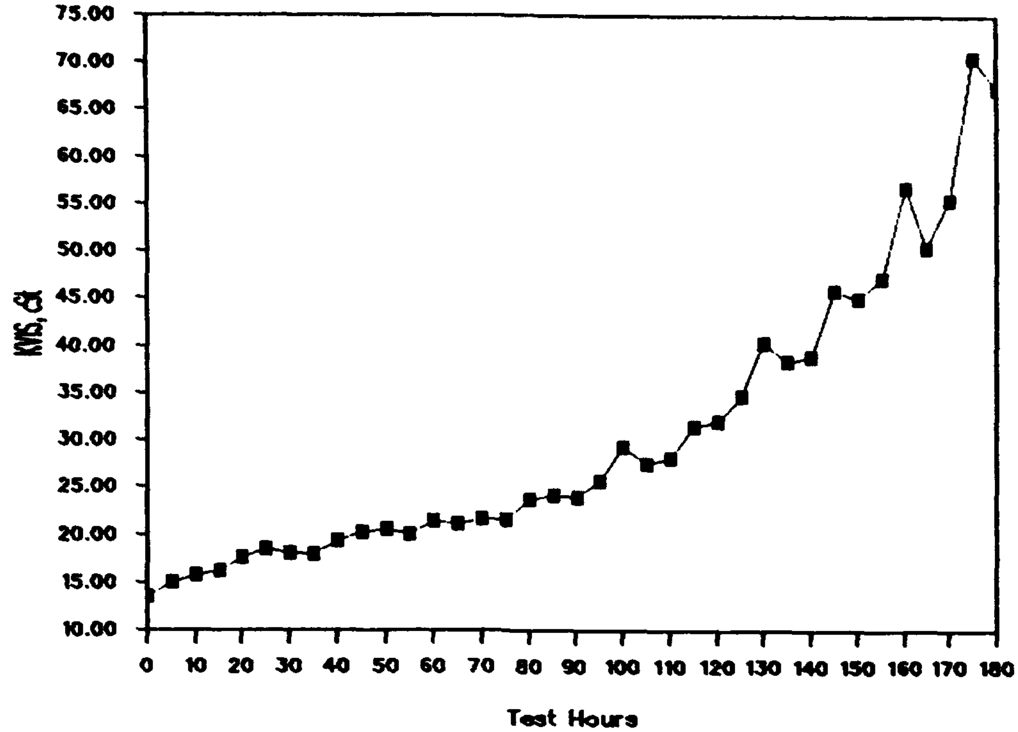

Figure B-17. Oil E, Test No. HT1F, 290°F OST, KVis. 100°C

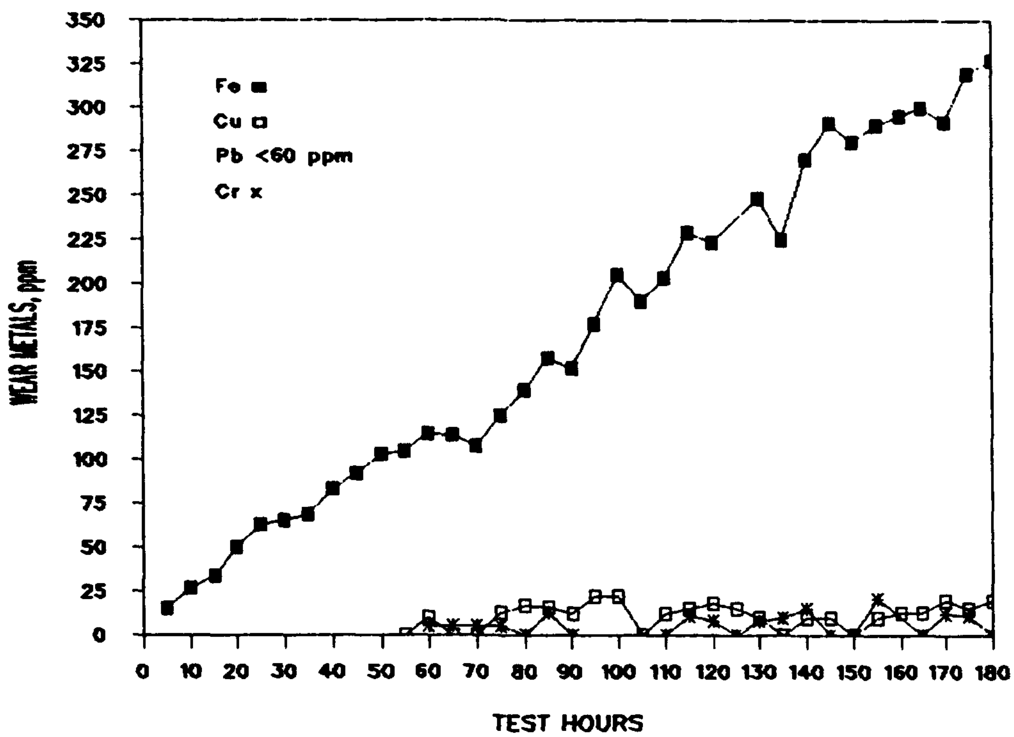

Figure B-18. Oil E, Test No. HT1F, 290°F OST, wear metals, ppm

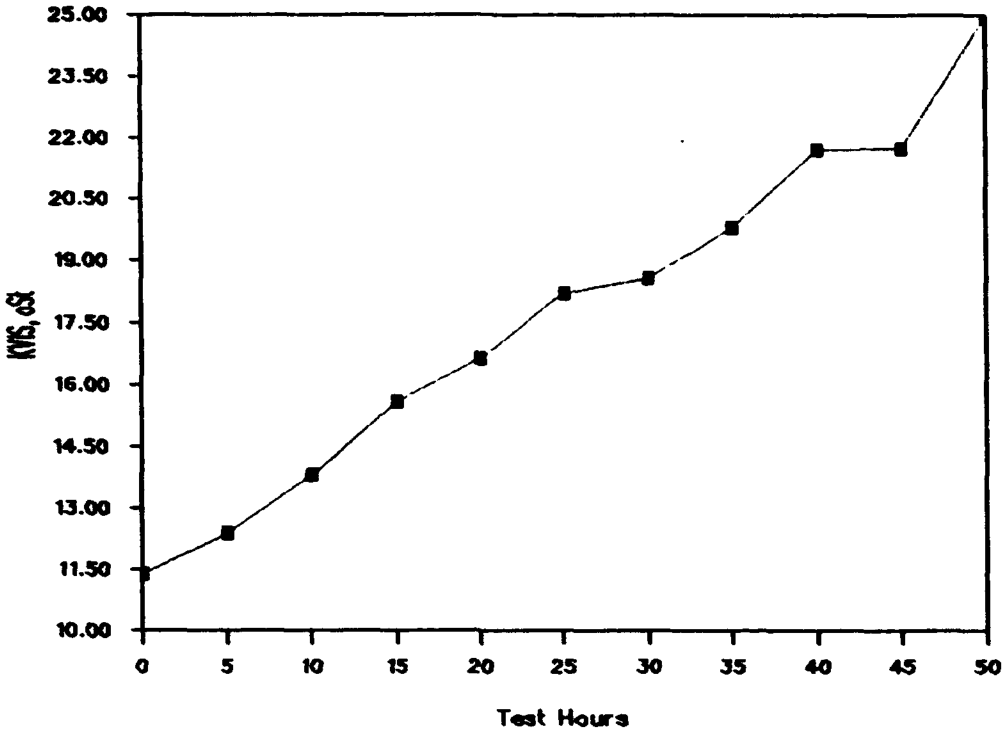

Figure B-19. __Oil B, Test No. HT1G, 290°F OST, KVis. 100°C__

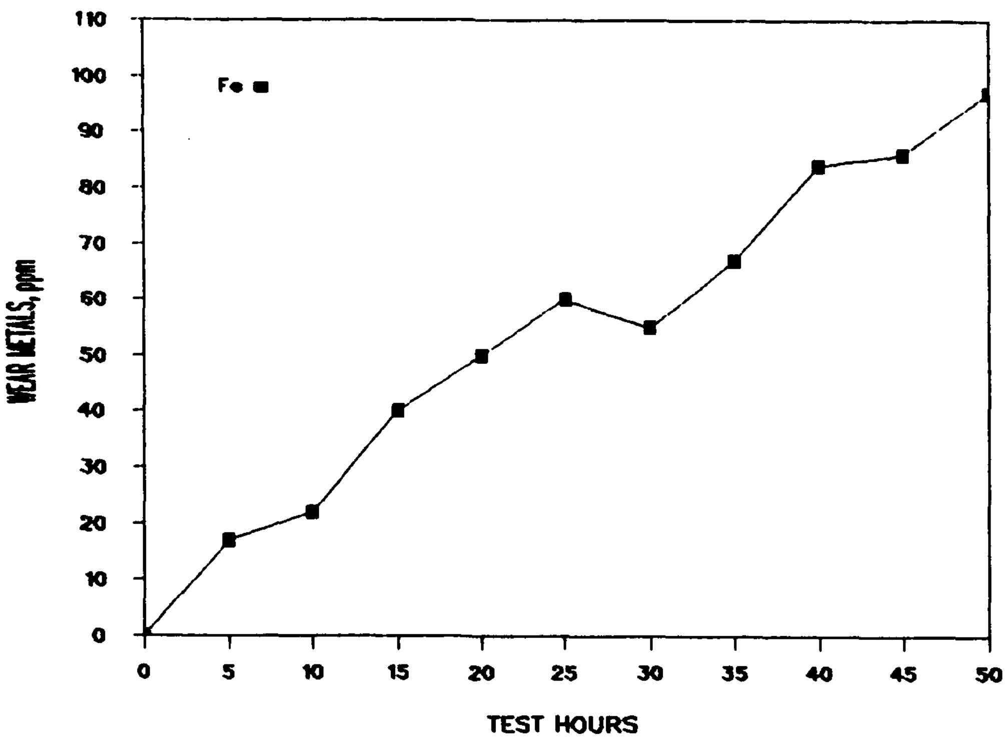

Figure B-20. __Oil B, Test No. HT1G, 290°F OST, wear metals, ppm__

APPENDIX C

Viscosity Versus Test Hours, Wear Metals Versus Test Hours

(VTA-903T Engine Tests)

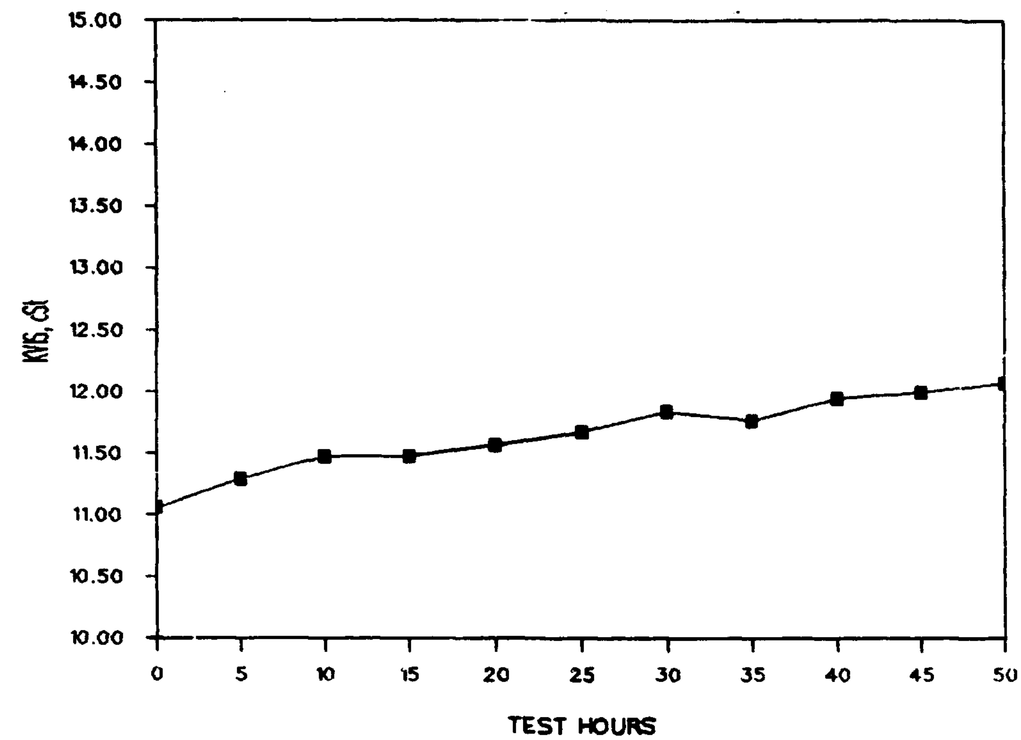

Figure C-1. **<u>Oil A, Test No. CHT-1, 275°F max OST, KVis. 100°C</u>**

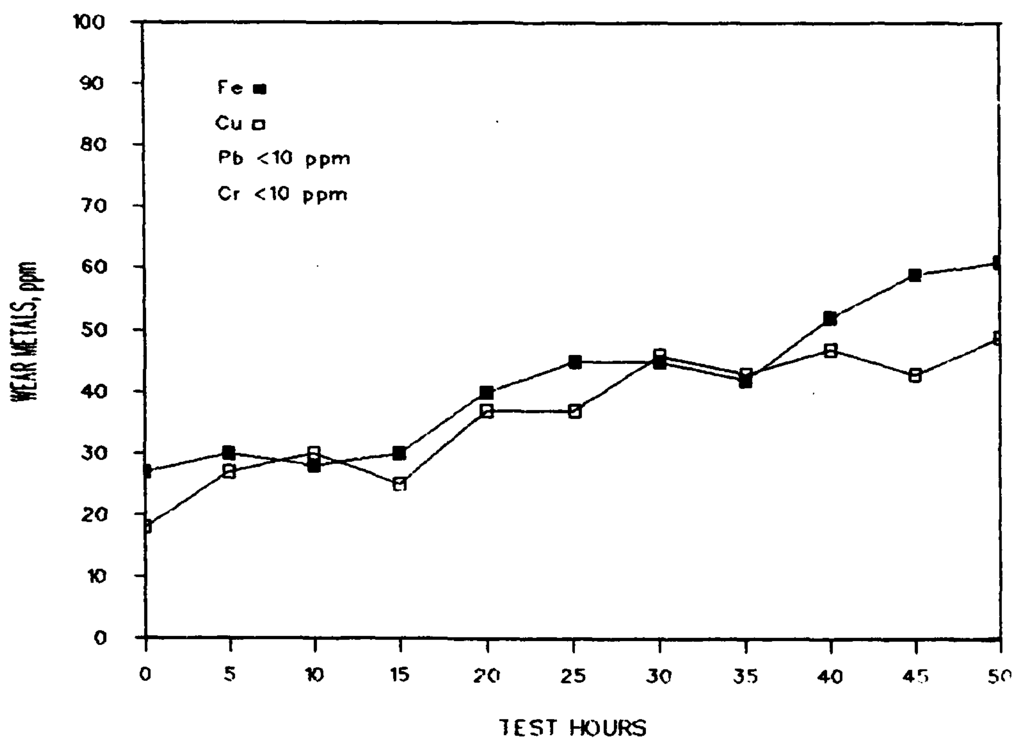

Figure C-2. **<u>Oil A, Test No. CHT-1, 275°F max OST, wear metals, ppm</u>**

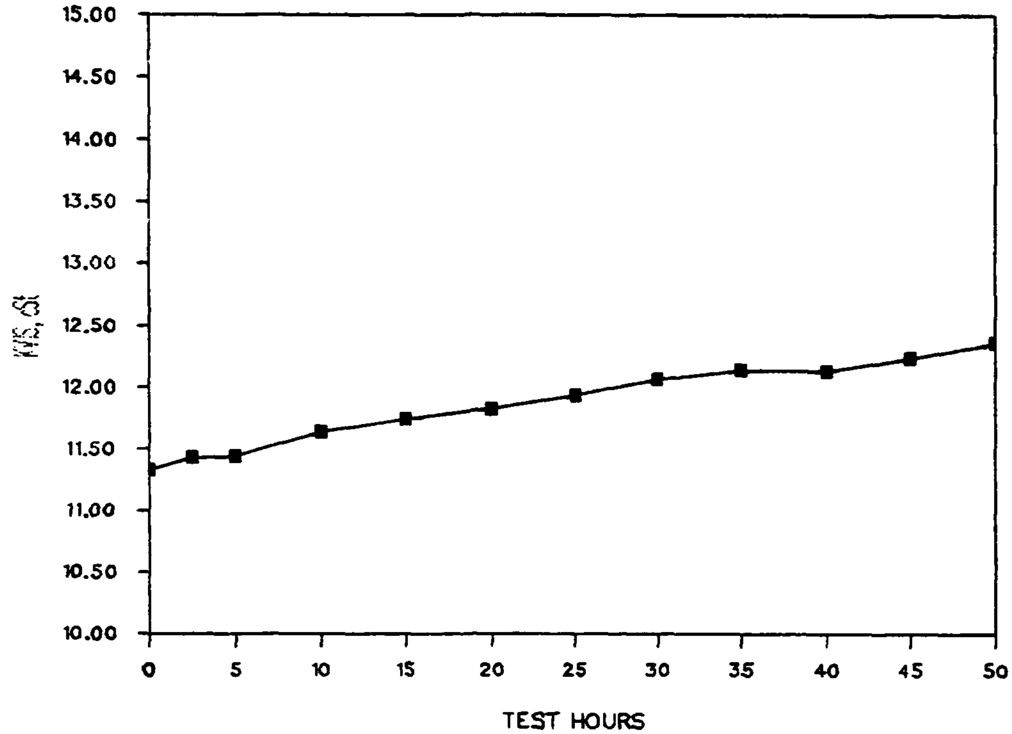

Figure C-3. <u>Oil A, Test No. CHT-1A1, 290°F max OST, KVis. 100°C</u>

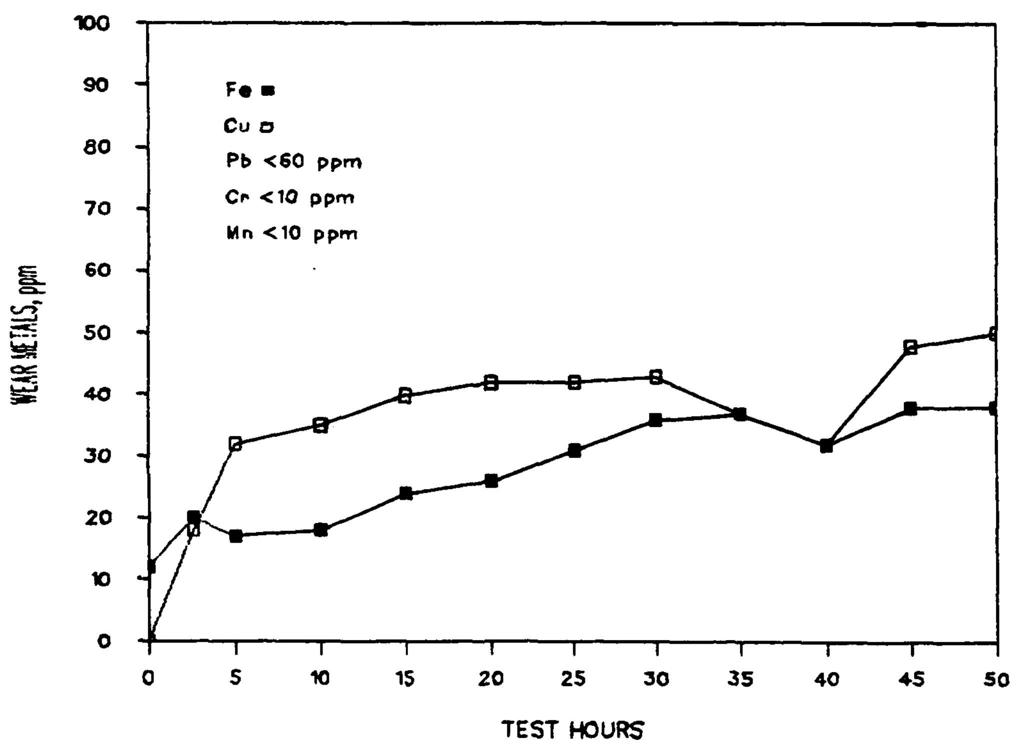

Figure C-4. <u>Oil A, Test No. CHT-1A1, 290°F max OST, wear metals, ppm</u>

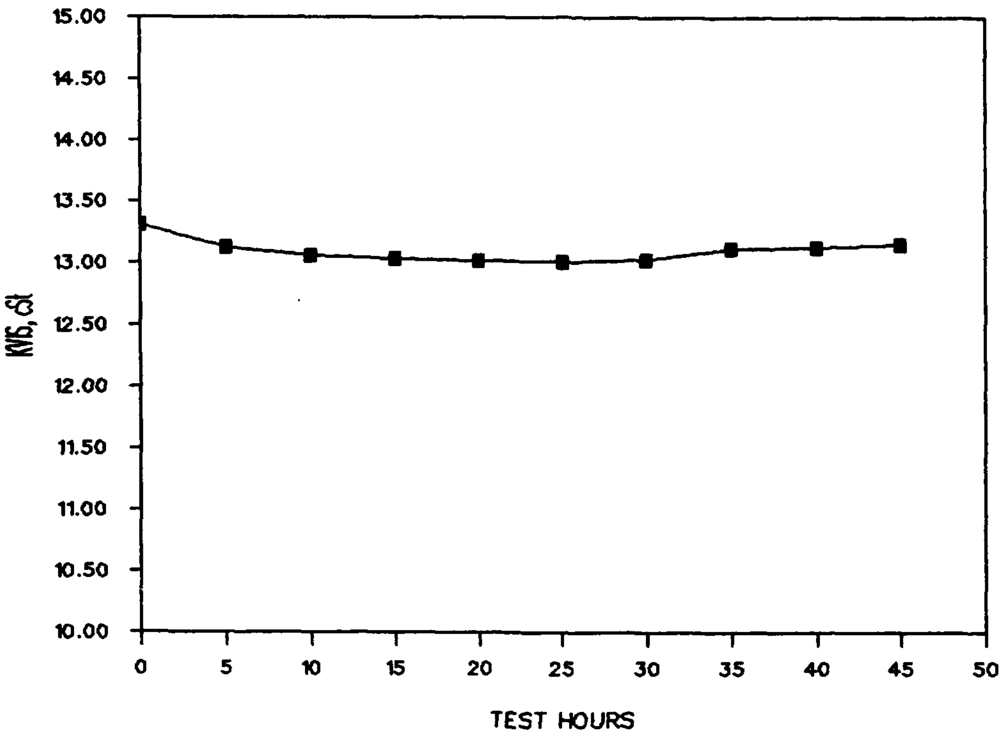

Figure C-5. **Oil E, Test No. CHT-1C, 275°F max OST, KVis. 100°C**

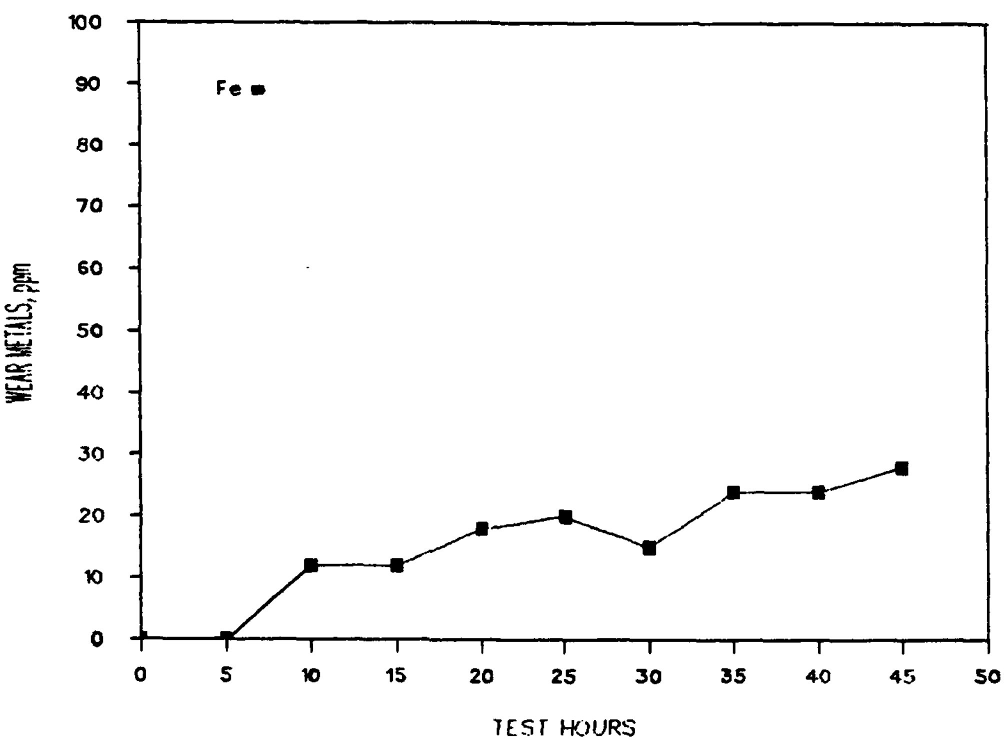

Figure C-6. **Oil E, Test No. CHT-1C, 275°F max OST, wear metals, ppm**

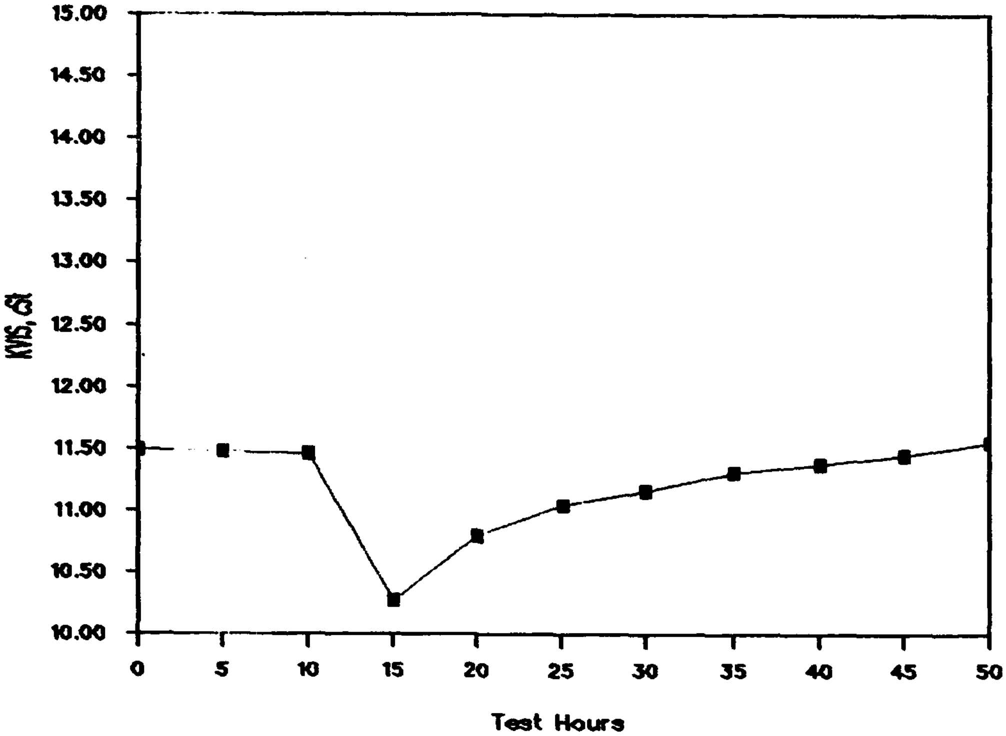

Figure C-7. <u>**Oil A, Test No. CHT-2, 250°F max OST, KVis. 100°C**</u>

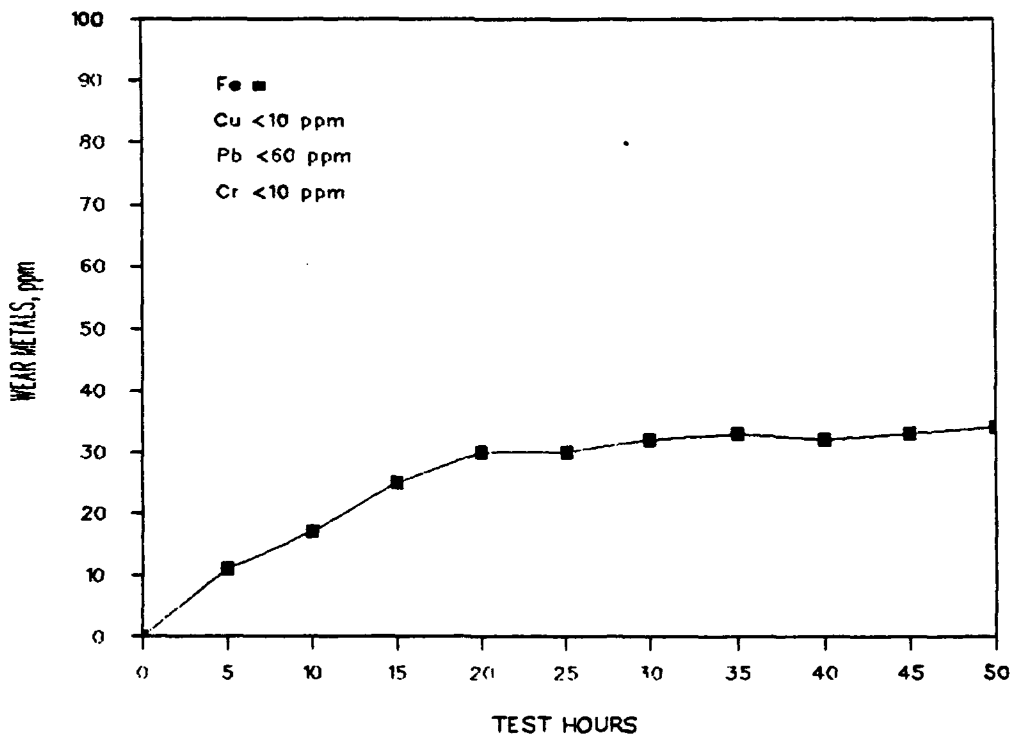

Figure C-8. <u>**Oil A, Test No. CHT-2, 250°F max OST, wear metals, ppm**</u>

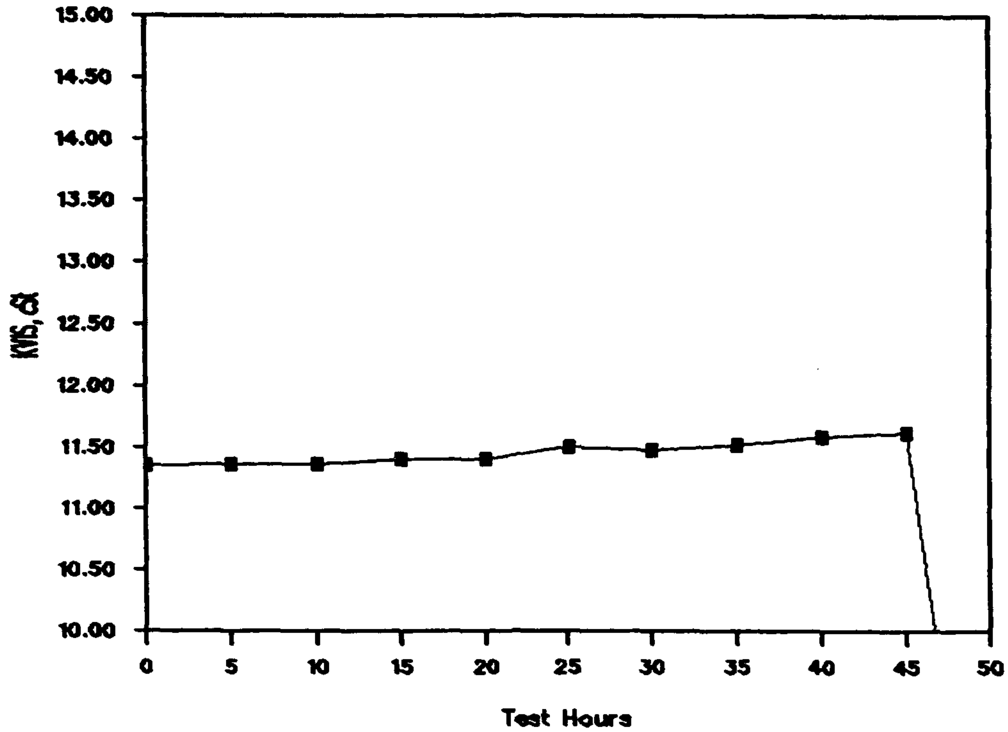

Figure C-9. Oil A, Test No. CHT-2A, 250°F max OST, KVis. 100°C

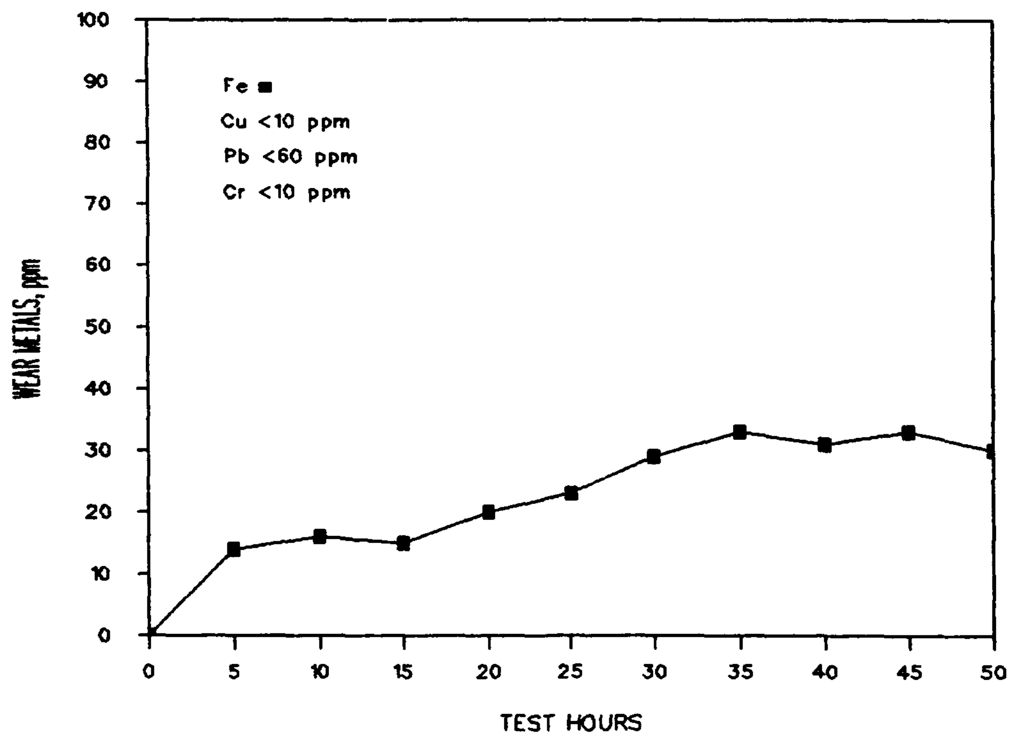

Figure C-10. Oil A, Test No. CHT-2A, 250°F max OST, wear metals, ppm

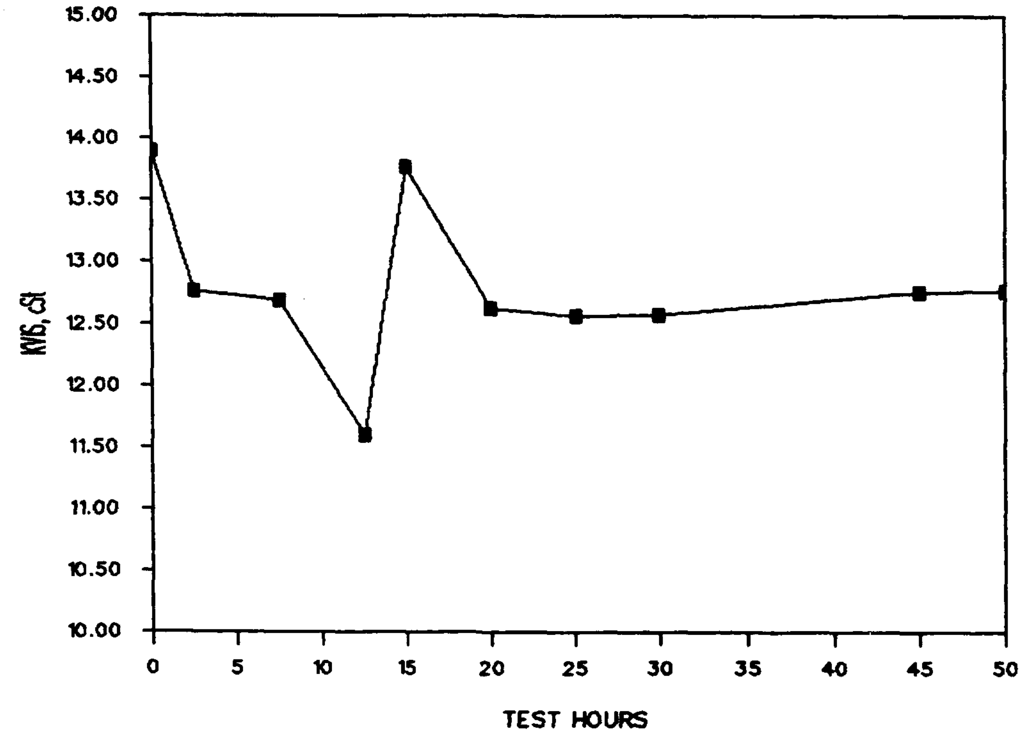

Figure C-11. **Oil F, Test No. CHT-3, 290°F max OST, KVis. 100°C**

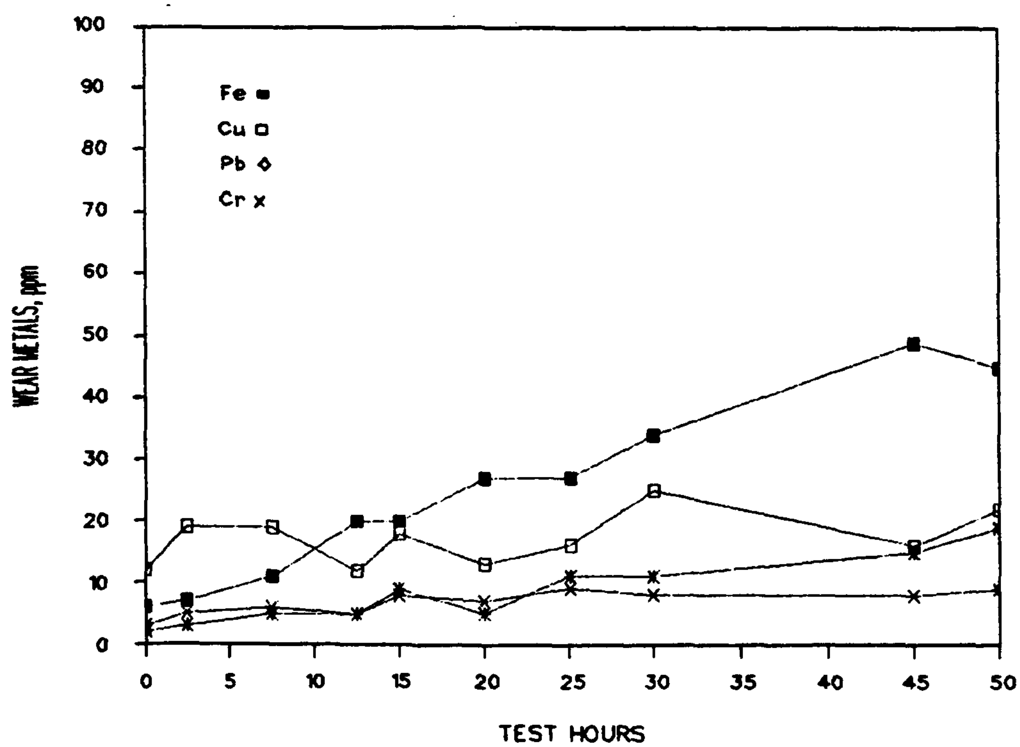

Figure C-12. **Oil F, Test No. CHT-3, 290°F max OST, wear metals, ppm**

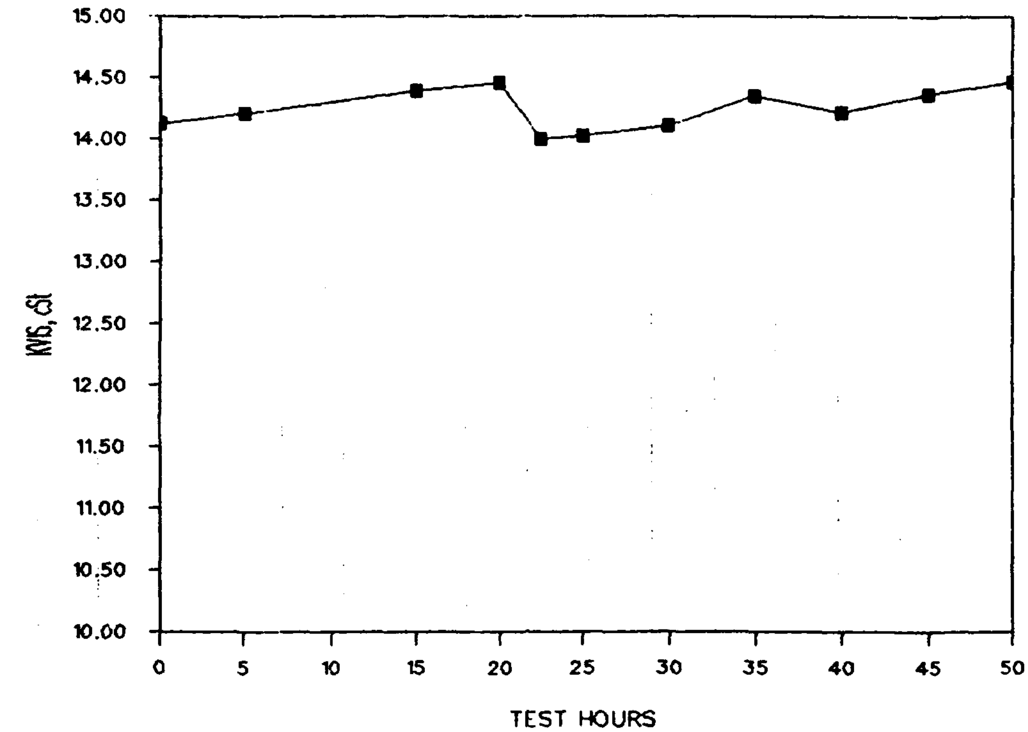

Figure C-13. Oil D, Test No. CHT-4, 290°F max OST, KVis. 100°C

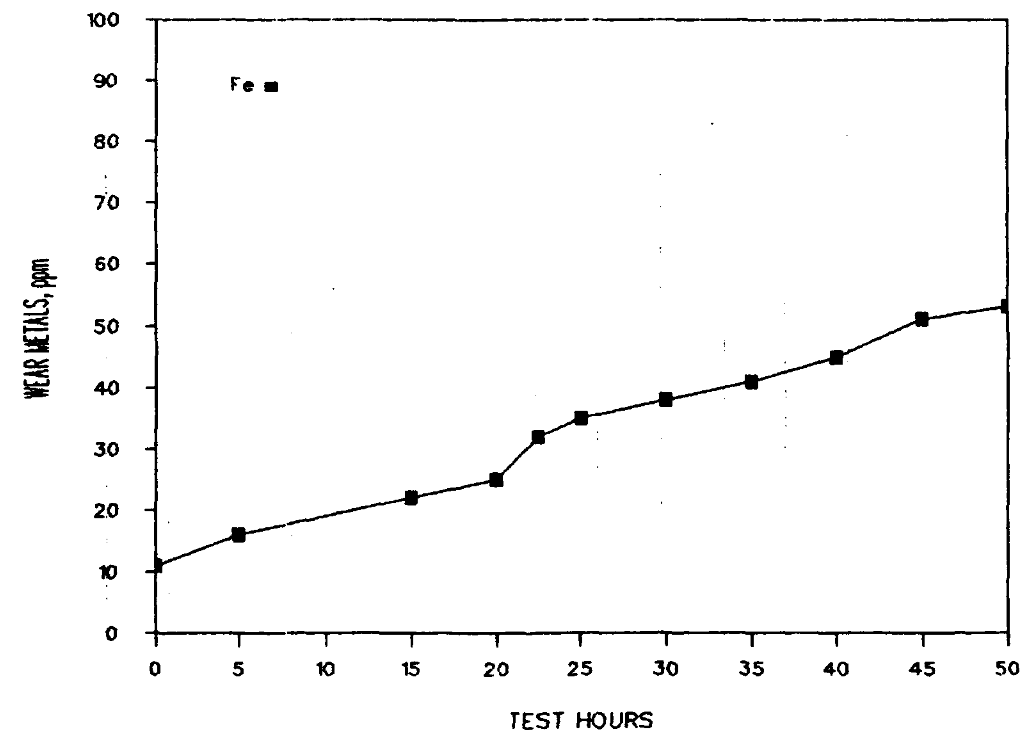

Figure C-14. Oil D, Test No. CHT-4, 290°F max OST, wear metals, ppm

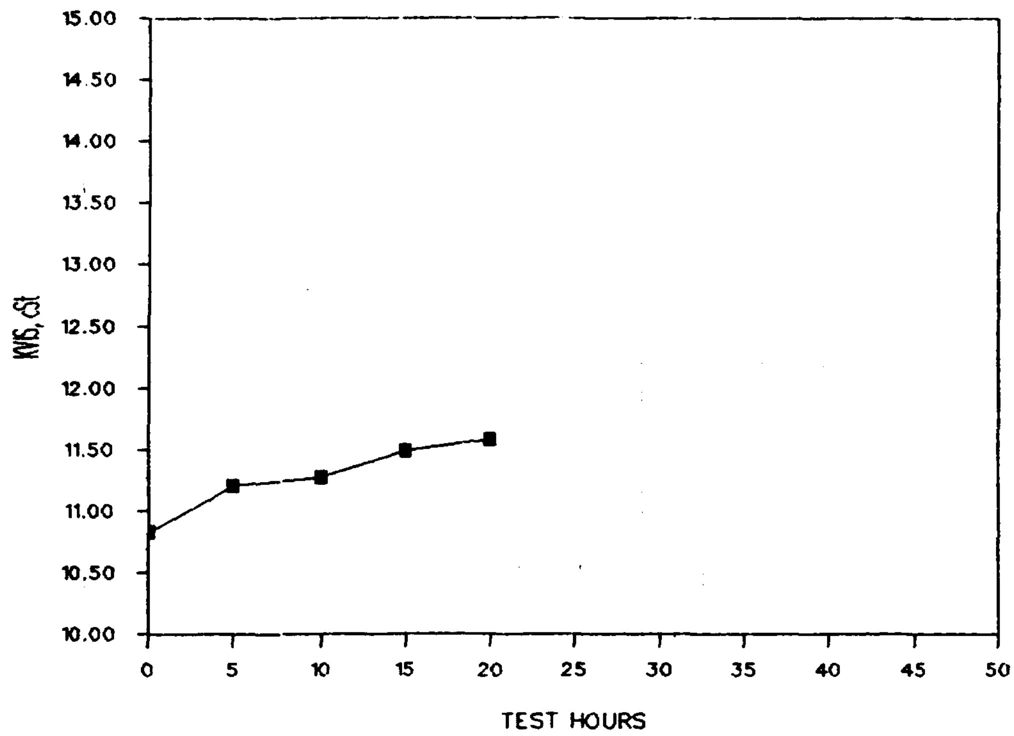

Figure C-15. **Oil A, Test No. CHT-5, 310°F max OST, KVis. 100°C**

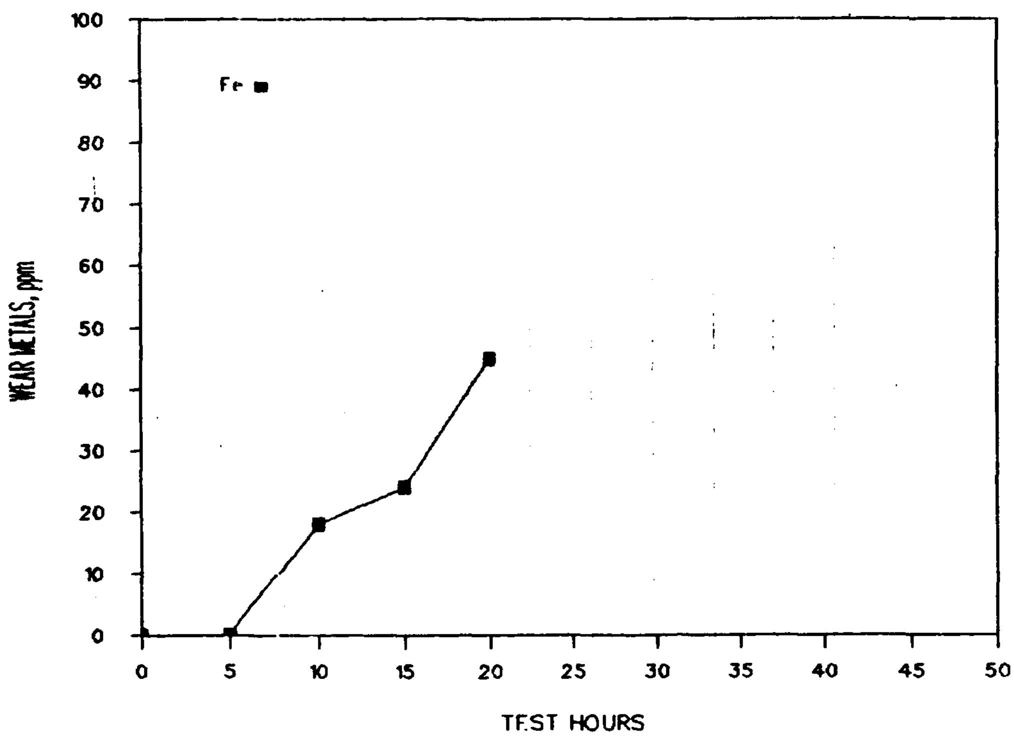

Figure C-16. **Oil A, Test No. CHT-5, 310°F max OST, wear metals, ppm**

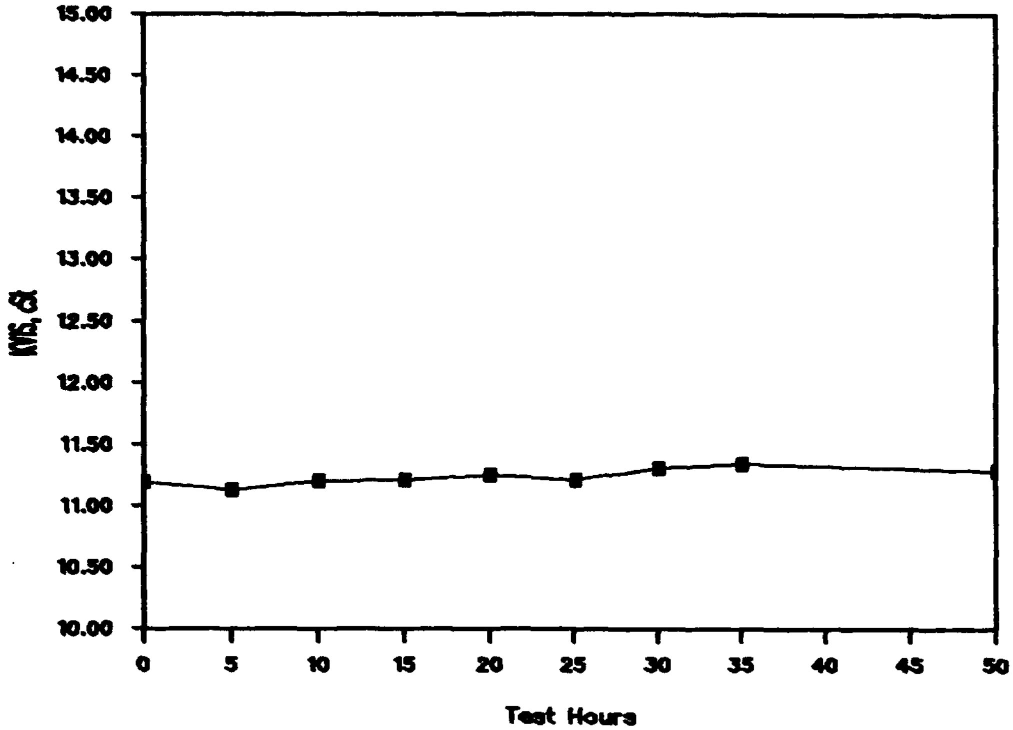

Figure C-17. Oil A, Test No. CHT-5A, 250°F max OST, KVis. 100°C

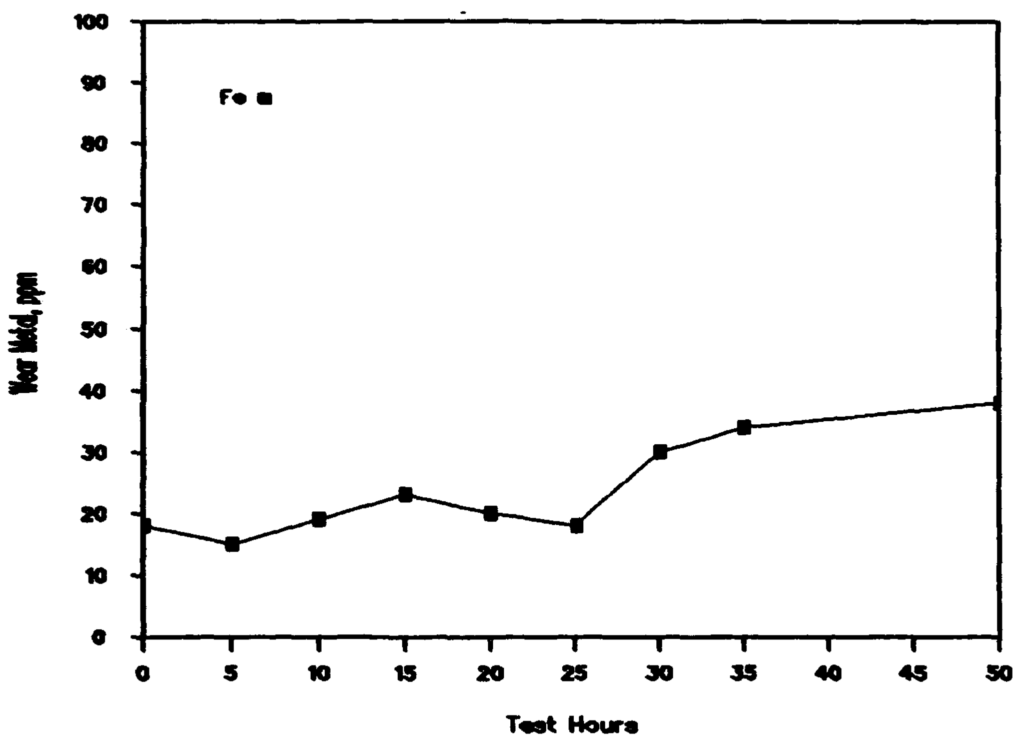

Figure C-18. Oil A, Test No. CHT-5A, 250°F max OST, wear metals, ppm

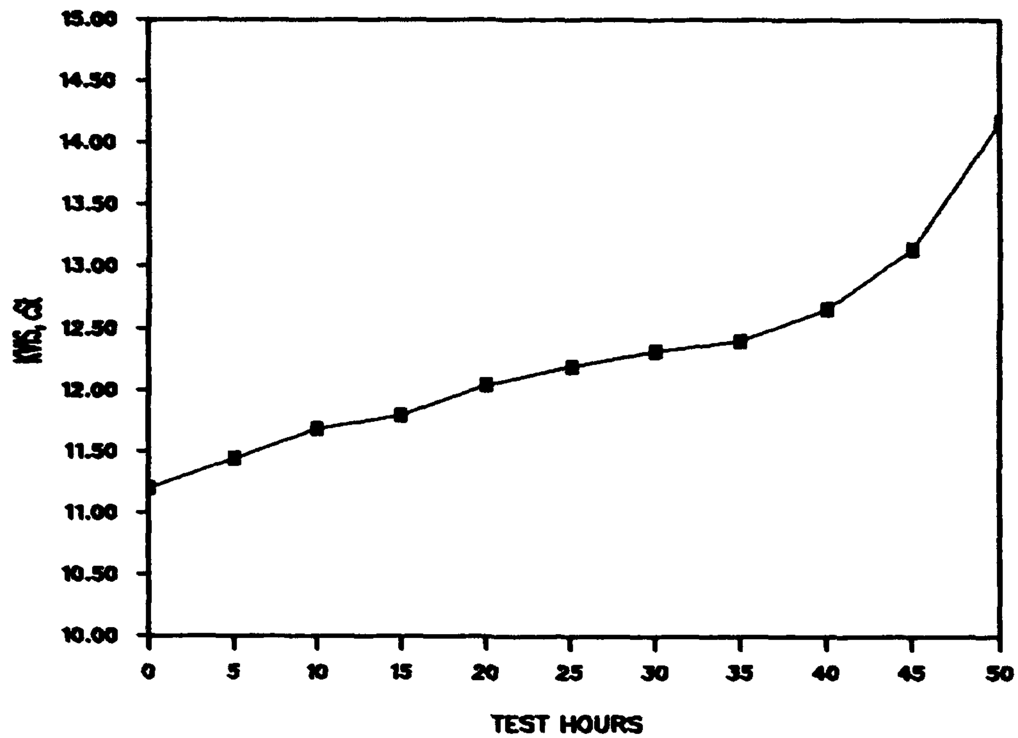

Figure C-19. __Oil A, Test No. CHT-6, 310°F max OST, KVis. 100°C__

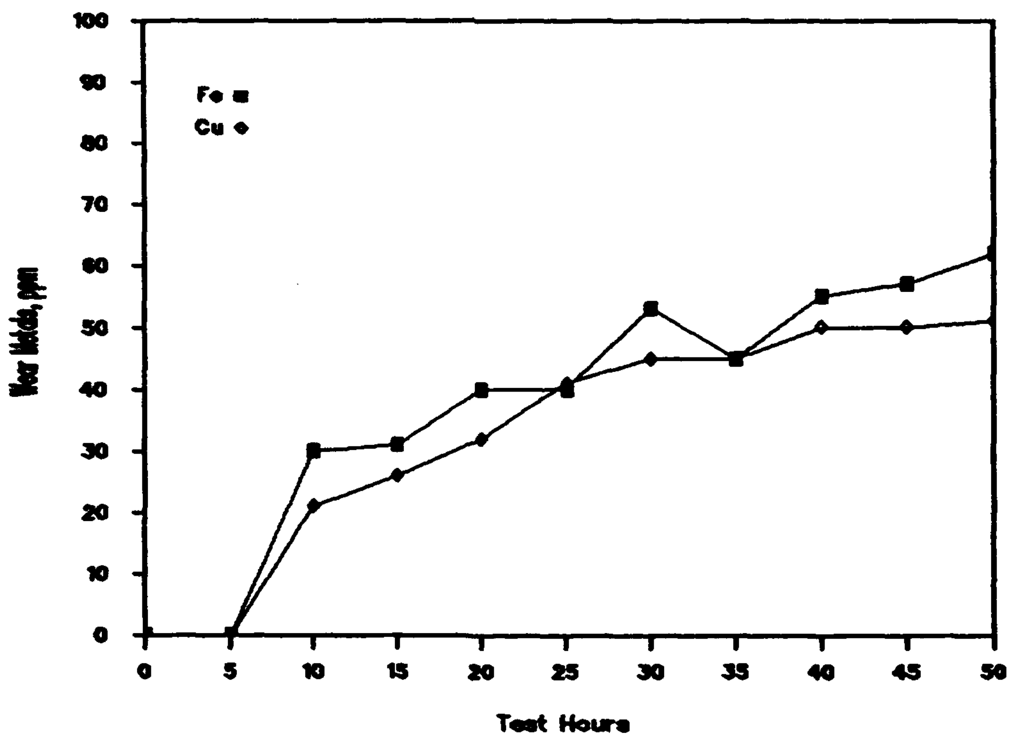

Figure C-20. __Oil A, Test No. CHT-6, 310°F max OST, wear metals, ppm__

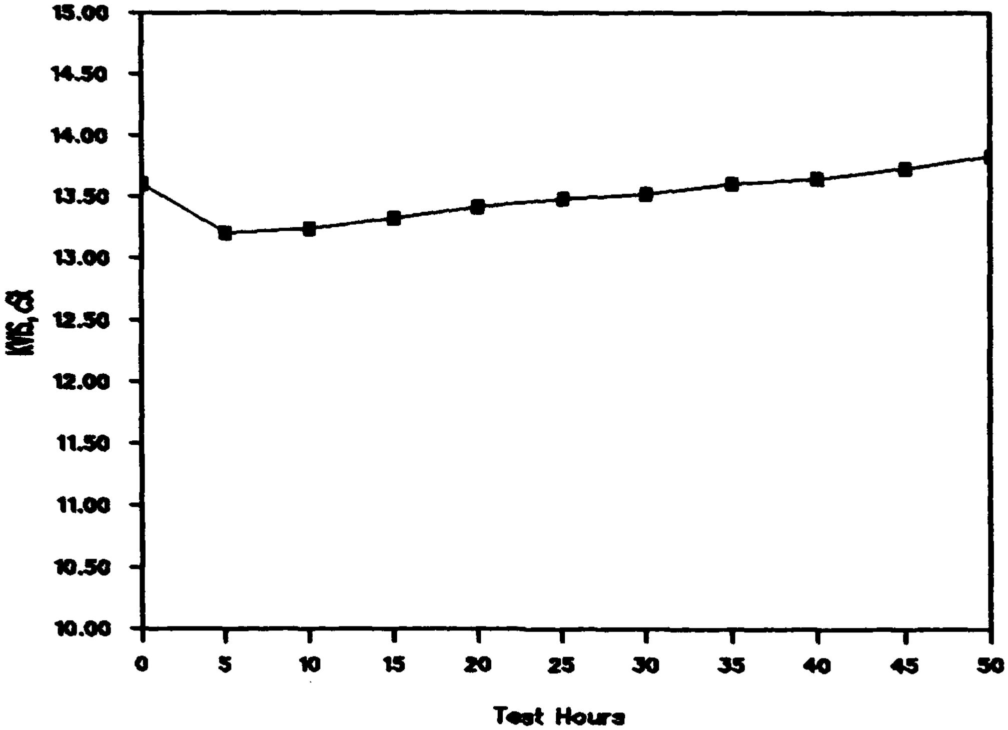

Figure C-21. Oil H, Test No. CHT-7, 290°F max OST, KVis. 100°C

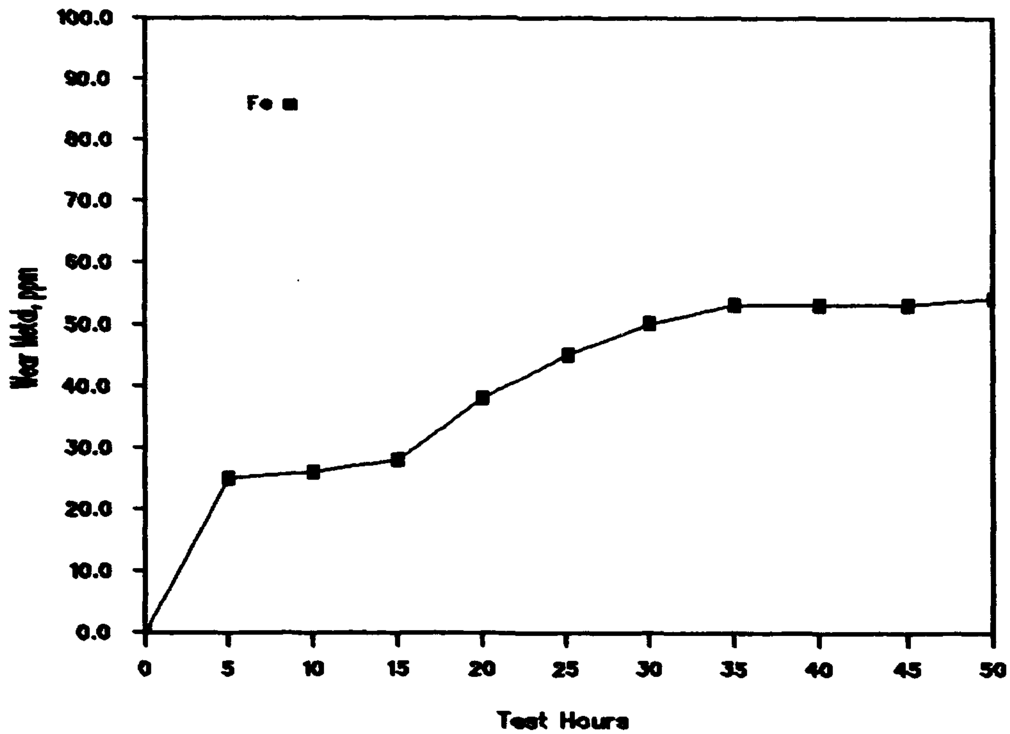

Figure C-22. Oil H, Test No. CHT-7, 290°F max OST, wear metals, ppm

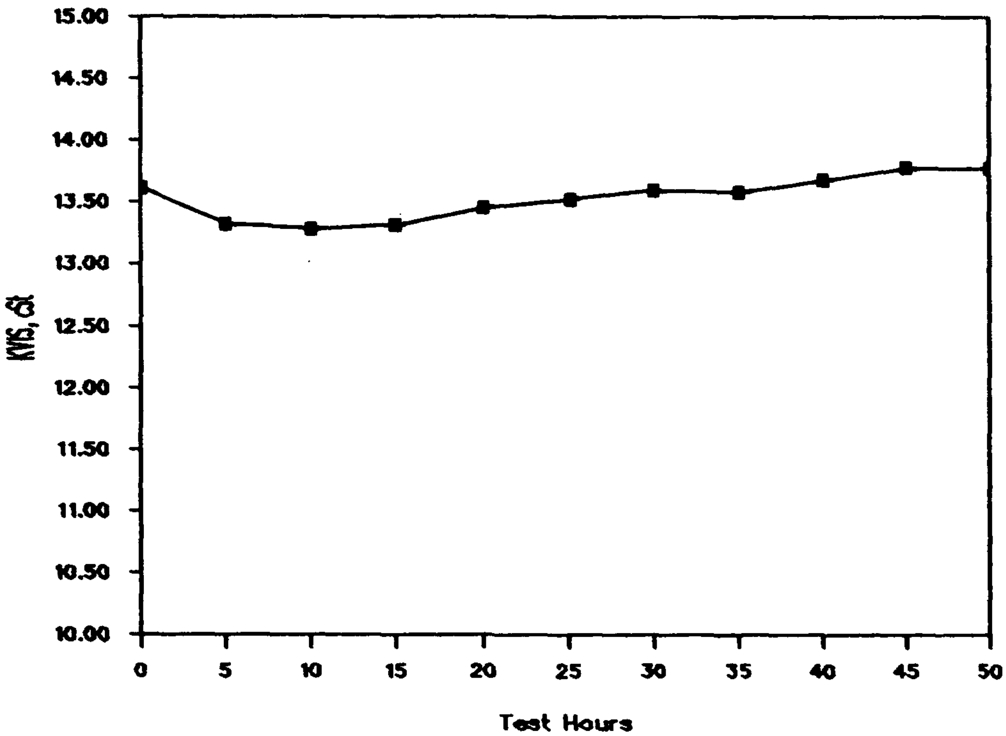

Figure C-23. **Oil I, Test No. CHT-8, 290°F max OST, KVis. 100°C**

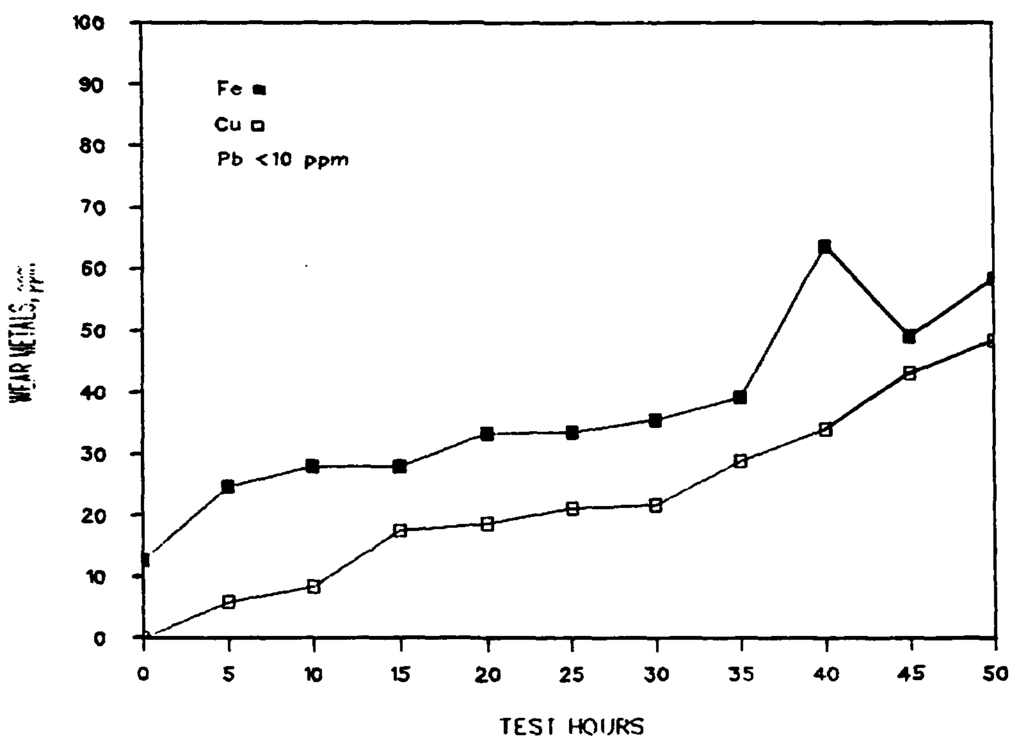

Figure C-24. **Oil I, Test No. CHT-8, 290°F max OST, wear metals, ppm**

LUBRICANTS DISTRIBUTION LIST

Department of Defense

DEFENSE TECH INFO CTR 12
CAMERON STATION
ALEXANDRIA VA 22314

ODUSD
ATTN: (L) MRM 1
PETROLEUM STAFF ANALYST
PENTAGON
WASHINGTON DC 20301-8000

ODUSD
ATTN: (ES) CI 1
400 ARMY NAVY DR
STE 206
ARLINGTON VA 22202

HQ USEUCOM
ATTN: ECJU L1J 1
UNIT 30400 BOX 1000
APO AE 09128-4209

US CINCPAC
ATTN: J422 BOX 64020 1
CAMP H M SMITH
HI 96861-4020

JOAP TSC 1
BLDG 780
NAVAL AIR STA
PENSACOLA FL 32508-5300

DIR DLA
ATTN: DLA MMDI 1
DLA MMSB 1
CAMERON STA
ALEXANDRIA VA 22304-6100

CDR
DEFENSE FUEL SUPPLY CTR
ATTN: DFSC Q BLDG 8 1
DFSC S BLDG 8 1
CAMERON STA
ALEXANDRIA VA 22304-6160

CDR
DEFENSE GEN SUPPLY CTR
ATTN: DGSC SSA 1
DGSC STA 1
8000 JEFFERSON DAVIS HWY
RICHMOND VA 23297-5678

DIR ADV RSCH PROJ AGENCY
ATTN: ARPA/ASTO 1
3701 N FAIRFAX DR
ARLINGTON VA 22203-1714

Department of the Army

HQDA
ATTN: DALO TSE 1
DALO SM 1
PENTAGON
WASHINGTON DC 20310-0103

SARDA
ATTN: SARD TL 1
PENTAGON
WASHINGTON DC 20310-0103

CDR AMC
ATTN: AMCRD S 1
AMCRD E 1
AMCRD IM 1
AMCRD IT 1
AMCEN A 1
AMCLG MS 1
AMCLG MT 1
AMCICP ISI 1
5001 EISENHOWER AVE
ALEXANDRIA VA 22333-0001

TARDEC
ATTN: AMSTA CMA 1
AMSTA CMB 1
AMSTA CME 1
AMSTA HBM 1
AMSTA N 1
AMSTA R 1
AMSTA RG 1
AMCPM ATP 1
AMSTA Q 1
AMSTA UE 1
AMSTA UG 1
CDR TACOM
WARREN MI 48397-5000

CDR ARMY TACOM
ATTN: AMSTA FP 1
AMSTA KL 1
AMSTA MM 1
AMSTA MT 1
AMSTA MC 1
AMSTA GT 1
AMSTA FNG 1
AMSTA FR 1
USMC LNO 1
AMCPM LAV 1
AMCPM M 113/M60 1
AMCPM CCE/SMHE 1
WARREN MI 48397-5000

MOBILITY TECH CTR BELVOIR
ATTN: AMSTA RBF 10
AMSTA RBXA 1
5941 WILSON RD STE 230
FT BELVOIR VA 22060-5843

PROG EXEC OFFICER
ARMORED SYS MODERNIZATION
ATTN: SFAE ASM S 1
SFAE ASM BV 1
SFAE ASM CV 1
SFAE ASM AG 1
CDR TACOM
WARREN MI 48397-5000

PROG EXEC OFFICER
ARMORED SYS MODERNIZATION
ATTN: SFAE ASM FR 1
SFAE ASM AF 1
PICATINNY ARSENAL
NJ 07806-5000

PROG EXEC OFFICER
COMBAT SUPPORT
ATTN: SFAE CS TVL 1
SFAE CS TVM 1
SFAE CS TVH 1
CDR TACOM
WARREN MI 48397-5000

PROG EXEC OFFICER
ARMAMENTS
ATTN: SFAE AR HIP 1
SFAE AR TMA 1
PICATINNY ARSENAL
NJ 07806-5000

PROJ MGR
UNMANNED GROUND VEH
ATTN: AMCPM UG 1
REDSTONE ARSENAL
AL 35898-8060

DIR
ARMY RSCH LAB
ATTN: AMSRL CP PW 1
2800 POWDER MILL RD
ADELPHIA MD 20783-1145

VEHICLE PROPULSION DIR
ATTN: AMSRL VP (MS 77 12) 1
NASA LEWIS RSCH CTR
21000 BROOKPARK RD
CLEVELAND OH 44135

CDR AMSAA
ATTN: AMXSY CM 1
AMXSY L 1
APG MD 21005-5071

CDR ARO
ATTN: AMXRO EN (D MANN) 1
RSCH TRIANGLE PK
NC 27709-2211

DIR
AMC PKG STO CONT CTR
ATTN: SDSTO TE S 1
TOBYHANNA PA 18466-5097

CDR AEC
ATTN: SFIM AEC ECC (T ECCLES) 1
APG MD 21010-5401

CDR ARMY ATCOM	
ATTN: AMSAT I ME (L HEPLER)	1
AMSAT I LA (V SALISBURY)	1
AMSAT R EP (V EDWARD)	1
4300 GOODFELLOW BLVD	
ST LOUIS MO 63120-1798	
CDR AVIA APPL TECH DIR	
ATTN: AMSAT R TP (H MORROW)	1
FT EUSTIS VA 23604-5577	
CDR ARMY NRDEC	
ATTN: SATNC US (J SIEGEL)	1
SATNC UE	1
NATICK MA 01760-5018	
CDR ARMY ARDEC	
ATTN: SMCAR CC	1
SMCAR ESC S	1
PICATINNY ARSENAL	
NJ 07808-5000	
CDR ARMY DESCOM	
ATTN: AMSDS MN	1
AMSDS EN	1
CHAMBERSBURG PA 17201-4170	
CDR ARMY AMCCOM	
ATTN: AMSMC MA	1
ROCK ISLAND IL 61299-6000	
CDR ARMY WATERVLIET ARSN	
ATTN: SARWY RDD	1
WATERVLIET NY 12189	
DIR AMC LOG SPT ACT	
ATTN: AMXLS LA	1
REDSTONE ARSENAL	
AL 35890-7466	
CDR APC	
ATTN: SATPC Q	1
SATPC QE (BLDG 85-3)	1
NEW CUMBERLAND PA 17070-5005	
PETROL TEST FAC WEST	1
BLDG 247 TRACEY LOC	
DDRW	
P O BOX 96001	
STOCKTON CA 95296-0960	
CDR ARMY LEA	
ATTN: LOEA PL	1
NEW CUMBERLAND PA 17070-5007	
CDR ARMY TECOM	
ATTN: AMSTE TA R	1
AMSTE TC D	1
AMSTE EQ	1
APG MD 21005-5006	
PROJ MGR PETROL WATER LOG	
ATTN: AMCPM PWL	1
4300 GOODFELLOW BLVD	
ST LOUIS MO 63120-1798	
PROJ MGM MOBILE ELEC PWR	
ATTN: AMCPM MEP	1
7798 CISSNA RD STE 200	
SPRINGFIELD VA 22150-3199	
CDR	
ARMY COLD REGION TEST CTR	
ATTN: STECR TM	1
STECR LG	1
APO AP 96508-7850	
CDR	
ARMY BIOMED RSCH DEV LAB	
ATTN: SGRD UBZ A	1
FT DETRICK MD 21702-5010	
CDR FORSCOM	
ATTN: AFLG TRS	1
FT MCPHERSON GA 30330-6000	
CDR TRADOC	
ATTN: ATCD SL 5	1
INGALLS RD BLDG 163	
FT MONROE VA 23651-5194	
CDR ARMY ARMOR CTR	
ATTN: ATSB CD ML	1
ATSB TSM T	1
FT KNOX KY 40121-5000	
CDR ARMY QM SCHOOL	
ATTN: ATSM CD	1
ATSM PWD	1
FT LEE VA 23001-5000	
CDR	
ARMY COMBINED ARMS SPT CMD	
ATTN: ATCL CD	1
ATCL MS	1
FT LEE VA 23801-6000	
CDR ARMY FIELD ARTY SCH	
ATTN: ATSF CD	1
FT SILL OK 73503	

CDR ARMY TRANS SCHOOL
ATTN: ATSP CD MS 1
FT EUSTIS VA 23604-5000

CDR ARMY INF SCHOOL
ATTN: ATSH CD 1
ATSH AT 1
FT BENNING GA 31905-5000

CDR ARMY AVIA CTR
ATTN: ATZQ DOL M 1
ATZQ DI 1
FT RUCKER AL 36362-5115

CDR ARMY CACDA
ATTN: ATZL CD 1
FT LEAVENWORTH KA 66027-5300

CDR ARMY ENGR SCHOOL
ATTN: ATSE CD 1
FT LEONARD WOOD MO 65473-5000

CDR ARMY ORDN CTR
ATTN: ATSL CD CS 1
APG MD 21005

CDR ARMY SAFETY CTR
ATTN: CSSC PMG 1
CSSC SPS 1
FT RUCKER AL 36362-5363

CDR ARMY CSTA
ATTN: STECS EN 1
STECS LI 1
STECS AE 1
STECS AA 1
APG MD 21005-5059

CDR ARMY YPG
ATTN: STEYP MT TL M 1
YUMA AZ 85365-9130

CDR ARMY CERL
ATTN: CECER EN 1
P O BOX 9005
CHAMPAIGN IL 61826-9005

DIR 1
AMC FAST PROGRAM
10101 GRIDLEY RD STE 104
FT BELVOIR VA 22060-5818

CDR I CORPS AND FT LEWIS
ATTN: AFZH CSS 1
FT LEWIS WA 98433-5000

CDR
RED RIVER ARMY DEPOT
ATTN: SDSRR M 1
SDSRR Q 1
TEXARKANA TX 75501-5000

PS MAGAZINE DIV
ATTN: AMXLS PS 1
DIR LOGSA
REDSTONE ARSENAL AL 35898-7466

CDR 6TH ID (L)
ATTN: APUR LG M 1
1060 GAFFNEY RD
FT WAINWRIGHT AK 99703

Department of the Navy

OFC OF NAVAL RSCH
ATTN: ONR 464 1
800 N QUINCY ST
ARLINGTON VA 22217-5660

CDR
NAVAL SEA SYSTEMS CMD
ATTN: SEA 03M3 1
2531 JEFFERSON DAVIS HWY
ARLINGTON VA 22242-5160

CDR
NAVAL SURFACE WARFARE CTR
ATTN: CODE 632 1
CODE 859 1
3A LEGGETT CIRCLE
ANNAPOLIS MD 21401-5067

CDR
NAVAL RSCH LABORATORY
ATTN: CODE 6181 1
WASHINGTON DC 20375-5342

CDR
NAVAL AIR WARFARE CTR
ATTN: CODE PE33 AJD 1
P O BOX 7176
TRENTON NJ 08628-0176

CDR 1
NAVAL PETROLEUM OFFICE
CAMERON STA T 40
5010 DUKE STREET
ALEXANDRIA VA 22304-6180

OFC ASST SEC NAVY (I & E) 1
CRYSTAL PLAZA 5
2211 JEFFERSON DAVIS HWY
ARLINGTON VA 22244-5110

CDR
NAVAL AIR SYSTEMS CMD
ATTN: AIR 53623C 1
1421 JEFFERSON DAVIS HWY
ARLINGTON VA 22243-5360

Department of the Navy/U.S. Marine Corps

HQ USMC
ATTN: LPP 1
WASHINGTON DC 20380-0001

PROG MGR COMBAT SER SPT 1
MARINE CORPS SYS CMD
2033 BARNETT AVE STE 315
QUANTICO VA 22134-5080

PROG MGR GROUND WEAPONS 1
MARINE CORPS SYS CMD
2033 BARNETT AVE
QUANTICO VA 22134-5080

PROG MGR ENGR SYS 1
MARINE CORPS SYS CMD
2033 BARNETT AVE
QUANTICO VA 22134-5080

CDR
MARINE CORPS SYS CMD
ATTN: SSE 1
2033 BARNETT AVE STE 315
QUANTICO VA 22134-5010

CDR
BLOUNT ISLAND CMD
ATTN: CODE 922/1 1
5880 CHANNEL VIEW BLVD
JACKSONVILLE FL 32226-3404

CDR
MARINE CORPS LOGISTICS BA
ATTN: CODE 837 1
814 RADFORD BLVD
ALBANY GA 31704-1128

CDR 1
2ND MARINE DIV
PSC BOX 20090
CAMP LEJEUNNE NC 28542-0090

CDR 1
1ST MARINE DIV
CAMP PENDLETON CA 92055-5702

CDR 1
FMFPAC G4
BOX 64118
CAMP H M SMITH HI 96861-4118

Department of the Air Force

HQ USAF/LGSSF
ATTN: FUELS POLICY 1
1030 AIR FORCE PENTAGON
WASHINGTON DC 20330-1030

HQ USAF/LGTV
ATTN: VEH EQUIP/FACILITY 1
1030 AIR FORCE PENTAGON
WASHINGTON DC 20330-1030

AIR FORCE WRIGHT LAB
ATTN: WL/POS 1
WL/POSF 1
WL/POSL 1
1790 LOOP RD N
WRIGHT PATTERSON AFB
OH 45433-7103

AIR FORCE WRIGHT LAB
ATTN: WL/MLBT 1
2941 P ST STE 1
WRIGHT PATTERSON AFB
OH 45433-7750

AIR FORCE WRIGHT LAB
ATTN: WL/MLSE 1
2179 12TH ST STE 1
WRIGHT PATTERSON AFB
OH 45433-7718

AIR FORCE MEEP MGMT OFC 1
615 SMSQ/LGTV MEEP
201 BISCAYNE DR STE 2
ENGLIN AFB FL 32542-5303

SA ALC/SFT 1
1014 ANDREWS RD STE 1
KELLY AFB TX 78241-5603

WR ALC/LVRS 1
225 OCMULGEE CT
ROBINS AFB GA 31098-1647

Other Federal Agencies

NASA
LEWIS RESEARCH CENTER 1
CLEVELAND OH 44135

NIPER
PO BOX 2128 1
BARTLESVILLE OK 74005

DOT
FAA
AWS 110 1
800 INDEPENDENCE AVE SW
WASHINGTON DC 20590

DOE
CE 151 (MR RUSSEL) 1
1000 INDEPENDENCE AVE SW
WASHINGTON DC 20585

EPA
AIR POLLUTION CONTROL 1
2565 PLYMOUTH RD
ANN ARBOR MI 48105